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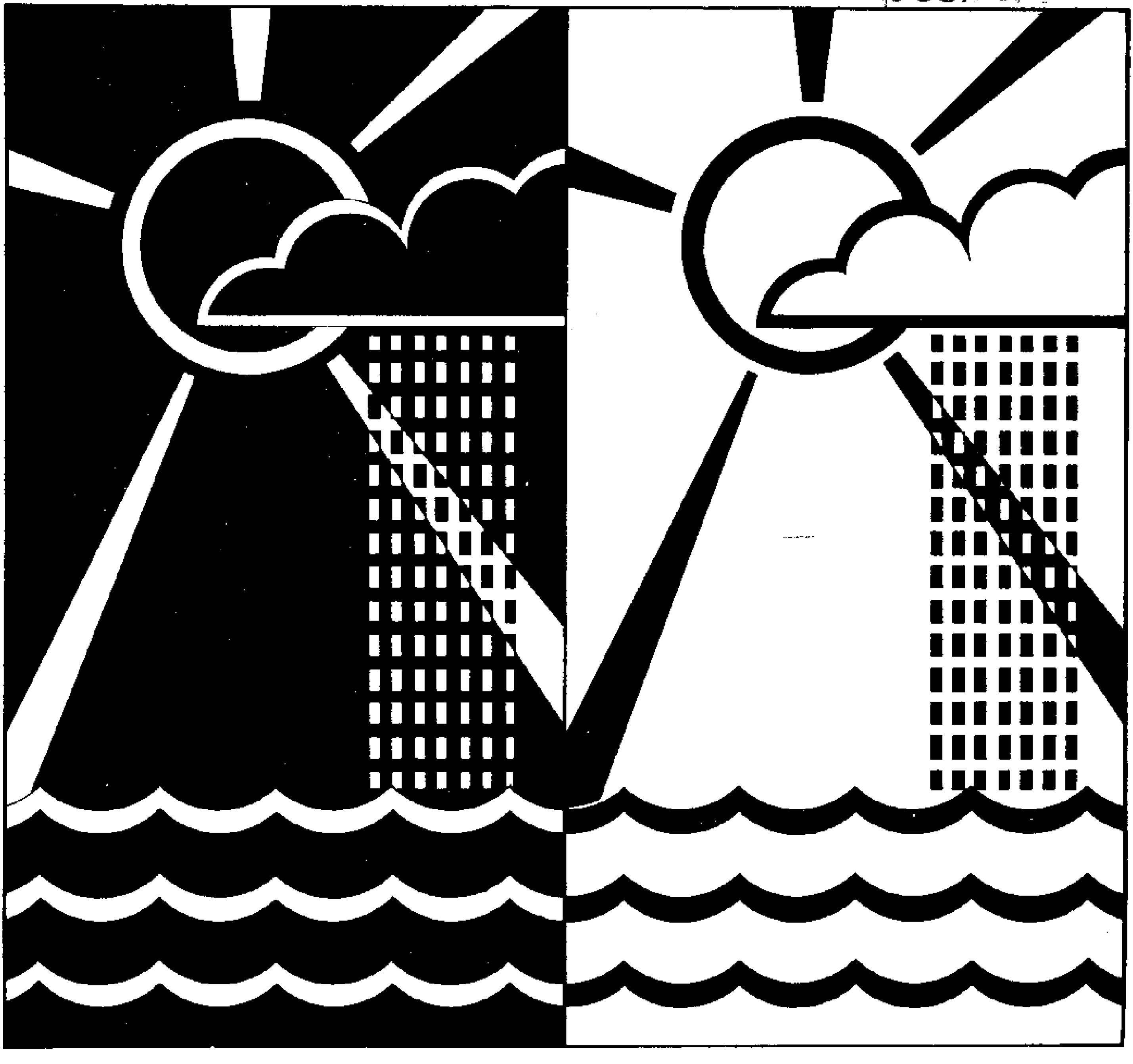

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college of marine studies ....university of delaware..........newark, delaware 19711

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PREFACE

To develop the commercially valuable marine resources of the Delaware estuary requires a full understanding of the influence of the environment on these resources. But estuarine environments are greatly modified by conditions over nearby land areas. Climatic conditions in the surrounding region, especially as they influence the runoff of fresh water, are of great importance in determining the conditions under which shellfish and other marine resources develop and live. Thus, understanding the relationship between the factors of the climatic water balance and estuarine conditions is central to any program to develop more viable and valuable marine resources.

The objectives of this project have been to determine, from analyses of available climatic data, a) the volume of fresh water flow into the Delaware estuary and its possible change over time with changes in land use in the Delaware River basin, and b) the relation between this fresh water flow and measures of water quality in the estuary of importance to shellfish.

The work on the project has proceeded along three separate, though related, lines.

1. Evaluation of long-term monthly climatic water balances for a large number of stations over the basin, and the determination of quantitative information on water inflows and outflows in the estuary.

2. Analysis of isochloric movements in the Delaware estuary during the period 1965-68; investigation of the relation between water flows and chlorinity at selected places in the estuary.

3. Study of the effect of changing land use on water runoff from one small sub-basin of the Delaware River.

The present report sums up the results of two years of work on these three lines of study under a grant originally from the National Science Foundation Sea Grant program and now administered by the National Oceanographic and Atmospheric Agency.

PART I

ESTUARINE RESPONSE TO FACTORS OF THE CLIMATIC WATER BALANCE

by

John R. Mather and Frank J. Swaye

I. INTRODUCTION

Most shellfish develop and live in an estuarine or coastal environment that is influenced by the conditions of water flow from the surrounding land, ocean, and atmosphere. In an estuary such as the Delaware, a simple balance of water inflows and outflows may be written as follows:

$$RO + P - E \pm S = I/O$$

where
RO is the runoff from the surrounding land area;
P is the precipitation on the estuary surface;
E is the evaporation from the estuary surface;
S is the seepage into or out of the estuary through the bottom;
I/O is the net inflow or outflow of water from or to the ocean needed to maintain the water level.

In practice, it is extremely difficult to evaluate S. It is usually assumed that this term is negligible although the validity of this assumption may be open to question. The remaining terms on the left-hand side of the relation can be evaluated with some precision so that the net inflow from or outflow to the ocean can be determined quantitatively. This type of water balance approach provides the only practical method for determining net inflow or outflow of water to an estuary since direct measurement is almost impossible.

The first three terms of the water balance equation (RO, P, E) involve climatic variables. Precipitation and evaporation are direct measures of the climate of an area while runoff involves a balance between the supply of water by precipitation and the need for water by evapotranspiration modified by changes in the amount of water stored in the soil through the year. Thus, knowledge of the various climatic factors can provide information on the quantity of water exchanged with the ocean and, hence, on the chloride content of the water in the estuary at any time, as well as on other aspects of its quality. Since climatic information is available for many years of record while measured values of specific conductance, chlorides or water quality may be of short duration, or of questionable reliability, the climatic water balance approach can provide basic and needed information.

The present investigation seeks to study the factors of the climatic water balance over the delaware River basin, and to relate these factors to environmental conditions in the waters of the estuary. It is recognized that other factors, in addition to the fresh water runoff from the land may influence the particular conditions in the estuary at any time so that close correlations between the factors of the water balance and the quality of the marine environment may not always be found. The work suggested here is not to achieve particularly high correlations between land and marine factors but rather to provide an understanding of the relationship that does exist and to see how changes in the factors of the climatic water balance, either willfully or inadvertently caused, can produce conditions in the marine environment either more or less favorable for fish, shellfish, and marshland resources.

Setting

The Delaware estuary receives fresh water directly falling on its surface in the form of precipitation as well as from surface and subsurface runoff from the surrounding catchment basin. The land basin for the Delaware river and bay covers parts of the states of New York, New Jersey, Pennsylvania, Delaware and Maryland - a total area of 12,900 square miles. The basin (figure 1) is elongated in shape being approximately 250 miles in a north-south direction and a maximum of 80 miles wide near the mid-point of the basin.

Carter (1958) has pointed out the complex physical and hydrologic characteristics of the basin, dividing it into several major divisions including: a) the Catskill Mountains in the north; b) the Pocono Mountains in the northwest; c) the Ridge and Valley area in the west-central portion of the area; and d) the Coastal Plains lowlands of Delaware and New Jersey.

> "In the Catskill Mountains region, the streams which unite to form the Delaware drain toward the southwest through topography which is rugged and has maximum elevations of more than 4000 feet and a minimum elevation at Port Jervis of about 500 feet. Three principal tributaries, the East and West Branches of the Delaware River and Beaver Kill, occupy the main valleys of the area. The region is a prime source of runoff for the basin.
>
> "The Pocono Mountains have less rugged relief and less well organized drainage patterns than the Catskill region. In the Pocono area, the term, plateau, is more appropriate than elsewhere in the basin; still, the Pocono plateau has sufficient elevation to be noticeably cooler and more moist than the lowlands so it is nearly as effective a source region for runoff to the rivers as the other mountains of the basin.
>
> "Ridges and valleys alternate to the southeast of the Pocono Mountains. The orientation of the valleys is clearly along the northeast-southwest direction but the ridges are less well defined than the valleys...
>
> "The lowlands of the southern third of the basin are comprised of two dissimilar areas... The lowlands west of the Delaware in Pennsylvania are rolling and occasionally contorted. Farm lands are interrupted by tracts of rocky, sometimes steep lands in forest where deep soils may be lacking.

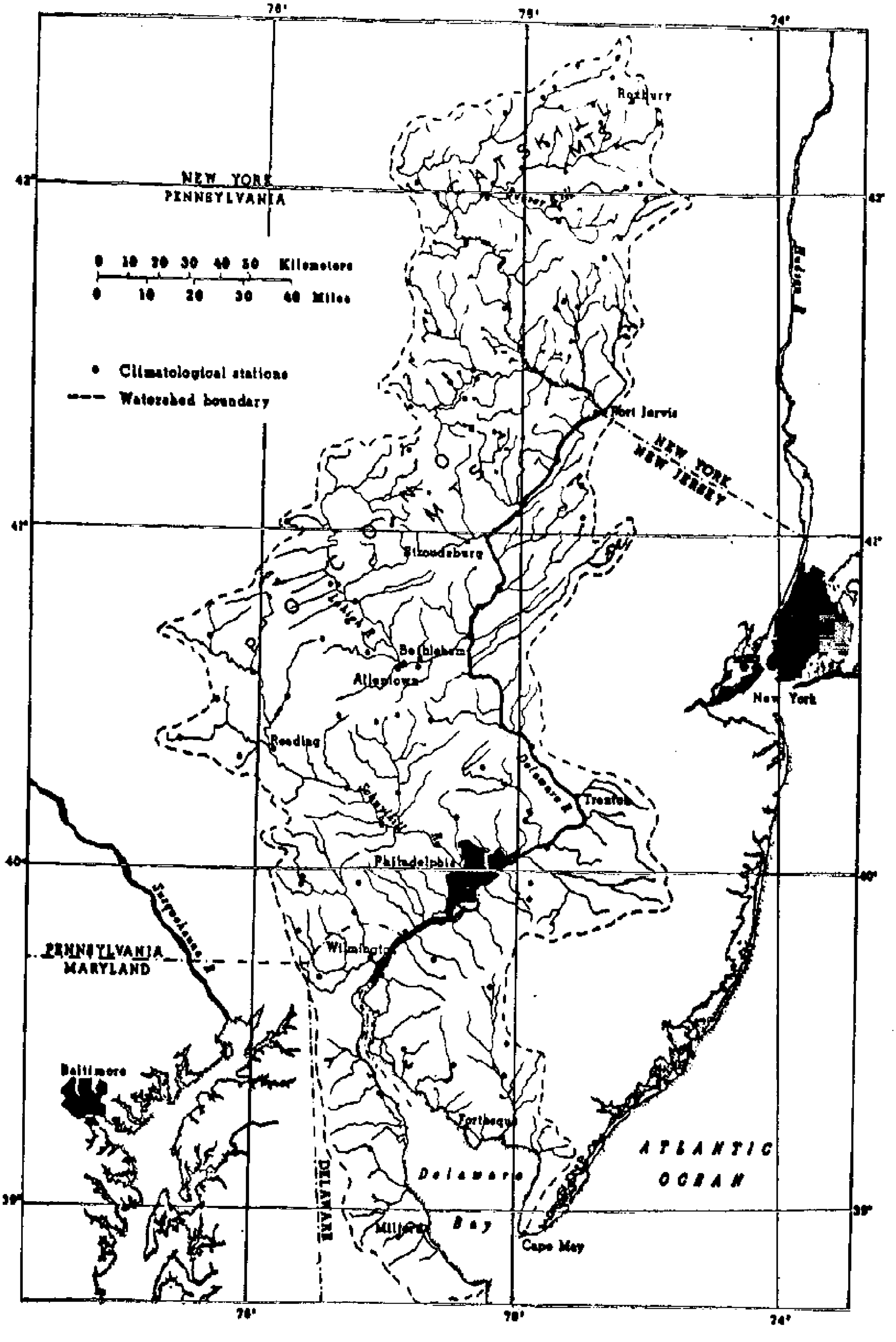

Figure 1. The Delaware River Basin

> "In New Jersey and Delaware, rocky lands are essentially absent. In much of this area the soils are too sandy for crop production and have remained in forest or have reverted to forest. Streams are generally sluggish and there is relatively less stream flow originating in this region than in any of the other major divisions." /Carter, 1958, pp 251-252/

The Delaware estuary, in the present context, is considered to extend from the Atlantic Ocean at Cape May, N. J. - Cape Henlopen, Delaware to Trenton, New Jersey a distance of approximately 134 miles. It varies in width from about 700 feet at Trenton, to 2,200 feet at Philadelphia, to 27 miles at its widest in the central bay area. It is 12 miles between Cape May and Cape Henlopen.

The tidal range increases up the estuary from a mean value of about 4.3 ft at the Capes, to 5.4 ft at Reedy Point, and 6.7 ft at Trenton. The Corps of Engineers has estimated the mean fresh water discharge to be 16,475 cfs just below the mouth of the Schuylkill River and about 20,200 cfs at the Capes (Corps of Engineers, 1956). With a flow of some 10,600 cfs just below the mouth of the Schuylkill, the Corps of Engineers found that the 100 ppm isochlor (line of constant chloride content) was located just about at the Pennsylvania-Delaware state line (Corps of Engineers, 1954).

II. DETERMINATION OF NET FLOW IN THE DELAWARE ESTUARY

Previous Work

No quantitative records of the net flow of water at the mouth of the Delaware estuary are known to exist. There have been a number of estimates of mean annual flow, similar to the one quoted earlier from the Corps of Engineers, of some 20,200 cfs, based on the available stream gaging records and extrapolations to cover those portions of the basin that are not gaged. Such average figures are of little real value for they a) provide no detail of seasonal changes; b) indicate nothing of possible year-to-year changes due to variable climatic conditions; and c) give no suggestions about spatial variations in water contributions to the total estuary flow.

Carter (1958) has obtained an estimate of the average monthly flow from the estuary to the ocean based on an evaluation of the various inputs and withdrawals of water over the entire basin rather than on the results from actually gaged streams. Carter considered that the only way in which fresh water can reach the estuary is by runoff from the basin surrounding the estuary and by precipitation onto the surface of the water body. Water leaves the estuary by evaporation from its surface. Carter did not consider any seepage of water through the bottom of the estuary. He felt that the net flow of water at the mouth of the estuary could be obtained as a simple balance between these inflow and outflow terms. If evaporation was greater than combined runoff and precipitation there would be a net salt water inflow into the estuary while if runoff and precipitation were larger than evaporation there would be a net outflow of water.

The American climatologist, C. W. Thornthwaite provided a relatively simple and straightforward bookkeeping procedure (1948) by which it is possible to determine monthly and annual values of stream runoff in mid-latitude areas with considerable accuracy. A later modification of the technique (Thornthwaite and Mather, 1955) has improved its usefulness and allowed the effect of different soils and vegetation covers to be considered. The technique has been used in many investigations of runoff (for example, Muller, 1966; Sanderson, 1966; Mather, 1969) in mid-latitude areas and found to give quite reliable results. Instructions on how to compute the climatic water balance are given in some detail in Appendix I.

In order to compute runoff climatically, it is necessary to have information on the precipitation and evapotranspiration of water over the land area. Since evapotranspiration is normally not measured, it is estimated, with reasonable reliability, from values of temperature.[1] Daily or monthly comparisons of the inputs of water (precipitation) with the losses of water (evapotranspiration) provide daily or monthly values of the moisture stored in the soil as well as information on any excess (surplus or runoff) or deficit that might exist in the soil. Measured and computed values of runoff have been found to agree quite closely.

Combining the average monthly runoff from the land as computed from the climatic water balance with the estimated amount of precipitation and evaporation over the estuary surface, Carter obtained values of average monthly net flow at the mouth of the Delaware estuary (table 1). The data were based on weather records for various time periods (generally 20 years or more) for at least 50 stations in the basin.

Carter's average annual value of outflow of some 19,833 cfs is remarkably close to the figure of 20,200 cfs achieved by the Corps of Engineers in their earlier study (1956) using stream gaging records. It indicates that the water balance technique has considerable validity and utility.

On the average there is a net outflow in every month of the year although there is a 17 to 1 variation in the monthly outflow figures through the year. Carter did not consider the actual magnitude of the monthly flow in individual years which could vary as much as the average figures.

Data

The net flow of water in the Delaware estuary consists of runoff (RO) from the land area surrounding the bay, precipitation (P) onto the water surface directly, and evaporation (E) from the water surface of the estuary (figure 2). In order to maintain the water level in the estuary in equilibrium

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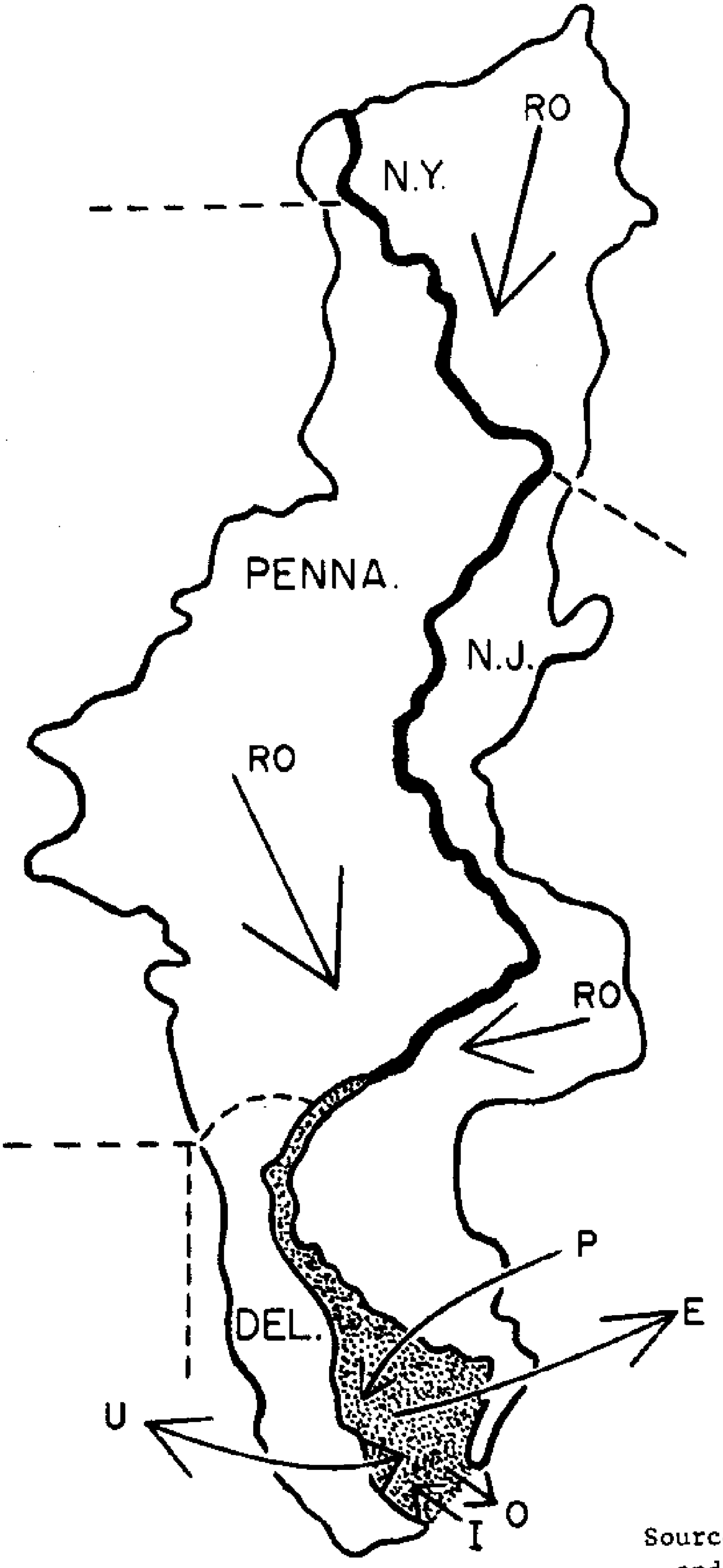
[1] There has been much heated debate over the method by which to determine evapotranspiration. In general, this is highly inappropriate for, in most cases, the various methods all provide values which are as reliable as the precipitation record. Considerable error can occur in extrapolating the precipitation record over the area between stations. The debate seems to be a case of misplaced emphasis for errors in precipitation may be much more serious than errors which result from the computations of evapotranspiration.



$$RO + P - E \pm U = I/O$$

Figure 2

Sources of Water Gains and Losses for the Delaware Estuary

Table 1

Average Monthly and Annual Water Balance of Delaware Bay
(Billions of Cubic Feet)

Month	Evaporation	Precipitation	Runoff	Net Outflow	Net Outflow (cfs)
January	0.1	6.0	42.3	48.2	17996
February	0.1	5.7	39.9	45.5	18808
March	1.3	6.7	88.2	93.6	34946
April	3.2	5.8	134.9	137.5	53048
May	6.3	6.4	91.8	91.9	34312
June	9.1	6.0	49.0	45.9	17708
July	10.9	6.6	26.1	21.8	8139
August	9.6	8.4	13.3	12.1	4518
September	7.0	6.4	8.6	8.0	3086
October	4.0	5.3	14.8	16.1	6011
November	1.6	5.9	43.7	48.0	18518
December	0.3	6.6	49.7	56.0	20908
					23798/12
Annual	53.5	75.8	602.3	624.6	19833

with the Atlantic Ocean, there must be a net inflow or outflow of water from the mouth of the estuary depending on the magnitude of the water additions or withdrawals involved. While the various terms are easily identified, it is more difficult to obtain quantitative values of these terms. Thus, often we have little more than educated guesses concerning the magnitude of the flow in an estuary.

Runoff.

The runoff of water from the catchment basin around a bay or estuary contributes, in most cases, the bulk of the fresh water flow to the estuary. In some areas we are fortunate enough to have many gaged streams around an estuary so that some reasonable estimate of this quantity, by days and months, is possible. However, in nearly all watersheds there are ungaged streams as well as areas of runoff directly from the land (either by surface or subsurface flow) which cannot be gaged in any way so that our quantitative knowledge of total runoff is inexact.

The Delaware bay or estuary area has one major tributary supplying fresh water runoff to it - the Delaware River. The last gaging station on the Delaware River is located at the so-called "head of tide" at Trenton, New Jersey, some 134 miles from the mouth of the estuary. The gaging station at Trenton is listed as having "excellent" records. The flow is regulated by a number of upstream reservoirs and lakes. Average discharge at Trenton is 11,930 cfs ranging from a maximum of 329,000 cfs to a minimum value of 1220 cfs.

Of the 12,900 square miles in the entire basin draining into the Delaware Bay, some 6780 square miles or 52.6 percent of the basin lies upstream from the gaging station at Trenton. The runoff from the remaining 6120 square miles (47.4 percent) lying downstream of the Trenton gaging station will not pass the Trenton gaging station. Based on the earlier Corps of Engineers figures (20,200 cfs runoff for the entire basin) it would appear that the Trenton gaging station measures slightly less than 60 percent of the total runoff of water reaching the ocean from the surrounding catchment basin.

There are several streams with gaging stations located on them in the basin downstream from Trenton. Table 2 provides a list of these gaged streams, the length of their records and the size of the watersheds drained. Actual measured stream records exist for essentially 50 percent of the basin below Trenton, although the length of time during which records have been accumulated is not always similar.

Table 2

Gaged Streams Tributary to the Delaware Estuary including Watershed Areas, and Date of Beginning of Records[1]

	Drainage Area (square miles)	Record Began
Delaware River at Trenton, N.J.	6780.0	Oct. 1912
Assunpink Creek at Trenton, N.J.	89.4	July 1923
Crosswicks Creek at Extonville, N.J.	83.6	Aug. 1940
Neshaminy Creek near Langhorne, Pa.	210.0	Oct. 1934
Middle Branch Mt. Misery Brook in Lebanon State Forest, N.J.	2.7	Oct. 1952
North Branch Rancocas Cr. at Pemberton, N.J.	111.0	Sept. 1921
Schuylkill River at Philadelphia, Pa.	1893.0	Sept. 1931
Mantua Creek at Pitman, N.J.	6.8	April 1940
Still Run at Mickleton, N.J.	3.9	Aug. 1957
Chester Creek at Chester, Pa.	61.1	Oct. 1931
Christina River at Coochs Bridge, Del.	20.5	April 1943
White Clay Cr. at Newark, Del.	87.8	Oct. 1931 (with gaps)
Red Clay Creek at Wooddale, Del.	47.0	April 1943
Brandywine Creek at Wilmington, Del.	314.0	Oct. 1946
Shellpot Creek at Wilmington, Del.	7.5	Dec. 1945
Salem River at Woodstown, N.J.	14.6	Dec. 1941
Alloway Creek at Alloway, N.J.	21.9	Oct. 1952
Blackbird Creek at Blackbird, Del.	3.8	Oct. 1956
St. Jones River at Dover, Del.	31.9	Jan. 1958
Beverdam Branch at Houston, Del.	2.8	May 1958
Sowbridge Branch at Milton, Del.	7.1	Oct. 1956
Total area for streams below Delaware River at Trenton, N.J.	3020.4	

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[1] Data from U.S. Dept. of Interior, 1960.

Two possible approaches exist for completing the record of runoff from the remainder of the basin or filling those gaps in the record which exist due to lapses in the records at the gaging stations. The simplest technique would be merely to extrapolate the available figures of measured runoff to obtain an estimated value for 100 percent of the basin. To do so, one would have to assume that the distribution of precipitation and evapotranspiration is fairly uniform over the entire basin, and that soils and slopes are generally similar so that the factors influencing runoff do not vary significantly from the gaged to the ungaged portions of the watershed. This might not be too great an assumption to make in the case of the Delaware estuary, particularly in view of the fact that the presently gaged portion of the basin is well distributed throughout the entire basin below Trenton. The second approach would be to calculate the runoff from the land areas to the estuary from the pertinent climatic data obtained over the land using a system such as the previously described Thornthwaite bookkeeping procedure (1948) by which it is possible to determine monthly and annual values of runoff in mid-latitude areas with considerable accuracy.

Both techniques (extrapolation and direct computation from the climatic water balance) would be able to provide reasonable estimates of the runoff from the ungaged portions of the Delaware basin. Since the climatic water balance technique a) provides information on all the runoff (both surface and subsurface) which is not possible if one just extrapolates the present measured figures to 100 percent of the watershed; and b) eliminates the need to evaluate carefully the gaged records from each of the stations in order to discard questionable data, it was decided to obtain the record of runoff of fresh water to the Delaware Bay by a combination of the two techniques. First, the record of runoff from that portion of the basin upstream of Trenton would be obtained from the "excellent" gaged record at Trenton. The contribution of runoff from the portion of the basin downstream from Trenton would be obtained by computation of the climatic water balance at all available stations. Combining the two records would provide the total runoff from the land to the estuary.

a) Runoff at Trenton. Table 3 provides the monthly values of the flow of water in the Delaware River at Trenton, New Jersey from 1949 to 1968. The record has been taken directly from the gaged record supplied by the U.S.G.S. in their Water Supply Papers (U.S. Dept. of Int., 1952-1962, 1962-1969) except that the water used by Trenton itself has been included. Trenton takes its water from the Delaware above the gaging station and its effluent is returned to the Delaware below the gaging station so that this water actually by-passes the gaging station. It can be assumed that there is no real loss of water in Trenton so that all that is removed is later returned to the river. The values appearing in table 3 have been adjusted to reflect the slightly larger amount of water - the gaged river flow plus the Trenton effluent. Since records of removal of water for the use of Trenton go back only to 1954, it has been necessary to extrapolate Trenton usage before that time. The values are actually quite small so little error results from this modification of the flow record.

Use of the Trenton gaging record eliminates one significant error that might occur if the climatic bookkeeping technique had been applied to this

Table 3

Monthly Water Balance of the Delaware Estuary, 1949-1968
(all values in cfs)

	Runoff at Trenton	Runoff from Basin Downstream from Trenton	Precipitation onto Estuary	Potential Evapotrans. from Estuary	Balance	
1949						
January	32,475	22,746	3,924	343	58,802	
February	19,115	23,009	3,396	371	45,149	
March	13,605	14,996	2,533	651	30,483	
April	16,095	12,095	1,770	1,385	28,575	
May	16,075	8,414	2,907	2,609	24,787	
June	5,727	4,279	359	3,984	31,168	
July	3,766	2,123	1,464	4,666	2,687	
August	2,746	1,109	2,304	3,872	2,287	
September	2,764	532	2,703	2,442	3,557	
October	2,830	218	2,623	1,794	3,877	
November	4,706	165	1,183	678	5,376	
December	10,985	875	1,624	327	13,157	
						20,825
1950						
January	13,915	2,541	1,535	585	17,406	
February	13,365	8,440	2,105	240	23,670	
March	21,905	17,438	2,890	398	41,835	
April	24,405	10,120	1,183	1,028	34,680	
May	13,605	7,618	2,963	2,284	21,902	
June	11,595	3,730	1,947	3,410	13,862	
July	7,619	1,752	2,672	4,158	7,885	
August	4,960	1,646	2,623	3,613	5,616	
September	4,766	965	4,245	2,433	7,543	
October	3,194	392	1,103	1,684	3,005	
November	14,295	5,459	3,130	807	22,077	
December	26,095	9,184	1,738	103	36,914	
						19,700
1951						
January	18,545	12,581	1,429	326	32,229	
February	27,595	16,338	2,408	224	46,117	
March	23,275	18,885	2,366	451	44,075	
April	29,645	12,616	1,784	1,269	32,776	
May	8,578	6,529	2,602	2,519	15,190	
June	8,094	4,663	2,958	3,576	12,139	
July	8,381	2,301	2,810	4,197	9,295	
August	6,919	1,274	2,241	3,718	6,716	
September	4,251	5,732	1,649	2,911	8,721	
October	5,685	457	1,957	1,772	6,327	
November	24,395	5,595	4,324	506	33,808	
December	18,635	16,403	4,274	253	39,059	
						24,704

Table 3

(Continued)

	Runoff at Trenton	Runoff from Basin Down-stream from Trenton	Precip-itation onto Estuary	Potential Evapotrans. from Estuary	Balance	
1952						
January	24,115	20,597	3,463	173	48,002	
February	18,725	16,910	1,448	185	36,898	
March	24,505	20,663	3,478	416	48,230	
April	36,275	23,916	4,137	1,512	62,816	
May	22,795	17,783	3,742	2,354	41,966	
June	13,565	8,804	2,036	4,001	20,404	
July	12,055	4,167	3,287	4,526	14,983	
August	6,352	2,431	5,711	3,723	10,771	
September	10,085	2,235	1,868	2,685	11,503	
October	3,685	1,224	503	1,179	4,233	
November	12,895	7,542	3,729	760	23,406	
December	26,175	14,386	2,731	203	43,089	
						30,525
1953						
January	22,205	19,216	3,005	305	44,121	
February	19,605	18,631	2,577	236	40,577	
March	25,735	22,322	3,993	645	51,405	
April	26,665	19,857	2,933	1,417	48,038	
May	20,095	16,881	3,872	2,759	38,089	
June	7,269	8,420	2,653	3,666	14,676	
July	3,828	3,782	2,297	4,233	5,674	
August	2,480	2,351	5,360	3,678	6,513	
September	2,740	1,412	359	2,868	1,634	
October	2,454	690	2,453	1,596	4,001	
November	5,911	510	2,667	749	8,339	
December	17,875	4,738	2,935	312	25,236	
						24,025
1954						
January	7,565	5,733	2,179	89	15,388	
February	14,575	9,227	1,135	384	24,553	
March	17,345	13,457	2,581	596	32,787	
April	14,025	9,023	2,761	1,598	24,211	
May	17,025	5,760	1,946	2,290	22,441	
June	5,137	2,825	470	3,688	4,744	
July	2,125	1,432	1,908	4,027	1,438	
August	1,873	690	4,018	3,631	2,950	
September	3,540	439	3,535	2,805	4,709	
October	2,532	212	1,391	1,891	2,244	
November	12,815	2,154	3,345	566	17,748	
December	13,155	5,613	2,286	219	20,835	
						14,504

Table 3

(Continued)

	Runoff at Trenton	Runoff from Basin Down-stream from Trenton	Precip-itation onto Estuary	Potential Evapotrans. from Estuary	Balance	
1955						
January	10,445	2,951	372	69	13,663	
February	8,923	9,815	2,113	134	20,717	
March	21,015	15,301	2,855	632	38,539	
April	13,155	9,215	1,974	1,548	22,796	
May	6,500	4,539	1,040	2,550	9,529	
June	5,062	2,476	4,030	3,298	8,270	
July	2,522	1,218	708	4,679	-231	
August	30,337	4,403	6,564	4,163	37,141	
September	7,454	2,043	1,975	2,668	8,804	
October	28,751	4,804	2,783	1,672	34,666	
November	21,670	5,718	1,475	570	28,293	
December	7,783	2,521	374	69	10,609	
						19,400
1956						
January	6,896	3,583	1,939	69	12,349	
February	13,190	17,109	2,541	239	32,601	
March	19,829	19,376	2,890	411	41,684	
April	30,939	13,741	1,707	1,145	45,242	
May	18,081	7,249	1,756	2,242	24,844	
June	10,194	3,736	2,847	3,629	13,148	
July	8,453	2,528	5,010	3,955	12,036	
August	4,096	1,199	1,839	3,669	3,465	
September	5,654	907	2,352	2,571	6,342	
October	5,218	1,872	4,358	1,625	9,823	
November	8,229	7,844	3,227	726	18,574	
December	16,206	12,262	2,719	512	30,675	
						20,899
1957						
January	9,736	7,326	1,421	69	18,414	
February	10,022	15,148	2,366	211	27,325	
March	13,408	12,687	2,168	473	27,790	
April	25,298	13,110	2,241	489	40,160	
May	8,427	6,131	619	2,567	12,610	
June	4,344	3,538	2,182	3,945	6,119	
July	2,952	1,662	642	4,141	1,115	
August	2,062	749	1,579	3,639	751	
September	2,294	406	3,592	2,918	3,374	
October	2,418	212	1,724	1,291	3,063	
November	3,940	125	3,693	753	7,005	
December	19,864	4,555	3,848	340	27,927	
						14,638

Table 3

(Continued)

	Runoff at Trenton	Runoff from Basin Downstream from Trenton	Precipitation onto Estuary	Potential Evapotrans. from Estuary	Balance	
1958						
January	14,217	7,286	2,345	69	23,779	
February	10,368	3,673	2,831	77	16,795	
March	20,967	33,921	4,592	383	59,097	
April	39,265	27,152	3,456	1,434	68,439	
May	20,316	14,359	3,032	2,295	35,412	
June	6,253	7,817	2,617	3,339	13,348	
July	4,712	4,963	5,440	4,413	10,702	
August	3,746	7,015	7,383	3,661	14,483	
September	4,077	3,694	1,893	2,633	7,031	
October	8,277	4,446	2,148	1,511	13,360	
November	12,142	6,720	2,126	742	20,246	
December	9,328	3,450	1,225	69	13,934	
						24,719
1959						
January	10,532	5,985	1,096	69	17,544	
February	10,943	9,550	1,383	194	21,682	
March	14,781	15,607	2,293	641	32,040	
April	20,582	10,258	2,079	1,577	31,324	
May	8,291	4,565	1,001	2,962	10,895	
June	4,647	2,293	1,492	3,989	4,443	
July	3,917	1,473	5,530	4,253	6,667	
August	4,068	794	3,796	4,080	4,578	
September	4,304	384	932	3,058	2,562	
October	8,074	268	2,526	1,898	8,970	
November	13,422	2,392	3,592	721	18,685	
December	19,442	8,176	2,005	300	29,323	
						15,728
1960						
January	15,572	12,209	1,849	183	29,447	
February	18,261	18,839	2,854	217	39,737	
March	8,824	13,085	1,395	104	23,200	
April	33,322	10,422	1,768	1,804	43,708	
May	11,325	8,560	2,907	2,325	20,467	
June	10,839	4,251	1,488	3,747	12,831	
July	6,249	2,487	4,469	3,947	9,258	
August	7,488	1,177	2,644	3,936	7,373	
September	19,387	8,722	5,700	2,745	31,064	
October	7,666	6,503	1,794	1,481	14,482	
November	6,266	5,787	1,172	751	12,474	
December	5,051	3,344	1,717	69	10,043	
						21,174

Table 3

(Continued)

	Runoff at Trenton	Runoff from Basin Downstream from Trenton	Precipitation onto Estuary	Potential Evapotrans. from Estuary	Balance	
<u>1961</u>						
January	4,751	1,946	2,210	69	8,838	
February	15,730	24,926	3,480	184	43,952	
March	24,940	24,631	3,303	624	52,250	
April	27,560	21,722	2,549	1,147	50,684	
May	16,170	11,174	2,665	2,190	27,819	
June	7,188	6,198	3,678	3,453	13,611	
July	5,201	4,990	3,490	4,222	9,459	
August	5,658	2,482	2,338	3,751	6,727	
September	4,257	1,280	1,972	3,295	4,214	
October	2,950	743	3,733	1,606	5,820	
November	5,388	1,135	1,502	764	7,261	
December	6,378	2,805	2,623	107	11,699	
						20,195
<u>1962</u>						
January	13,015	4,406	2,349	93	19,677	
February	8,178	6,818	2,674	77	17,593	
March	19,384	22,242	2,422	426	43,622	
April	23,484	17,389	2,753	1,412	42,214	
May	6,197	8,759	1,102	2,635	13,423	
June	3,463	4,772	2,782	3,754	7,263	
July	2,546	2,296	2,540	3,916	3,466	
August	3,066	1,699	1,471	3,646	2,590	
September	2,681	1,830	2,083	2,463	4,131	
October	4,560	1,364	729	1,593	5,060	
November	10,905	4,017	3,707	471	18,158	
December	7,362	2,362	2,397	88	12,033	
						15,769
<u>1963</u>						
January	6,589	2,341	1,516	69	10,377	
February	6,121	1,701	1,517	77	9,262	
March	23,545	26,489	3,671	660	53,045	
April	14,589	13,604	853	1,419	27,627	
May	8,138	6,967	1,509	2,290	14,324	
June	4,447	4,087	3,334	3,479	8,389	
July	3,302	1,741	1,596	4,204	2,435	
August	2,925	849	2,692	3,577	2,889	
September	2,575	494	2,947	2,320	3,696	
October	2,167	212	92	1,675	796	
November	4,095	2,883	4,976	878	11,076	
December	7,216	1,956	1,599	69	10,702	
						12,577

Table 3

(Continued)

	Runoff at Trenton	Runoff from Basin Down-stream from Trenton	Precip-itation onto Estuary	Potential Evapotrans. from Estuary	Balance	
1964						
January	13,993	11,073	3,483	137	28,412	
February	9,182	11,065	3,731	92	23,886	
March	21,867	19,535	1,992	626	42,768	
April	17,057	21,722	4,180	1,183	41,776	
May	10,775	10,272	340	2,651	18,736	
June	4,398	5,293	692	3,704	6,679	
July	3,163	2,479	2,776	4,144	4,274	
August	2,535	1,258	559	3,564	788	
September	2,194	823	3,205	2,779	3,443	
October	2,200	372	1,640	1,352	2,860	
November	1,967	165	1,262	805	2,589	
December	3,964	846	2,179	288	6,701	
						15,243
1965						
January	4,988	429	2,086	69	7,434	
February	12,169	7,099	1,414	141	20,541	
March	9,082	13,855	2,436	387	24,986	
April	9,881	9,215	1,613	1,122	19,587	
May	5,264	4,141	850	2,872	7,383	
June	2,633	2,436	1,348	3,437	2,980	
July	1,603	1,235	1,853	3,914	777	
August	1,864	690	2,852	3,655	1,751	
September	2,142	329	1,671	2,992	1,150	
October	3,528	259	677	1,411	3,053	
November	2,707	605	595	699	3,208	
December	5,090	304	729	200	5,926	
						8,231
1966						
January	5,080	217	2,026	69	7,254	
February	9,126	7,711	3,065	77	19,825	
March	17,790	10,444	1,135	450	28,919	
April	7,833	10,751	2,983	1,013	20,554	
May	10,680	6,529	2,602	2,286	17,525	
June	6,275	3,407	1,807	3,673	7,816	
July	2,625	1,499	1,034	4,259	899	
August	2,547	881	989	3,773	644	
September	2,781	473	4,761	2,609	5,409	
October	3,686	1,781	3,386	1,381	7,472	
November	4,605	2,745	1,219	746	7,823	
December	7,072	9,178	2,855	153	18,952	
						11,924

Table 3

(Continued)

	Runoff at Trenton	Runoff from Basin Down-stream from Trenton	Precip-itation onto Estuary	Potential Evapotrans. from Estuary	Balance	
1967						
January	10,144	8,905	815	212	19,652	
February	8,724	6,847	2,159	77	17,651	
March	18,512	19,641	2,297	331	40,119	
April	18,291	12,671	1,850	1,366	31,446	
May	15,100	10,404	3,164	1,948	26,720	
June	6,293	5,883	2,216	3,618	10,774	
July	5,675	3,697	3,241	3,984	8,629	
August	10,159	10,484	8,591	3,636	25,598	
September	4,835	6,349	1,778	2,422	10,540	
October	5,078	3,291	1,082	1,418	8,033	
November	8,961	5,225	1,309	423	15,072	
December	14,754	15,023	3,733	248	33,262	
						20,625
1968						
January	6,879	7,724	1,704	69	16,238	
February	9,885	6,412	742	74	16,965	
March	16,704	19,960	3,619	639	39,644	
April	11,874	11,656	1,034	1,427	21,137	
May	15,603	12,103	2,991	2,251	28,446	
June	20,357	7,899	2,746	3,691	27,311	
July	7,169	4,109	881	4,252	7,907	
August	4,450	1,922	1,416	4,040	3,748	
September	4,779	1,020	805	2,746	3,858	
October	4,467	664	1,946	1,645	5,432	
November	9,769	1,360	2,839	740	13,228	
December	10,789	2,785	1,804	76	15,302	
						16,768

portion of the watershed. New York City obtains a portion of its water supplies from the upper reaches of the Delaware. This withdrawal varies from year to year depending on other supplies of water and the changing demand from the city. At the same time, there are periodic releases of water to the river from storage reservoirs in the headwaters regions in order to maintain acceptable salinity levels at the Philadelphia water supply intake at Torresdale. It would be almost impossible to identify all removals and additions of water to the river upstream from Trenton especially since these quantities have changed over the years. Such an effort would be necessary to determine river flow using the climatic bookkeeping approach. However, use of the actual gaged record at

Trenton eliminates the need to be concerned with any additions or withdrawals of water above that point - for the net result of all such changes will be reflected in the actual quantity of water flowing in the river at Trenton.

b) Runoff Downstream from Trenton. For later analysis purposes, the basin downstream from Trenton, New Jersey has been divided into three separate subbasins and values of monthly runoff from each portion of the whole basin have been computed by means of the climatic water balance for different time periods. The results are included in the appropriate columns of tables 3, 5, and 6.

The drainage basin downstream from Trenton was subdivided at a line connecting Liston Point, Delaware and Stony Point, New Jersey (see figure 3) so that four subbasins of the Delaware estuary could be considered. The basins (numbers 3 and 4 on figure 3) seaward from the Liston Point-Stony Point line drain directly into Delaware Bay from the sandy coastal plain watersheds of Delaware and New Jersey. The line from Liston Point to Stony Point is about 50 miles from the mouth of the bay and approximates the boundary between Delaware Bay and the Delaware River estuary to the north as defined in the Governor's Task Force Report (1972).

The land area seaward of the Liston Point-Stony Point line contains 1381 square miles or slightly less than 11 percent of the total Delaware River drainage basin of 12,900 square miles. Of this area, 612 square miles lies within Delaware while 769 square miles lies within New Jersey.

Values of the runoff from the entire basin downstream from Trenton for the period 1949-1968, included in table 3, were obtained by evaluating the monthly climatic water balance for the 20-year period of record at each of 34 weather stations located both in and just outside the basin. A list of the stations used is included in Appendix II. While soils and slopes vary, it was decided that, as a first approximation, it would be satisfactory to use a value of six inches soil moisture storage capacity for all areas and a runoff factor of 50 percent of the available surplus each month. Using these assumptions, the actual runoff of water at each station, in inches depth for each month of interest, has been determined.

The computed values of runoff were plotted on large-scale maps of the lower basin - a total of some 240 maps. These maps were then analyzed to determine the pattern of runoff from the portion of the basin seaward of Trenton. Finally, the distributions were planimetered in order to determine the area between each successive isoline. Multiplying the area by the mid-value of the runoff, in inches depth, between successive isolines provided values of the volume of runoff contributed by that particular area. Summing all these contributions over the lower basin area resulted in monthly values of the runoff from the basin downstream from Trenton. These are the values that appear in the appropriate column of table 3.

In computing the runoff, it has been assumed that there are no additions or withdrawals of water that are not ultimately self-correcting. That is to say, if a city does remove water from a stream draining a portion of the basin, it is assumed that it will also return the effluent to the watershed so that it is not ultimately lost. It also assumes that there are negligible transfers of water either into or out of the basin as well as storages of water within reservoirs in the basin for later use or release to the streams. These assumptions are generally quite reasonable; in the lower portion of the Delaware basin rolling or flat terrain provides little opportunity for reservoir storage and there is very little consumptive use of water (actual removal of water from the total runoff system) except for summertime agricultural irrigation. Temporary removal for use within an urban area would not result in any great error in the monthly computations but might create a problem if daily values were being considered.

Precipitation.

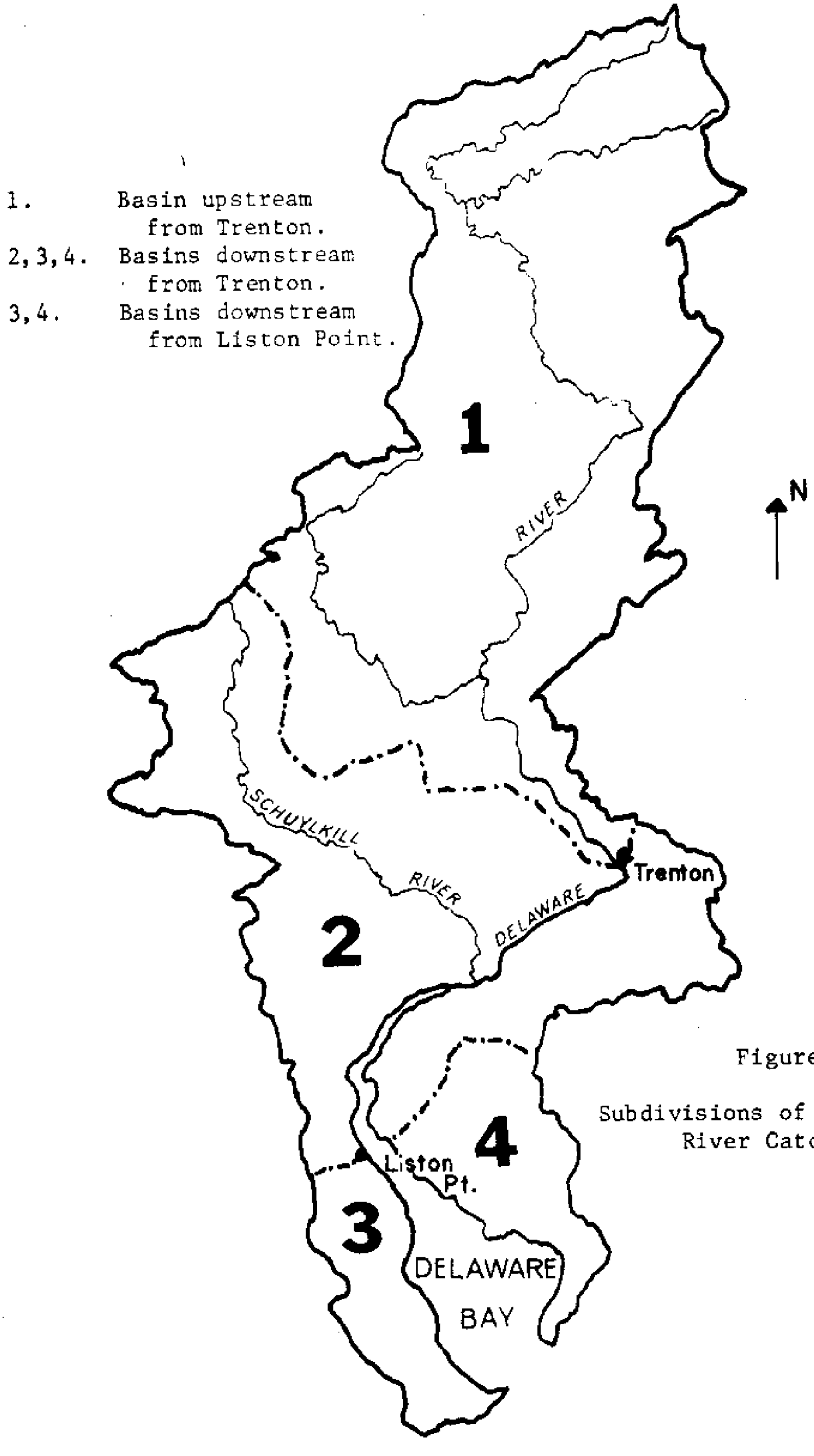
Precipitation onto the estuary surface adds water directly to the system. Since the actual water surface of the estuary is small in relation to the surface area of the basin surrounding the estuary (790 square miles of water surface below Philadelphia), the actual volume of water contributed to the water balance of the estuary is considerably smaller than that contributed by runoff but it still can be significant in certain months of the year when runoff is low (late summer and fall).

Precipitation is hardly ever measured directly over the water surface of an estuary. Most raingages are located around the borders of the estuary and at varying distances from the shore. The Delaware Bay area is no exception. While there are several lightships or lighthouses located in the lower bay region, their records are not sufficient to provide us with any reliable record of the possible precipitation over the whole estuary area.

Precipitation data from land stations may be reliable for the particular point of observations; extrapolation of the land-based data out over the water surface raises significant questions. Temperature conditions at a water surface may differ from those existing at a land surface. The water is cooler in the summertime and warmer in the winter season of the year. This will affect the movement and intensity of storms (especially thunderstorms and other forms of convective activity) and, thus, influence the quantity of precipitation obtained from convective-type storms. It should have less influence on the widespread precipitation conditions resulting from frontal-type weather situations.

The surface of the estuary is flat while the air moving over the nearby land surfaces may be either moving upward or downward due to the influence of the rolling topography. The slight upward movement of the air as it flows from Lake Ontario over portions of upper New York contributes to the very high snowfall found in the belt just south and east of the lake. This orographic influence would not be as noticeable in the case of the Delaware estuary since the salt marsh area on both sides of the estuary is extensive and flat. Even the land area behind the salt marshes is quite low lying so that the amount of vertical movement of the air is minimal.

Sanderson (1966) in discussing the problem of estimating over-water precipitation for Lake Erie cited several previous estimates that had been obtained. She pointed out that Freeman (1926) considered over-water and perimeter precipitation (precipitation as measured at stations around the perimeter of the lake) to be the same, while Horton and Grunsky (1927) felt



1. Basin upstream from Trenton.
2,3,4. Basins downstream from Trenton.
3,4. Basins downstream from Liston Point.

Figure 3

Subdivisions of the Delaware River Catchment that lake precipitation was 84 percent of perimeter precipitation in winter and 85 percent of perimeter precipitation in summer. Hunt (1958) considered over-water precipitation to be 60 percent of the perimeter precipitation in August and 90 percent of the perimeter precipitation in January for Lake Michigan. Sanderson suggested that these figures were open to question; a later Lake Michigan study (Blust and DeCooke, 1960) showed over-water precipitation to be 93 percent of the perimeter precipitation in summer and 114 percent of the perimeter precipitation in winter.

Returning to Lake Erie, Sanderson reported,

> "Derecki . . . used thirteen years of records to compare precipitation at three stations in Western Lake Erie with five perimeter stations and obtained the following ratios, P water/P land.
>
> | | | | |
> |---|---|---|---|
> | January | .95 | July | 1.04 |
> | February | .89 | August | 1.03 |
> | March | 1.03 | September | .95 |
> | April | 1.04 | October | .89 |
> | May | 1.07 | November | 1.02 |
> | June | .92 | December | 1.03 |
>
> The current practice of the Corps of Engineers, U.S. Lake Survey, in computing over water precipitation is to assume that the precipitation on the north half of the lake is the average of eleven stations on the north shore, and that the precipitation on the south half is the average of eight stations along the south shore." (Sanderson, 1966, p. 30)

Lacking any better estimate of precipitation over the water surface, and recognizing that the influence of temperature and orographic effects must be minimal in the particular case of the Delaware estuary, it was decided to estimate over-water precipitation from the values obtained at nearby land stations. Any errors in using land data for water surfaces should be more than outweighted by the errors inherent in the attempt to extrapolate precipitation from point observations to surrounding areas of even relatively small size.

Large-scale maps of the estuary and surrounding land area were obtained and the values of monthly precipitation at 19 nearby land stations were plotted on them. (A list of the stations is included in Appendix II.) The maps were analyzed and isohyets were drawn across the estuary area. The areas between successive isohyets were determined by planimetering and these values were multiplied by the mid-value of precipitation between successive isohyets and summed over the entire estuary to provide values of the volume of water added by precipitation directly to the water surface itself. These values are tabulated by months in table 3.

Evaporation.

Evaporation from the surface of the estuary removes water from the system directly. There is a significant seasonal change in evaporation in a mid-latitude area since it is strongly influenced by temperature (actually energy receipts from the sun), wind, and humidity conditions. Here, again we have no measurements whatsoever of evaporation from the estuary surface and so we must estimate over-water evaporation on the basis of theory and any available land observations that exist.

Sanderson (1966) described three possible methods of estimating over-water evaporation: a) the energy budget method; b) the water budget method; and c) the mass transfer method. As its name implies, the energy budget method requires information on the energy exchange between the atmosphere and the water surface. While it provided good results at Lake Hefner (1954) and Lake Mead (1958), it requires more detailed energy data than any available in the Delaware estuary. The water budget approach requires knowledge of the various water input and output terms. The value of evaporation is solved for as the only unknown. Thus if we knew inflow or outflow at the mouth of the estuary (as well as runoff, underflow, precipitation) it would be possible to solve for evaporation. Since evaporation can be estimated more easily than inflow or outflow, this method is of little help. The mass transfer method utilizes the theory of the turbulent transfer of heat and moisture. It requires detailed observations of profiles of wind and water vapor. While it can provide excellent short-period values of moisture flux, it is not practical for long-term use over an extensive estuary.

Lacking sufficient data to apply any of these three methods to compute over-water evaporation, it is necessary to use the less accurate techniques involving water pans or computed potential evapotranspiration. Water pans are limited in their usefulness. The limited surface area of a pan will be strongly influenced by the condition of the air moving over it. If this air is quite dry, evaporation from the surface will be great, while if it is moist, a somewhat lower rate of evaporation exists. The effect of moisture content of the air on size of evaporating surface is quite marked over small evaporating surfaces but not as pronounced over a large lake or estuary surface. Thornthwaite and Mather (Mather, 1954) have qualitatively illustrated the effect of size of evaporating surface and moisture content of the air on evaporation (figure 4). It is clear that it is not even possible to apply a constant correction factor to the pan records since the correction must vary with the changing moisture condition of the air.

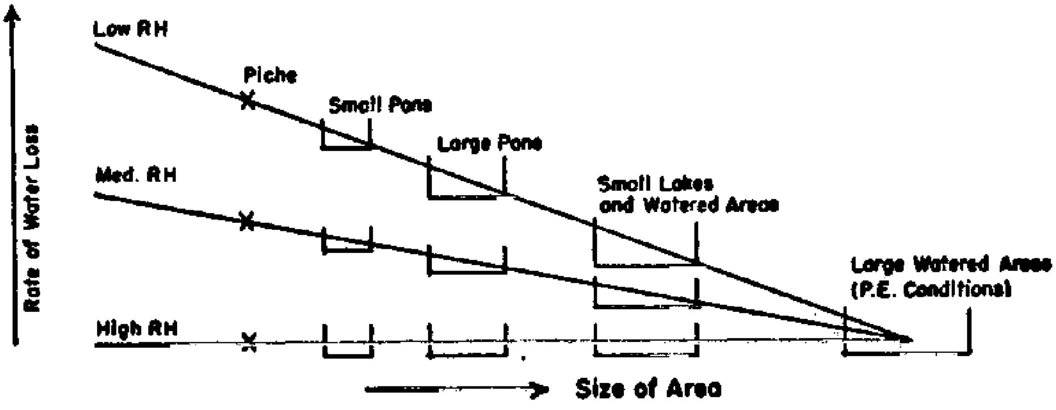


Figure 4. Relation between size of evaporating surface, moisture condition of the air, and rate of water loss. (from Mather, 1954)

Potential evapotranspiration has been defined by Thornthwaite (Mather, 1954) as the water loss from a large closed, homogeneous vegetation surface (albedo 0.25) that never suffers from a lack of water. It has been found to be independent of advection effects and of changes in the vegetation cover as long as the albedo does not change. It is primarily influenced by the net radiation, the energy available at the earth's surface after reflection, absorption and reradiation are considered. Thornthwaite and Mather found that in mid-latitudes, essentially all of the net radiation (80-90 percent) is utilized for potential evapotranspiration as long as the evaporating surface remains moist.

Potential evapotranspiration is a good measure of the climatic demands for water over a vegetated surface where the air temperature and the temperature of the evaporating surface are in accord. Potential evapotranspiration is not necessarily a good measure of evaporation from a lake or ocean surface since the temperature regime of the water surface is often quite different from the temperature in the air. It can be used to approximate the evaporation over a water surface only if the water temperature approximates the air temperature.

The Delaware estuary is a fairly shallow, rather land-locked water body. Its temperature is easily modified by the temperature of the air passing over it or the temperature of the water entering it as runoff or precipitation. Thus, at least to a first order of approximation, water temperature and air temperature might be thought of as similar. Records of water temperature at Reedy Point, Delaware (for 1955) show changes from 33 F in January to 77 F in July. Other records at the Delaware Memorial Bridge, in the upper estuary show changes from high water temperatures of 80 to 85 F in July and August to 32 to 35 F during January and February (U. S. Geological Survey, unpublished data). These are not only of the same order of magnitude as changes over land but the changes occur in seasonal phase with the air temperature changes.

Typically water temperatures increase in an upstream direction during the summer months and reflect the air temperature regime of the river basin. Water temperatures increase in a downstream direction during the spring and early winter months as the lower estuary is moderated by the inflow of warmer marine water from the Atlantic Ocean (Cronin et al., 1962).

The du Pont de Nemours Co. recorded water temperatures during low tide slack water periods at selected points between Ship John Light and Chester, Pa. (table 4). The data cover forty-six cruises in all seasons of the year during the period from 1967 to 1971. Analysis of these data indicates that water temperatures can vary a maximum of 5 to 6 F within the upper estuary between Chester and Ship John Light within one sample run. However, several data sets show that the same reach of the estuary can also be essentially isothermal. All except one of thirteen cruises during 1969 show higher water temperatures on the upper reaches of the estuary than on the downstream zone in all seasons. In 1970, 17 of 18 cruises show a similar trend, and in 1968, 6 of 9 show the same. These temperature regimes appear to be the result of heated effluent discharges from urbanized and industrialized areas of the basin.

Table 4

Temperatures (°F) in Surface Water Layer of Delaware Bay During Regular Cruises, 1967-1971 (Data courtesy of du Pont de Nemours Co.)

Date/ /Location	1*	2	3	4	5	6	7	8	9	10	11	12
1967												
4/25/67						54.0	54.0	54.0	54.0	54.0	54.0	
5/15/67						57.0	57.0	57.0	57.0	56.0	56.0	
5/18/67						60.0	60.0	60.0	59.0	59.0	59.0	
12/13/67			42.0	42.0	43.0	42.0	42.0	42.0				
1968												
4/18/68		50.0	50.0	52.0	54.0	54.0	54.0	54.0	54.0			
5/22/68		58.0	58.0	58.0	59.0	59.0	59.0	59.0	59.0	59.0	59.0	59.0
6/13/68		64.0	62.0	62.0	60.0	60.0	60.0	60.0	61.0	61.0	61.0	
6/17/68				64.0	64.0	64.0	64.0	64.0	64.0	64.0		
7/16/68		82.0	82.0	82.0	83.0	84.0	85.0	85.0	85.0	85.0	85.0	85.0
7/22/68			82.0	81.0	81.0	80.0	81.0	81.0	81.0	82.0	81.0	81.0
8/20/68				83.0	84.0	85.0	83.0	85.0	85.0	85.0		
9/14/68		72.0	72.0	73.0	73.0	73.0	73.5	73.5	73.5	74.0	74.0	74.5
11/11/68				51.0	52.0	53.0	52.0	55.0	55.0			
1969												
4/22/69					54.0	55.0	57.0	57.0	58.0	58.0	58.0	
5/26/69				66.0	67.0	67.0	68.0	68.0	68.0	69.0	69.0	
6/19/69				73.0	73.0	75.0	75.0	77.0	77.0	76.0	78.0	
7/18/69				77.0	77.0	79.0	79.0	79.0	79.0	79.0	81.0	
8/ 5/69				77.0	77.0	75.0	75.0	73.0	75.0	75.0	73.0	
9/ 2/69				78.0	80.0	80.0	82.0	82.0	82.0	82.0	82.0	
9/16/69				74.5	74.5	74.0	74.5	76.0	75.0	77.5	77.0	
9/30/69				68.0	70.0	70.0	71.0	72.0	72.0	73.0	73.0	
10/31/69				54.0	55.0	57.0	57.0	58.0	58.0	59.0	59.0	
11/13/69				49.0	50.0	54.0	54.0	54.0	54.0	55.0	55.0	
11/26/69				47.0	47.0	48.0	49.0	50.0	50.0	52.0	52.0	
12/ 3/69					45.0	46.0	46.0	47.0	46.0			
12/11/69						43.0	45.0	45.0	46.0	46.0	46.0	

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*Numbers refer to the following observation points:

1 - Ship John
2 - Liston Point
3 - Artificial Island
4 - Reedy Point
5 - Pea Patch Island
6 - New Castle
7 - Delaware Memorial Bridge
8 - Cherry Island
9 - Oldmans Creek
10 - Marcus Hook
11 - Chester Island
12 - Mantua Creek

Table 4 (Continued)

Temperatures (°F) in Surface Water Layer of Delaware Bay
During Regular Cruises, 1967-1971

/Location Date/	1	2	3	4	5	6	7	8	9	10	11	12
1970-71												
3/17/70	39.0			41.0	41.0	42.0	42.0	43.0	43.0	44.0		
3/26/70	41.0		42.0	42.0	41.5	41.0	42.0	42.0	42.5	43.0		
4/13/70	48.0		48.0	48.0	48.5	49.0	50.0	50.0	50.0			
4/23/70	50.0											
4/29/70				56.0	57.0	57.0	57.0	57.0	57.0	56.0	56.0	58.0
5/ 8/70	57.0		57.0	57.0	58.0	58.0	58.0	59.0	59.0	60.0	60.0	61.0
5/26/70	66.0			69.0	69.5	70.0	71.0	72.0	72.0	72.0		
6/ 8/70	71.0		71.0	71.0	71.0	72.0	72.0	72.0	72.0	72.0	73.0	73.0
6/23/60	74.0		72.0	73.0	74.0	74.0	75.0	74.0	75.0	75.0	75.0	75.0
6/29/70	74.0		74.0	75.5	76.0	76.0	77.0	77.0	77.0			
7/ 8/70	76.0		75.0	75.5	76.0	77.0	77.0	76.5	77.0	78.0	78.0	77.5
7/22/70	76.0		75.0	76.0	77.0	77.0	77.0	77.0	78.0			
8/ 5/70	78.0		78.0	78.0	80.0	79.0	79.0	80.0	79.0	80.0	80.0	81.0
8/25/70	79.0		79.0	79.0	79.0	80.0	80.0	81.0	80.0	81.0	80.0	80.0
9/11/70	76.0		75.0	75.0	77.0	76.0	78.0	79.0	79.0	79.0	79.0	78.0
9/23/70	77.0											
10/ 5/70			75.0	74.0	75.0	75.0	77.0	76.0	77.0	79.0	78.0	78.0
11/ 6/70			58.0	58.0	58.0	59.0	50.0	52.0	51.0	56.0	52.0	52.0
2/17/71			32.0	32.0	32.0	32.0	32.0	32.0	33.0	33.0		
3/ 2/71				42.0	42.0	43.0	43.0	44.0	44.0	43.0	43.0	43.0

Lacking any better way by which to estimate evaporation from the estuary surface, it has been assumed to be approximated by the potential evapotranspiration determined from information at perimeter weather stations. Monthly values of potential evapotranspiration, thus, were computed from temperature values at the perimeter stations. These values were plotted on large scale maps of the estuary and analyzed. The areas between isolines of constant evapotranspiration (evaporation over the water) were determined by planimetry. Multiplying each area value by the average evaporation for the area provides values of monthly volumes of evaporation. Summing these values for the whole estuary results in monthly values of evaporation from the water surface. These values, limited by the assumptions and approximations that had to be made, are summed in table 3.

The values in table 3 are all in cubic feet per second. The last column of the table provides the actual values of net inflow or outflow in cubic feet per second (cfs) averaged for each day of the month. The value at the bottom of this column is the average outflow at the mouth of the estuary in cubic feet per second for the whole year.

Runoff from sub-basins downstream from Trenton.

Ketchum (1952) estimated the volume of fresh water entering Delaware Bay downstream of Trenton, N. J. averaged about 57 percent of the flow at Trenton. The present water balance study can provide the necessary information to refine this average estimate and to investigate seasonal changes in the contribution from various portions of the basin. For this study, water balance computations for all stations in the Delaware Basin for the period 1959-1968 were considered. New maps of the monthly computed runoff from the basin seaward of the previously mentioned Liston Point-Stony Point line (areas 3 and 4 on figure 3) were prepared and the volumes of runoff from these basins were determined by planimetry. These monthly computed values were then subtracted from the previously calculated values (table 3) of runoff from the entire basin seaward of Trenton, to provide values of the monthly runoff from the basin upstream of Trenton (basin 1), from the basin between Trenton and the Liston Point-Stony Point line (basin 2), and the basin seaward of Liston Point-Stony Point (basins 3 and 4) as shown in figure 3. The results, along with values of the different basin runoff as a percent of the total Delaware Basin runoff, are given in table 5.

Table 5

Monthly Values of Runoff (in cfs and percent of total) from Sub-basins of Delaware River and Bay, 1959-1968

	Runoff at Trenton (cfs)	Runoff between Liston Pt. and Trenton (cfs)	Runoff from basin seaward of Liston Pt.-Stony Pt. (cfs)	Runoff at Trenton as % of Total (%)	Runoff below Liston Pt. as % of Total (%)
1959					
January	10,532	3,344	2,641	63.76	15.99
February	10,943	7,016	2,534	53.40	12.37
March	14,781	12,345	3,262	48.64	10.73
April	20,582	8,141	2,117	66.74	6.86
May	8,291	3,549	1,016	64.49	7.90
June	4,647	1,791	502	66.96	7.23
July	3,917	999	474	72.67	8.79
August	4,068	541	253	83.67	5.20
September	4,304	279	105	91.81	2.24
October	8,074	162	106	96.79	1.27
November	13,422	1,821	571	84.87	3.61
December	19,442	6,833	1,343	70.40	4.86

Table 5

Monthly Values of Runoff (in cfs and percent of total) from Sub-basins of Delaware River and Bay, 1959-1968 (continued)

	Runoff at Trenton (cfs)	Runoff between Liston Pt. and Trenton (cfs)	Runoff from basin seaward of Liston Pt.-Stony Pt. (cfs)	Runoff at Trenton as % of Total (%)	Runoff below Liston Pt. as % of Total (%)
1960					
January	15,572	9,588	2,621	56.05	9.43
February	18,261	15,054	3,785	49.22	10.20
March	8,824	9,853	3,232	40.28	14.75
April	33,322	8,579	1,843	76.18	4.21
May	11,325	6,907	1,653	56.95	8.31
June	10,839	3,445	806	71.83	5.34
July	6,249	2,147	340	71.53	3.89
August	7,488	1,007	170	86.42	1.96
September	19,387	7,489	1,233	68.97	4.39
October	7,666	5,425	1,078	54.10	7.61
November	6,266	4,638	1,149	51.99	9.53
December	5,051	2,222	1,122	60.17	13.37
1961					
January	4,751	1,222	724	70.94	10.81
February	15,730	17,328	7,598	38.69	18.69
March	24,940	19,049	5,582	50.31	11.26
April	27,560	17,176	4,546	55.92	9.22
May	16,170	8,347	2,827	59.14	10.34
June	7,188	4,430	1,768	53.70	13.21
July	5,201	3,808	1,182	51.04	11.60
August	5,658	2,021	461	69.51	5.66
September	4,257	1,040	240	76.88	4.33
October	2,950	565	178	79.88	4.82
November	5,388	715	420	82.60	6.44
December	6,378	1,271	1,534	69.45	16.70
1962					
January	13,015	1,698	2,708	74.71	15.54
February	8,178	2,847	3,971	54.53	26.48
March	19,384	18,278	3,964	46.57	9.52
April	23,484	14,072	3,317	57.46	8.12
May	6,197	7,149	1,610	41.43	10.76
June	3,463	3,778	994	42.05	12.07
July	2,546	1,839	457	52.58	9.44
August	3,066	1,438	261	64.34	5.48
September	2,681	1,668	162	59.43	3.59
October	4,560	1,299	65	76.98	1.10
November	10,905	3,977	40	73.08	0.27
December	7,362	1,888	474	75.71	4.87

Table 5

Monthly Values of Runoff (in cfs and percent of total) from Sub-basins of Delaware River and Bay, 1959-1968 (continued)

	Runoff at Trenton (cfs)	Runoff between Liston Pt. and Trenton (cfs)	Runoff from basin seaward of Liston Pt.-Stony Pt. (cfs)	Runoff at Trenton as % of Total (%)	Runoff below Liston Pt. as % of Total (%)
1963					
January	6,589	1,251	1,090	73.78	12.21
February	6,121	793	908	78.25	11.61
March	23,545	20,750	5,739	47.06	11.47
April	14,589	10,699	2,905	51.75	10.30
May	8,138	5,545	1,422	53.88	9.41
June	4,447	3,203	884	52.11	10.36
July	3,302	1,350	391	65.48	7.75
August	2,925	640	209	77.50	5.54
September	2,575	373	121	83.90	3.94
October	2,167	160	52	91.09	2.19
November	4,095	2,613	270	58.68	3.87
December	7,216	1,437	519	78.67	5.66
1964					
January	13,993	7,237	3,836	55.82	15.30
February	9,182	5,098	5,967	45.35	29.47
March	21,867	16,014	3,521	52.82	8.50
April	17,057	17,047	4,675	43.99	12.06
May	10,775	8,049	2,223	51.19	10.56
June	4,398	3,529	1,764	45.38	18.20
July	3,163	1,958	521	56.06	9.23
August	2,535	974	284	66.83	7.49
September	2,194	621	202	72.72	6.70
October	2,200	281	91	85.54	3.54
November	1,967	125	40	92.26	1.88
December	3,964	820	26	82.41	0.54
1965					
January	4,988	334	95	92.08	1.75
February	12,169	5,129	1,970	63.16	10.22
March	9,082	11,200	2,655	39.60	11.58
April	9,881	7,481	1,734	51.74	9.08
May	5,264	3,346	795	55.97	8.45
June	2,633	2,032	404	51.94	7.97
July	1,603	1,038	197	56.48	6.94
August	1,864	521	169	72.98	6.62
September	2,142	248	81	86.69	3.28
October	3,528	220	39	93.16	1.03
November	2,707	578	27	81.73	0.82
December	5,090	291	13	94.36	0.24

Table 5

Monthly Values of Runoff (in cfs and percent of total) from
Sub-basins of Delaware River and Bay, 1959-1968
(continued)

	Runoff at Trenton (cfs)	Runoff between Liston Pt. and Trenton (cfs)	Runoff from basin seaward of Liston Pt.-Stony Pt. (cfs)	Runoff at Trenton as % of Total (%)	Runoff below Liston Pt. as % of Total (%)
1966					
January	5,080	182	35	95.90	0.66
February	9,126	6,915	796	54.20	4.73
March	17,790	9,642	802	63.01	2.84
April	7,833	8,927	1,824	42.15	9.81
May	10,680	5,457	1,072	62.06	6.23
June	6,275	2,820	587	64.81	6.06
July	2,625	1,218	281	63.65	6.81
August	2,547	752	129	74.30	3.76
September	2,781	373	100	85.46	3.07
October	3,686	1,474	307	67.42	5.62
November	4,605	2,174	571	62.62	7.77
December	7,072	6,726	2,452	43.52	15.09
1967					
January	10,144	6,983	1,922	59.70	13.67
February	8,724	4,525	2,322	56.03	14.91
March	18,512	15,781	3,860	48.52	10.12
April	18,291	10,025	2,646	59.08	8.55
May	15,100	8,424	1,980	59.21	7.76
June	6,293	4,848	1,035	51.68	8.50
July	5,675	3,121	576	60.55	6.15
August	10,159	7,445	3,039	49.21	14.72
September	4,835	4,295	2,054	43.23	18.37
October	5,078	2,218	1,073	60.68	12.82
November	8,961	3,854	1,371	63.17	9.66
December	14,754	10,982	4,041	49.55	13.57
1968					
January	6,879	5,431	2,293	47.11	15.70
February	9,885	3,831	2,581	60.66	15.84
March	16,704	15,284	4,676	45.56	12.75
April	11,874	9,171	2,485	50.46	10.56
May	15,603	10,269	1,834	56.32	6.62
June	20,357	6,747	1,152	72.04	4.08
July	7,169	3,543	566	63.57	5.02
August	4,450	1,661	261	69.84	4.10
September	4,779	885	135	82.41	2.33
October	4,467	599	65	87.06	1.27
November	4,769	1,293	67	87.78	0.60
December	10,789	2,532	253	79.48	1.86

Between 1959 and 1968, the drainage area seaward of Liston Point-Stony Point contributed annually from 5.7 to 11.6 percent of the total fresh water runoff of the entire basin. The mean annual contribution is 8.2 percent for the 10-year period, slightly less than the contribution of land area in the basin to the total basin land area. Thus, the southern, coastal plains areas of Delaware and New Jersey contribute, in general, less than their proportionate share to the total basin runoff. This result might be anticipated in view of the fact that evapotranspiration losses will be higher from this portion of the basin.

There is a marked seasonal change in the contribution from the basin seaward of Liston Point-Stony Point just as there is from the basin upstream from Trenton. On the average 15.4 percent of the total basin runoff comes from the basin seaward of Liston Point-Stony Point in February, followed by 11.1 percent in January, and 10.4 percent in March. The monthly maximum from the area south of Liston Point-Stony Point occurred in February, 1964, when nearly 30 percent of the total runoff for that month came from the small Delaware-New Jersey sub-basin. February, 1962 had 26.5 percent of the total basin runoff from the basin seaward of Liston Point-Stony Point.

The late fall months usually experienced the lowest flows from the basin seaward of Liston Point. Values of less than 2 percent of the total basin runoff occurred four times in October, four in November, three in December, and twice in January during the 10-year period. The minimum contribution came in December, 1965, when only 0.24 percent of the total basin runoff came from the area seaward of Liston Point.

In comparison, the runoff at Trenton contributed a high value of 72 percent of the total basin runoff in 1959 and a low value of 55 percent in 1967. Over the 10-year period, the average annual contribution by the Delaware River at Trenton is 64 percent of the total or about 7 percent different from Ketchum's estimate. The difference reflects not only the different method of estimation but also the different years of the study. The monthly data reflect the importance of the runoff from the basin upstream from Trenton during the late summer and fall when the flow at Trenton accounts for 70-80 percent of the total fresh water input while a very low percentage of the flow originates in the area below Liston Point during the latter half of the year. For the 10-years of record, mean maximum monthly contribution to total runoff at Trenton occurred in October, 1959 (96.8 percent) and January, 1966 (95.9 percent) while the minimum contribution was found in March, 1965 (39.6 percent).

For the year 1962, the actual contributions to basin runoff from the Delaware and New Jersey portions of the basin seaward of Liston Point-Stony Point were calculated in the manner described previously. The results are given in table 6. The errors in these data may be somewhat greater than in other portions of the study because as the size of the area or the volume of the runoff decreases, the accuracy of the calculated runoff tends to decrease. For 1962, maximum runoff occurred in Feburary from Delaware and in March from New Jersey. Minimum runoff occurred in November from both portions of the area. As might be expected, the seasonality corresponds closely with the data generated for the entire basin seaward of Trenton presented earlier (table 3).

Table 6

Monthly Runoff from Delaware and New Jersey Portions of Basin
Seaward of Liston Point-Stony Point, 1962

	Mean Monthly Runoff Below Liston Point (cfs)	Runoff from New Jersey Portion of Basin (cfs)	Runoff from Delaware Portion of Basin (cfs)
January	2708	1602	1106
February	3971	2011	1960
March	3964	2323	1641
April	3317	1823	1494
May	1610	887	723
June	994	546	448
July	457	254	203
August	261	145	116
September	162	90	72
October	65	36	29
November	40	23	17
December	474	289	185

New Jersey basin area	769 mi^2
Delaware basin area	612 mi^2

Analysis of the Results

A considerable amount of information has been included in table 3. The actual monthly values of runoff, precipitation, and evaporation are included so that others can perform additional analyses if desired. Values of mean annual net flow in cubic feet per second are plotted in figure 5 for the 20-year record. This graph shows a progressive decrease in the net flow of water outward from the estuary to the ocean during the period of record. While year-to-year fluctuations are evident, it is also apparent that the drought over the eastern part of the country during the early and mid-1960's was quite marked as far as stream flow was concerned.

From a value of over 21,000 cfs in 1960, outflow decreased each year except one until 1965 when it reached a value of just over 8,000 cfs. This appreciable reduction in outflow had significant implications as far as the intrusion of salinity into the bay was concerned. During the 1950's there were year-to-year fluctuations but no appreciable trends developed. Average net outflow over the 20-year record is 18,400 cfs, just slightly below the values estimated by the Corps of Engineers and by Carter in earlier studies using different time periods. Variation around the mean is clearly appreciable, ranging from a high of over 30,000 cfs in 1952 to a low of just over 8,000 cfs in 1965. Net flow at the mouth of the estuary is strongly dependent on the climatic conditions over the whole drainage basin.

Review of the individual monthly totals of net flow given in table 3 reveals that only one month in the total of 240 months actually had a minus value of outflow (or therefore a net inflow from the Atlantic Ocean). This occurred in July, 1955, in a year that had slightly above average outflow, and interestingly enough, in a month just before the August with the highest net outflow in the whole 20-year record. Because of the way in which runoff from land areas is calculated (50 percent of the available surplus runs off each month and the remainder is held over and added to the surplus of the next month for possible runoff), it requires a significant increase in precipitation for any real change in runoff to occur within a one-month period. In this case, the major change between July and August, 1955, occurred in the measured runoff at Trenton which increased from 2,478 cfs in July to 30,292 cfs in August. The volume of precipitation falling on the estuary also increased - from 708 cfs in July to 6,564 cfs in July to 4,403 cfs in August while runoff from the basin downstream from Trenton increased from 1,218 cfs in July to 4,403 cfs in August.

In twelve of the 20 years of record, the highest net outflow value occurred in March, while in five other years it occurred in April. In only three years did the peak flow occur in any other month and they were December, 1950 and February, 1949 and 1951. Clearly peak outflow occurs in late winter and early spring when reduced evaporation, coupled with the melting of the winter snows and fairly reliable precipitation, results in a maximum of water reaching the estuary. In only three of the 20 years was the peak monthly flow less than 30,000 cfs while only twice was the peak value greater than 60,000 cfs. Actually monthly values over 50,000 cfs occurred in only five of the 20 years.

Minimum outflow values in each year of record were more variable than maximum values. July experienced the lowest outflow in two of the 20 years (including the only negative value as discussed previously), August had the lowest outflow in seven years, September in four years, and October in seven years. In eleven of the 20 years, the lowest outflow was below 3,000 cfs and in six of these years it was below 1,000 cfs. Low outflow, of course, results from the decreased runoff from the land during the summer and fall period, not as a result of lowered precipitation (for July and August tend to be the months with highest rainfall in the Delaware Valley) but because of the greatly increased demand for water for evaporation and evapotranspiration.

As a result of these changes through the year, most years experienced a 10- to 20-fold change in outflow from the spring to the fall of the year. These significant changes clearly influence the movement of saline water into the estuary as will be seen in a later section.

Study of the detailed monthly figures of runoff, precipitation, and evaporation given in table 3 reveals the seasonal contribution of each of these factors to the net outflow. First, the two values of runoff, from the basin upstream from Trenton and from the basin seaward of Trenton, follow the same general pattern. Runoff is high in late winter and early spring and low in late summer and fall in both basins but maximum and minimum values hardly ever occur in the same months in the two sub-basins. Actually in only five of the 20 years of record did both sub-basins reach their maximum flows in the same months. Table 7 provides a brief summary of the number of times each month of the year experienced the maximum or minimum value of runoff, precipitation, or evaporation during the whole period of record. For example, the table shows

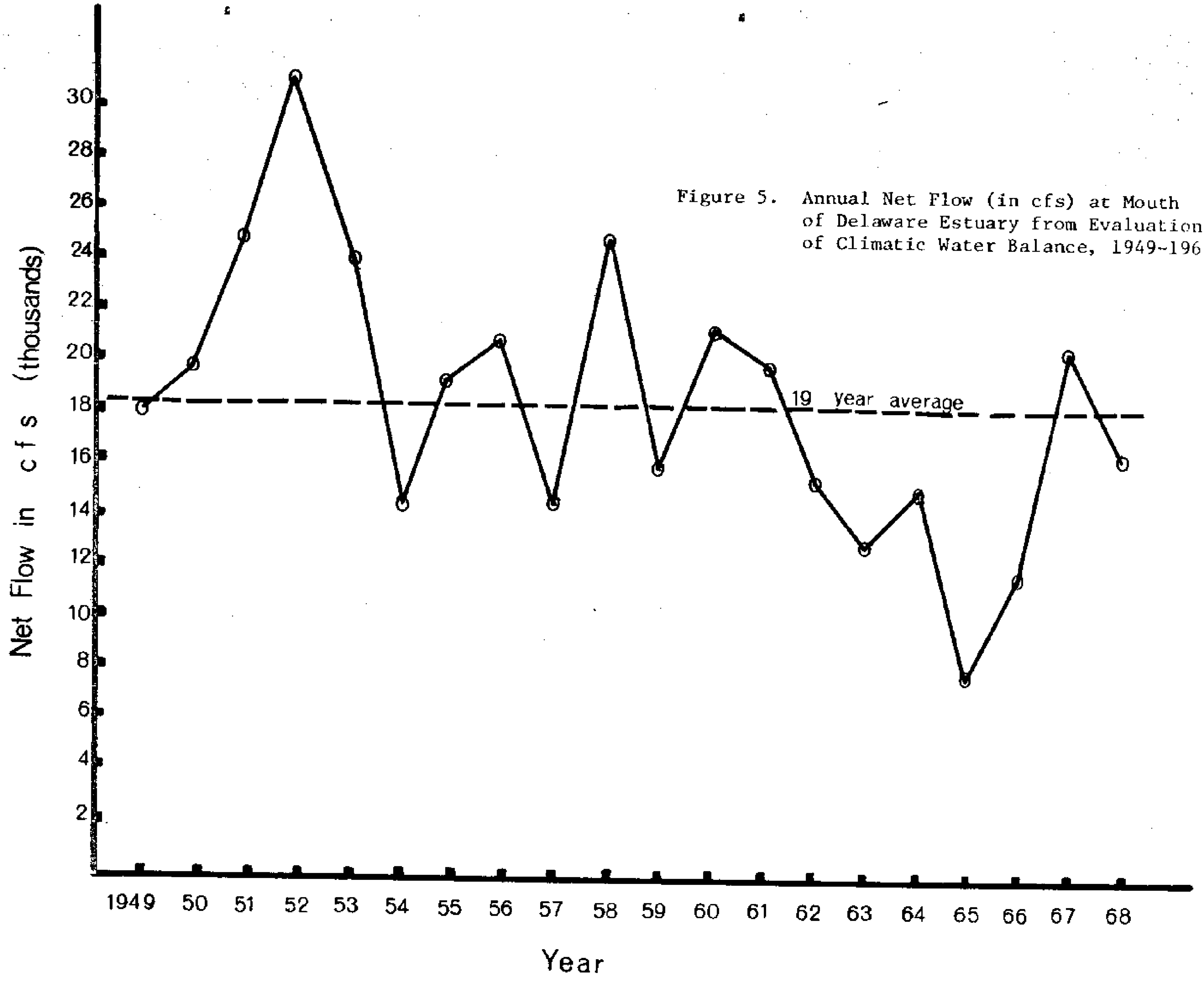

Figure 5. Annual Net Flow (in cfs) at Mouth of Delaware Estuary from Evaluation of Climatic Water Balance, 1949-1968

Table 7

Months of Occurrence of Maximum/Minimum Amounts of Various Hydrologic Factors, Delaware Basin, 1949-1967

	Runoff					
	Basin upstream from Trenton	Basin downstream from Trenton	Basin downstream from Liston Pt. (1959-1968)	Precip.	Evapo.	Net Outflow
January	1/0	1/1	0/1	1/3	0/12	0/0
February	1/0	2/1	4/0	0/1	0/5	2/0
March	5/0	15/0	4/0	1/0	0/0	12/0
April	11/0	2/0	0/0	1/1	0/0	5/0
May	0/0	0/0	0/0	0/3	0/0	0/0
June	1/0	0/0	0/0	0/2	0/0	0/0
July	0/3	0/1	0/1	2/0	20/0	0/2
August	1/6	0/1	0/1	7/1	0/0	0/7
September	0/3	0/1	0/1	3/1	0/0	0/4
October	0/6	0/11	0/3	1/4	0/0	0/7
November	0/1	0/4	0/1	2/3	0/0	0/0
December	0/1	0/0	2/2	2/1	0/3	1/0

that April experienced the maximum runoff from the basin upstream from Trenton eleven out of 20 years, while March experienced it five times. Conversely, runoff from the basin seaward of Trenton was a maximum in March fifteen times while February and April each had the maximum values twice. This shift is to be expected because of the general north-south orientation of the estuary. With warmer temperatures in the southern portion, resulting in earlier snow melting and actually less snow to melt, runoff occurs earlier from the basin south of Trenton. There is about a one month lag in the runoff from the portion of the basin north of Trenton.

In the five years in which the month of the maximum runoff in the basins upstream and downstream from Trenton agreed, the maximum net outflow from the estuary was also found in these months. In five other years, the maximum net outflow from the estuary occurred in the same month as the maximum runoff from the basin upstream from Trenton while in seven other years it agreed with the maximum runoff from the basin downstream from Trenton. The importance of the flow from the basin seaward of Trenton to the whole balance can also be seen in table 7 where March has the maximum net outflow twelve times and April only five times, indicating that the conditions of runoff from the basin seaward of Trenton are possibly more controlling than the runoff from the basin upstream from Trenton which peaks in April more of the time.

In twelve of the 20 years the minimum flow from the basin north of Trenton occurs in the summer months of July, August and September as opposed to only three out of 20 years from the basin south of Trenton. In the latter basin, October and November experience the low flow in fifteen years as compared with only seven years during those same months in the basin north of Trenton. One might conclude that maximum net outflow follows more directly the runoff contribution from the basin seaward of Trenton while low net outflow follows more closely the low runoff contribution from the basin upstream from Trenton.

The data in column 3, table 7, illustrate predominance of peak runoff in February and March of water flowing directly into the bay, a condition noted earlier when the entire basin seaward of Trenton was discussed. The two December maxima may reflect periods of heavy winter storms and rainfall rather than snow cover as in the upper portion of the basin. Minimum flows occurred in six out of ten years in October, November and December from the lower portion of the basin.

Table 7 also shows the relatively minor contribution to the balance played by precipitation onto the estuary surface. August had the highest precipitation total in seven months yet August never experienced the highest net outflow and, in fact, had the lowest net outflow in seven of the 20 years. That maximum precipitation is a late summer phenomenon clearly shows up in the figures but this seems to have no real influence on net outflow. This is to be expected since July and August are also the months with maximum evaporation (table 7 shows that July experienced maximum evaporation in all 20 years). The precipitation and evaporation are fairly well in balance in most years so that there is usually not a large surplus or deficit of water created by the seasonal changes in these factors. Only during very dry periods, when evaporation from the water surface remains high is there a significant reduction in net fresh water inflow, or during wet wintertime periods with reduced evaporation is there a significant increase in net fresh water inflow over the estuary due to the precipitation or evaporation factor.

III. RELATION OF ESTUARY FLOW TO SPECIFIC CONDUCTANCE OR WATER QUALITY

The data in table 3 provide quantitative values of net flow at the mouth of the estuary based on determinations of as many of the inputs and outputs as possible. The results agree well with the few other estimates of mean flow that are available. If these values are realistic, it should be possible to relate them in some fashion with observations of salinity or water quality in the estuary for the composition of the water at any place in the estuary must be related in some way to the various input and outputs of fresh water modified by tidal, wind, and circulation conditions.

The data in table 3 provide flow values at the mouth of the estuary. Unfortunately, we do not have many observations of water quality right at the mouth of the estuary. Instead, fairly routine observations of such things as temperature and specific conductance are taken at observation sites located well up the estuary. Observations at these places might not necessarily be closely related to flow at the mouth of the estuary but, of course, there should be some degree of correlation.

Seasonal Course of Chloride Concentration

The seasonal variations in chloride ion concentration for two distinctive hydrologic regimes are illustrated in figures 6 and 7 for four stations in the upper Delaware estuary - Reedy Point, Delaware; Delaware Memorial Bridge; Chester, Pennsylvania; and the Ben Franklin Bridge, Philadelphia. The period October, 1964, to October, 1965 (figure 6), had the lowest mean annual outflow during the 20-year period, 1949-1968. In contrast, the 1967-1968 hydrologic year (figure 7) experienced a near average net outflow of some 18,500 cfs. The decreased discharge of fresh water into Delaware Bay in 1964-65 should result in an increase in chloride (salinity) levels in the estuary (Ketchum, 1952; Cohen, 1957; Durfor and Keighton, 1954). The lines on the graphs represent data summarized from five-day averages. Note that the data are plotted on semi-log paper.

During the low water period, 1964-65, Reedy Point, the most seaward station, continually recorded chloride levels in excess of 1000 ppm. Maximum chloride levels occurred in October and November, 1964 (6,500 ppm), when the discharge at Trenton fell to 2,000 cfs (table 3) and the runoff into Delaware Bay from the area seaward of Liston Point fell to a mean monthly total of less than 100 cfs (table 5). The response to the low fresh water flows are evident at all stations; even the Ben Franklin Bridge (Philadelphia, Pa.) station recorded chloride levels exceeding 100 ppm with a peak value in November, 1964, of 250 ppm.

The 1967-1968 data indicate chloride concentrations during a more normal runoff year. The chlorinity levels are generally lower than found in 1964-65 for the entire estuary and bay. However, the 1967-1968 record is also distinctive because of the extreme variability shown particularly from December, 1967, through January, 1968, and March through April, 1968, at Chester, Delaware Memorial Bridge and Reedy Point. The cause of the December drop is evident in table 3. December, 1967, experienced high runoff at Trenton (14,703 cfs) and exceptionally high runoff from the basin seaward of Trenton (15,023 cfs) as well as above normal runoff from the area below Liston Point. January, 1968, however, was a period of low fresh water runoff so chloride levels rose rapidly again.

The catastrophic decline in chloride levels from 1,300 ppm to less than 70 ppm in March, 1968, at the Delaware Memorial Bridge was also caused by a combination of factors - high runoff at Trenton, plus nearly 20,000 cfs of additional runoff from the basin seaward of Trenton, the highest precipitation total for the year 1968 (3,619 cfs), all resulting in the maximum outflow for the year (39,594 cfs) compared with net outflow of approximately 17,000 cfs in February and 23,000 cfs in April.

Correlation of Net Outflow with Chloride Concentration

The technique by which the net flow at the mouth of the estuary has been evaluated, can, of course, be applied for any particular place in the estuary merely by computing the runoff from the catchment basin above that particular point as well as the precipitation gains and evaporation losses to the estuary above that point. Thus, it would be possible to determine the net flow at Reedy Point or the Delaware Memorial Bridge, for example, by considering only the contributions from the catchment basin and from precipitation and evaporation above these points. Before undertaking this work for many specific points, it is desirable to evaluate the more general relations between flow at the mouth of the estuary and water quality at selected spots. Based on the results obtained, a decision can be made whether the more detailed hydrologic evaluations would add significant new information.

The U. S. Geologic Survey has maintained continuous water quality sampling stations at a number of places in the Delaware estuary for nearly a decade (see figures 6 and 7). There are some gaps in these records when the samplers were not operating, and, of course, the observation sites are not always in the best locations because of the need to have fairly easy access for servicing. Still the records are of great value in attempting to determine the seasonal pattern of change of such things as temperature and chloride content. In this respect, they are of more value than those observations taken by means of cruises up or down the river. Cruises may be able to take the observations in the middle of the channel or in other particular locations of importance but they often lack the systematic and reproducible aspect of samples from a fixed location.

To study the effect of estuary flow on water quality, it was decided to test the relationship between average values of specific conductance at four selected sites in the estuary and net estuary flow derived from various combinations of fresh water inflow and outflow data.

Dissolved minerals when present in water will dissociate into positive and negative ions capable of conducting electricity. As the concentration of mineral matter increases so does the conductivity of the water. Thus conductivity becomes a fairly useful measure of the dissolved mineral matter in the water. The term specific conductance is defined as the reciprocal of the resistance of water to an electrical current between two one square centimeter electrodes which are exposed one centimeter apart (Durfor and Keighton, 1954). The units of specific conductance are micromhos.

Since conductivity increases as salinity increases, readings of specific conductance can also be used to reflect changes in salinity. Cohen (1957) suggested that chloride ion concentration was related to specific conductance by the expression

$$\text{Cl (ppm)} = \frac{\text{Sp. Cond.} - 400}{3.0}$$

for values of specific conductance between 4,000 and 16,000 micromhos. Below 4,000, the relation is non-linear. Foster, in a study under this grant, felt that it was preferable to use a series of linear equations for different ranges of chloride. Her relations were as follows:

Chloride 0-50 ppm
$$\text{Sp. cond} = 6.3\ (\text{Cl}) + 126.2$$
Chloride 50-1200 ppm
$$\text{Sp. cond} = 3.3\ (\text{Cl}) + 246.8$$
Chloride 1200-12,000 ppm
$$\text{Sp. cond} = 2.85\ (\text{Cl}) + 859.7$$

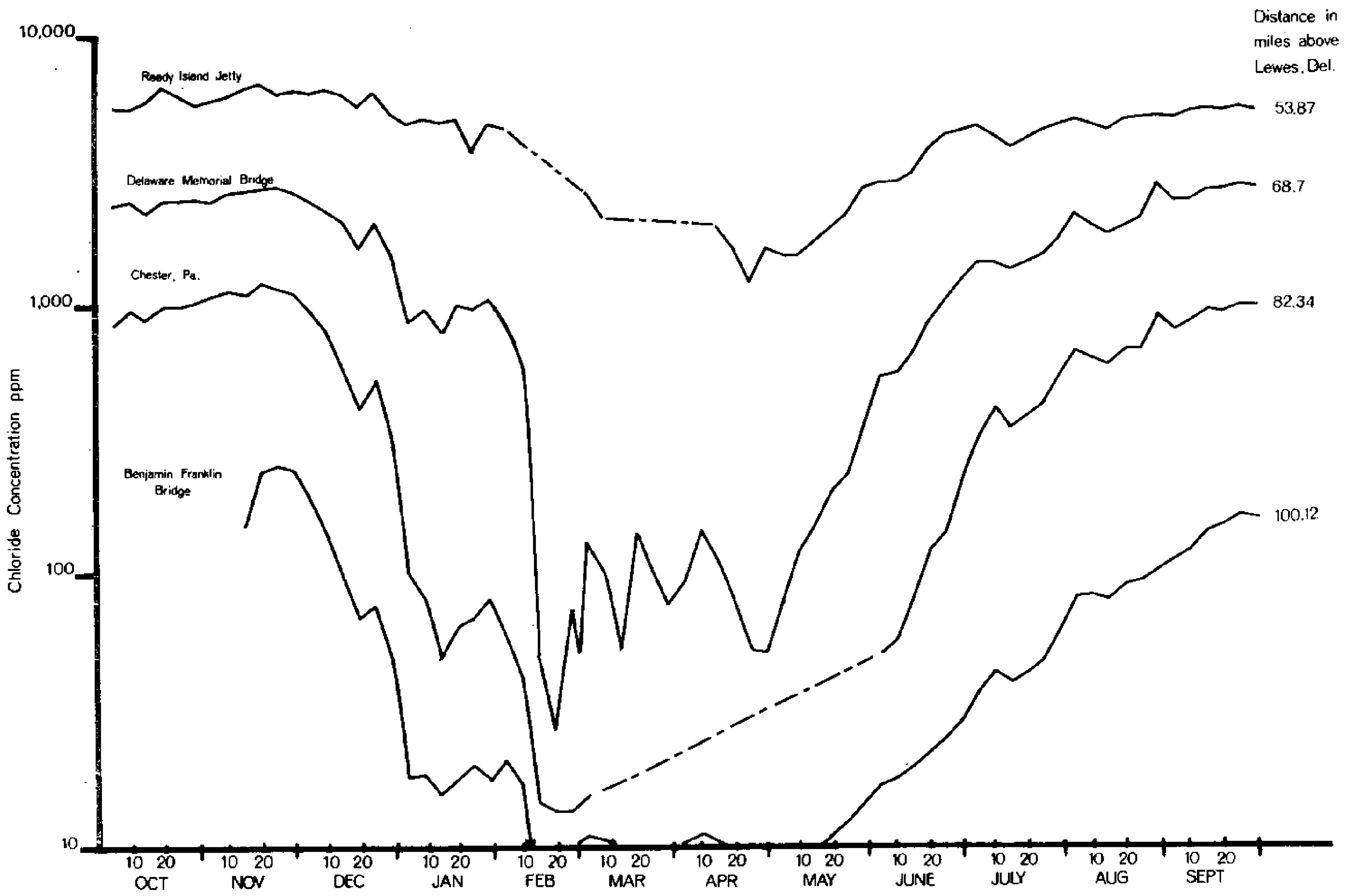

Figure 6. Monthly Variation in Chloride Ion Concentration (ppm) at Four Stations in the Delaware Estuary, October 1964 - September 1965.

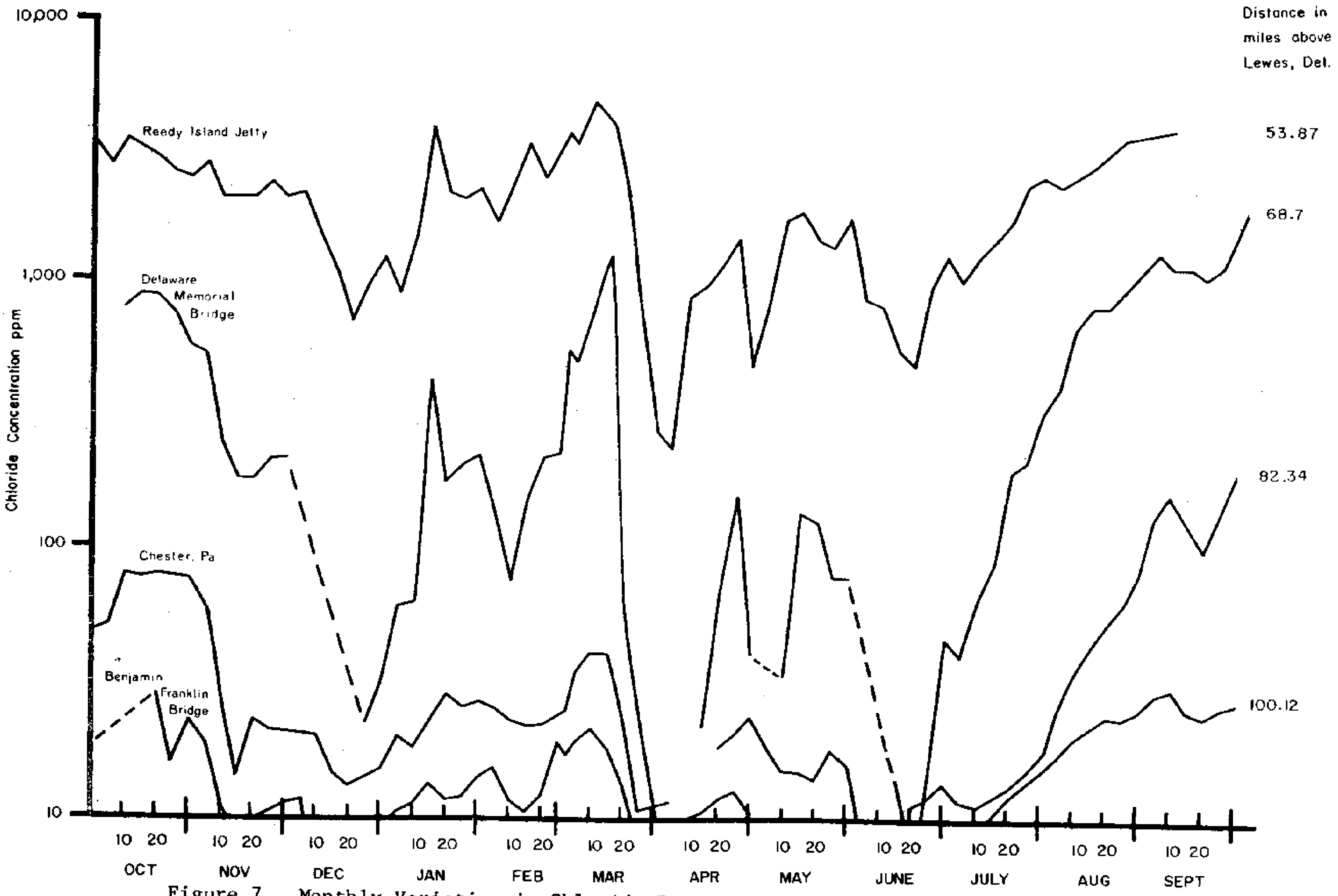

Figure 7. Monthly Variation in Chloride Ion Concentration (ppm) at Four Stations in the Delaware Estuary, October 1967 - September 1968.

Durfor and Keighton felt that the relation between chloride and conductance was logarithmic above 60 ppm rather than linear, and that for values below 60 ppm the action of sulfate and bicarbonate ions adversely affected the conductivity making it difficult to obtain any significant relationship. Foster also acknowledged the validity of a logarithmic relationship between chloride and conductance for values of chloride between 100 and 7,000 ppm or conductance between 500 and 20,000 micromhos.

The U. S. Geological Survey records provide daily maximum, minimum and mean values of specific conductance at various observation stations in the estuary. Since the estuary flow values are monthly figures and since specific conductance can change fairly markedly from day to day, it would be desirable to relate the flow values to some longer period average value of specific conductance in order to eliminate the dependence on just a single observation. Thus, the mean daily specific conductance values were averaged together for a five-day period at the beginning of each month and related to the monthly flow in the estuary. The mean value of specific conductance during the last two days of one month and the first three days of the following month was accepted as representative of the specific conductance at the beginning of the month.

These values of specific conductance were plotted against the values of mean outflow during the previous 30-day period and a curvilinear relationship resulted. Use of log-log paper provided a straight line relationship. Figures 8 and 9 show the results obtained when the outflow for the previous 60-day period is plotted against the values of specific conductance at the Ben Franklin Bridge (Philadelphia) and at Chester. While there is some scatter of the points they do approximate a straight line.

The relationship shown in figures 8 and 9 is of the form $y = ax^b$. By means of a straightforward statistical procedure, it is possible to obtain a least squares fit to such a parabolic function and to evaluate the correlation coefficient (r), the standard error of estimate (s), and the values of the constants a and b.

Table 8 lists these values for the relation between specific conductance and net flow in the estuary summed over the two previous months for all input and output factors (table 8a), and summed over the previous two months for runoff but only over the past month for estuary precipitation and evaporation (table 8b). In all cases, correlation coefficients very close to -0.9 were obtained indicating a fairly high degree of dependence of specific conductance on net flow.

Previous workers have suggested that water entering near the head of the estuary takes an appreciable amount of time to reach the mouth and flow into the Atlantic Ocean. Various periods ranging from one to three months of flow time in the estuary have been indicated. Because of this lag, it was felt that it would not be correct to use just the value of net outflow for a particular month (as given in table 3) to relate to specific conductance but that rather some lagged value of flow should be used.

Precipitation and evaporation directly over the water surface might enter more rapidly into the hydrologic system. Runoff entering at Trenton, however, might take considerably longer to reach the ocean than would runoff

Table 8

Various Statistical Relations Between Specific Conductance at Four Points in Delaware River and Net Flow at Mouth of Estuary

	B. Franklin Bridge	Chester	Del. Mem. Bridge	Reedy Point
a) Flow Based on Past Two Months Values of RO, P, E				
Correlation Coefficient	-0.898	-0.932	-0.910	-0.835
Standard Error of Estimate	0.080	0.145	0.218	0.141
Values of a in $y = ax^b$	116.58	1769.81	1703.91	702.18
b	-0.37	-0.87	-1.15	-0.52
b) Flow Based on Past Two Months Values of RO; one month of P, E				
Correlation Coefficient	-0.886	-0.932	-0.918	-0.860
Standard Error of Estimate	0.084	0.146	0.209	0.131
Values of a in $y = ax^b$	156.33	3489.56	3658.65	1033.39
b	-0.43	-1.02	-1.32	-0.61

entering from the basin below Trenton. In order to determine the effect of lagging of different terms of the hydrologic expression, the computer program for the least squares fit to a parobolic function was rerun several times with various combinations of input and output data. The various combinations tested are as follows:

1. Net outflow from the estuary in the previous month.
2. Net outflow from the estuary in the previous two months.
3. Net outflow from the estuary in the previous three months.
4. Net outflow consisting of past two months river flow at Trenton, past two months runoff from basin below Trenton, past month precipitation and evaporation over estuary.
5. Net outflow consisting of past three months river flow at Trenton, past two months runoff from basin below Trenton, past month precipitation and evaporation over estuary.
6. Net outflow consisting of past two months river flow at Trenton, past three months runoff from basin below Trenton, past month precipitation and evaporation over estuary.

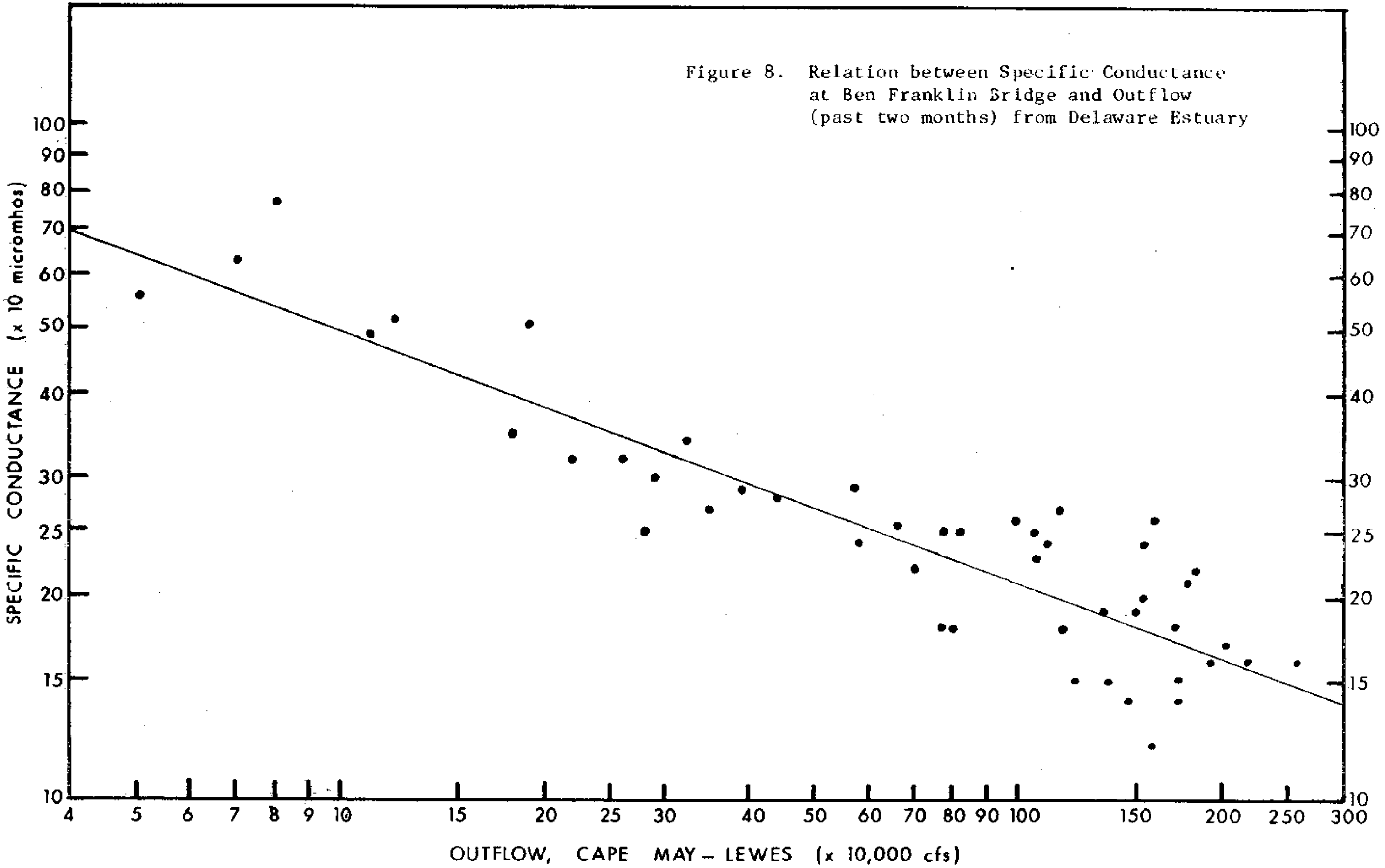

Figure 8. Relation between Specific Conductance at Ben Franklin Bridge and Outflow (past two months) from Delaware Estuary

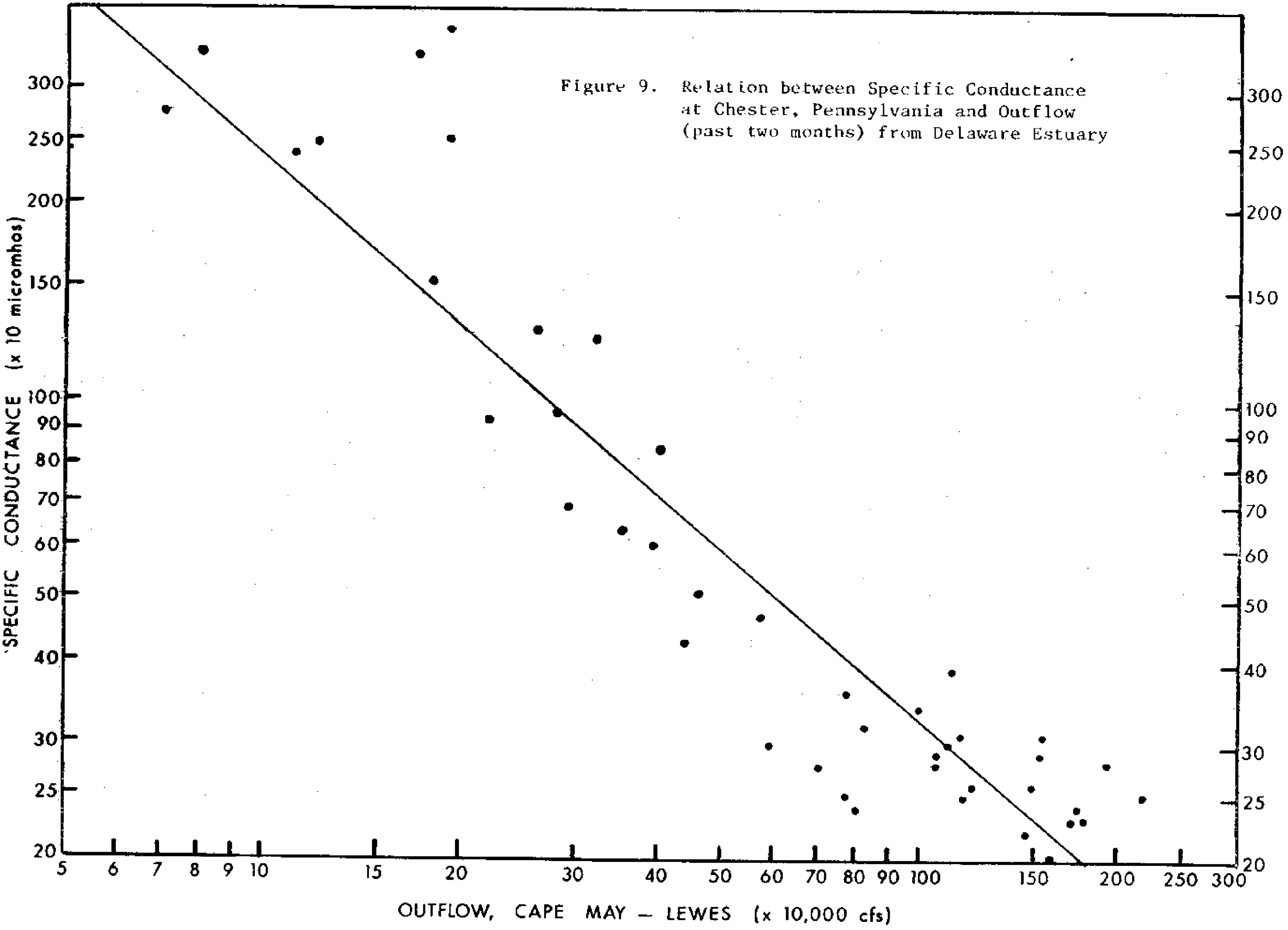

Figure 9. Relation between Specific Conductance at Chester, Pennsylvania and Outflow (past two months) from Delaware Estuary

In each case, these values of net outflow were related to the values of specific conductance (averaged over five days at the beginning of a month) at the four selected observation sites. The number of observations included in the study were 47 at the Ben Franklin Bridge, 42 at the Delaware Memorial Bridge, 44 at Chester, and 46 at Reedy Point.

Table 9 sums up the correlation coefficients found in each case Actually there was very little change in the coefficients from one station to another or among the different net outflow combinations The net outflow value achieved by combining two months runoff from the basin and only the past month precipitation and evaporation provides the most responsive expression of estuary conditions as far as specific conductance is concerned of the six combinations tested. At the same time, the different combinations involving three months of river flow from above Trenton provide the poorest correlation coefficients at all stations Evidently the longer time period, resulting in some accumulation of the flow record over periods with both high and low values, provides too little detail to be expressive of changes in specific conductance.

Higher correlation coefficients are found at Chester than at any of the other stations for all flow combinations except one The correlation between one month estuary flow and specific conductance is slightly higher at the Delaware Memorial Bridge than at Chester Otherwise, the Chester data are more closely related to all of the various flow combinations than the data from the other stations. This might indicate that the specific conductance data at Chester are possibly more representative than the data from other stations for if the specific conductance data were everywhere equally good, the short lag period flows should result in higher correlations with the upstream stations while the longer lag period flows should result in higher correlations with the downstream stations Instead the data from Reedy Point, the station located furthest downstream, has the poorest correlation with all combinations of flows, while the data at the Ben Franklin Bridge, the most upstream station, appears to have the next poorest correlation with all combinations of flows It could also indicate that local conditions (such as the influence of the Chesapeake and Delaware canal at Reedy Point, or tributary river flows at the Ben Franklin Bridge) are more important in specific conductance relationships than any lagged value of flow at the estuary mouth.

Seasonal Movements of Isochlors in the Delaware Estuary

Figures 10 through 14 are examples of maps showing the location of the 1,000 ppm and 5,000 ppm isochlors for the period 1965, 1966, 1967 and 1968. These maps were constructed from data similar to those used in the correlation analysis between net fresh water outflow and water quality (figures 6 and 7). The location of the 1,000 ppm isochlor at the first of each month is an indication of the extent of salt water intrusion into the upper Delaware estuary during a low net outflow period, 1965-1966 (8,000 and 12,000 cfs, respectively), an above average outflow year 1967 (20,000 cfs), and a slightly below average flow year, 1968 (16,000 cfs).

Table 9

Correlation Coefficients Between Net Flow at Estuary Mouth and Specific Conductance at Various Points in the River

Special Conductance at versus	Ben Franklin Bridge	Chester Pa.	Del. Mem. Bridge	Reedy Point
Estuary flow previous month	-.895	-.896	-.905	-.817
Estuary flow previous 2 months	-.898	-.932	-.910	-.835
Estuary flow previous 3 months	-.843	-.905	-.838	-.794
Various lagged flows*				
a)	-.886	-.932	-.918	-.860
b)	-.849	- 897	-.867	-.832
c)	-.839	-.897	-.872	-.834

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*a) Flow value made up of past 2 months of river flow at Trenton, past 2 months of runoff from basin below Trenton, past month of precipitation and evaporation over estuary.

b) Flow value made up of past 3 months of river flow at Trenton, past 2 months of runoff from basin below Trenton, past month of precipitation and evaporation over estuary.

c) Flow value made up of past 2 months of river flow at Trenton, past 3 months of runoff from basin below Trenton, past month of precipitation and evaporation over estuary.

Particularly evident is the seaward displacement of 1,000 ppm isochlor during the months of increased fresh water runoff and the large areal variations of the 1,000 ppm isochlor in 1965 and 1966, ranging from the vicinity of the Chesapeake and Delaware canal to Eddystone, Pa. a distance of some 40 miles. Similar data for 1967 shows the 1,000 ppm isochlors clustered between the Delaware Memorial Bridge and Reedy Point.

The upstream penetration of the 5,000 ppm isochlor above Reedy Point occurred only during times of extremely low flow at Trenton, accompanied by low flows from the lower basin as well.

Figure 10

Location of 1000 ppm Isochlor
in Delaware Estuary on
First of Each Month, 1965

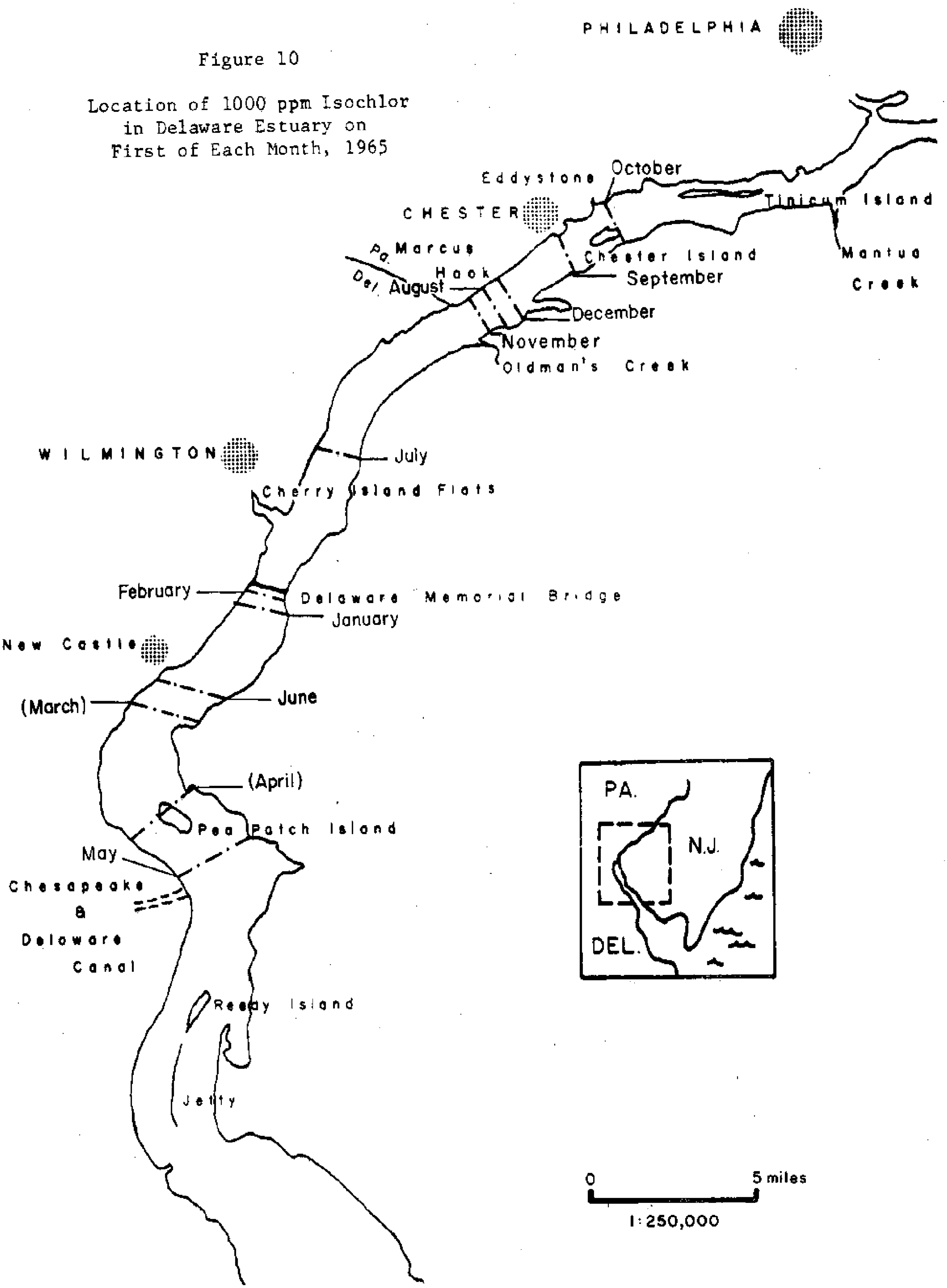


Figure 11

Location of 1000 ppm Isochlor
in Delaware Estuary on
First of Each Month, 1966

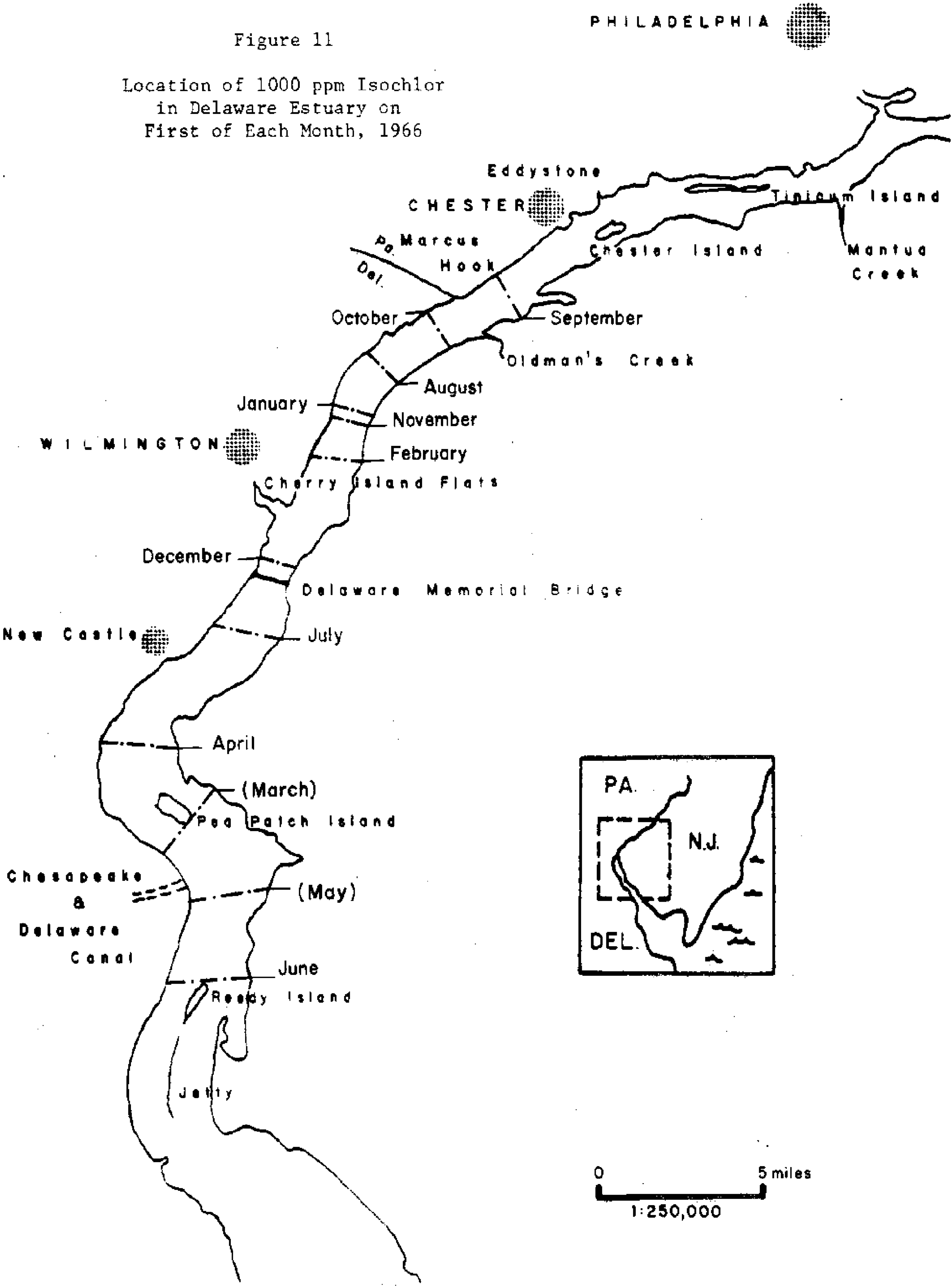


Figure 12

Location of 1000 ppm Isochlor in Delaware Estuary on First of Each Month, 1967

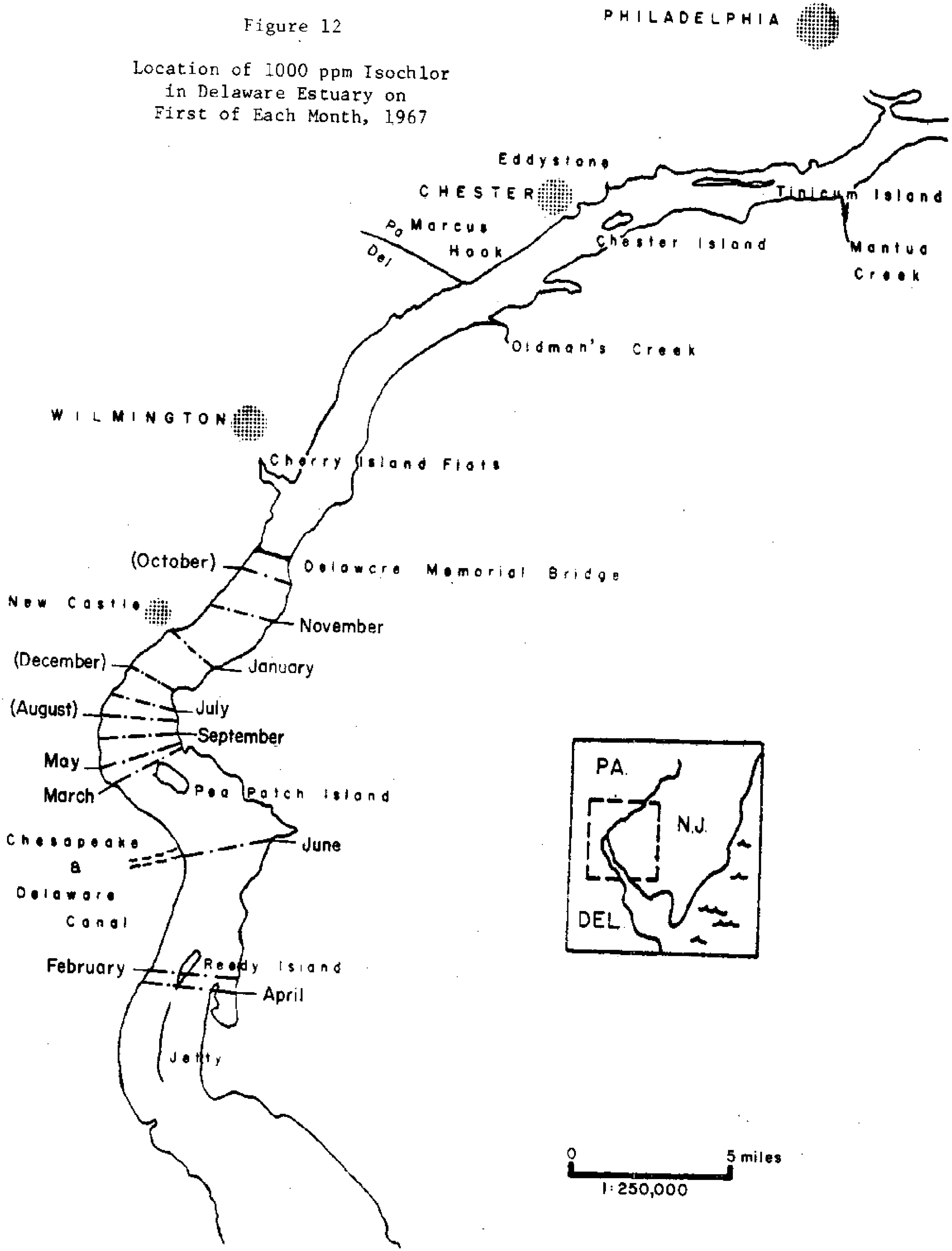


Figure 13

Location of 1000 ppm Isochlor in Delaware Estuary on First of Each Month, 1968

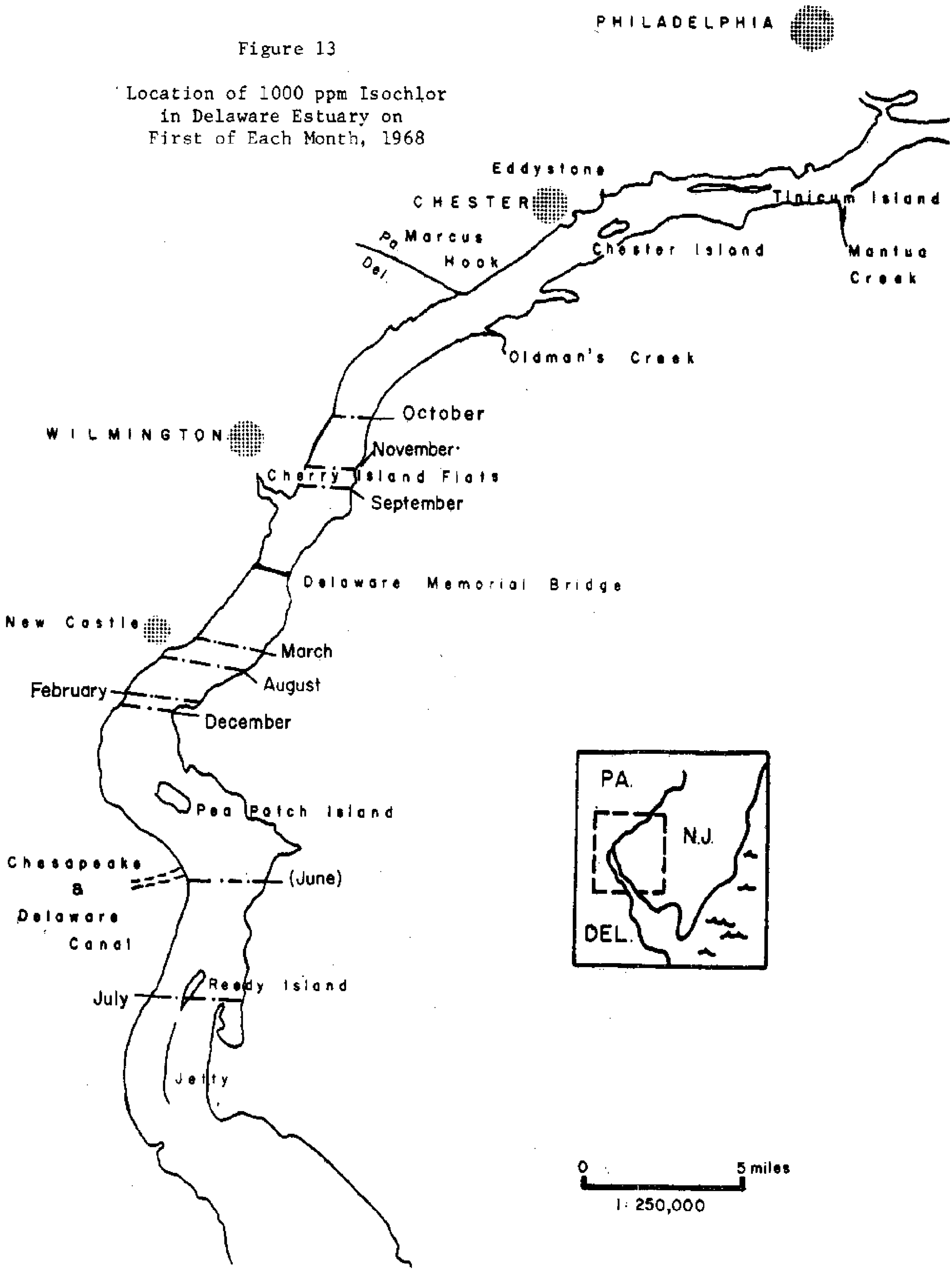
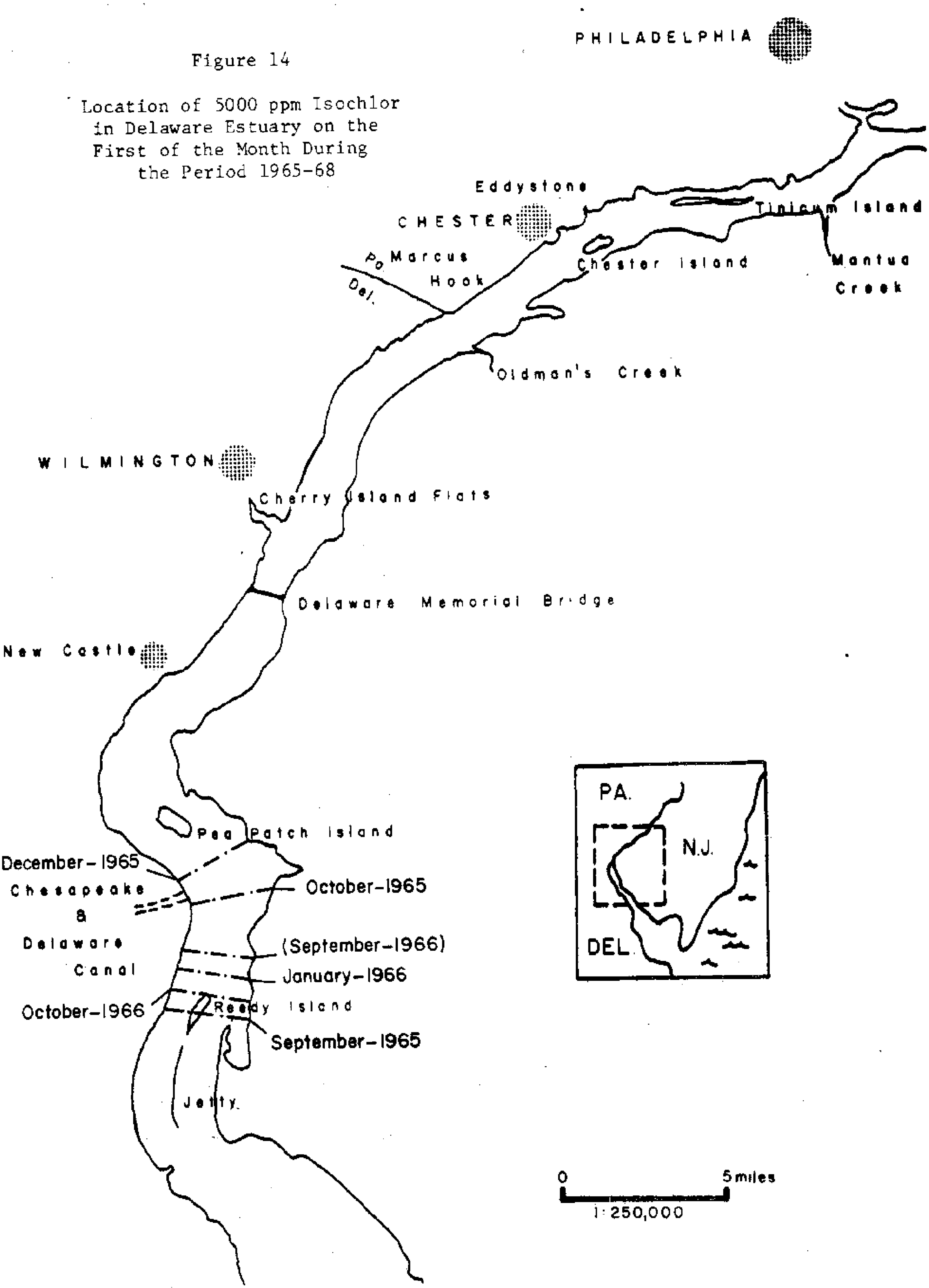


Figure 14

Location of 5000 ppm Isochlor in Delaware Estuary on the First of the Month During the Period 1965-68



IV. LIMITATIONS

A number of assumptions and approximations have been made in order to achieve the results described so far. Some of these have been fairly reasonable and will not result in significant errors while others have been quite crude and could result in significant modification of the results achieved. While it is not possible to establish any sort of order of magnitude to these various assumptions, it is desirable at least to recognize where assumptions have been made.

It was assumed in using the measured values of stream flow at Trenton that the record was reliable. The U. S. Geological Survey evaluation of the record was accepted; use of the measured record of runoff from the upper basin, corrected slightly for withdrawal for and later recharge from the city of Trenton itself, eliminates the need to evaluate upstream withdrawals, additions or transfers of water.

In determining the runoff from the basin seaward of Trenton, several assumptions had to be made. First, there is the basic assumption that it is even possible to compute runoff from the climatic data of precipitation and temperature with a reasonable degree of accuracy. If daily data were sought, this would be a questionable assumption. However, previous experience in mid-latitude areas has shown that it is possible to compute monthly runoff with fair accuracy, and the reasonable results obtained during the course of this research program would bear out the general correctness of this assumption.

Second, it was assumed that the rate of detention of surplus water on or in the soil was the same everywhere in the basin - namely, that 50 percent of the surplus water available for runoff actually did runoff each month, the rest being held over and added to the surplus of the following month. This assumption is quite reasonable for moderate to large watersheds with sandy loam soils, good vegetation cover and moderate slopes. It is quite possible that the percent detention should have been modified as the analysis moved from the rolling piedmont and mountain areas of the northwestern part of the basin onto the level sandy coastal plains of the south and east portions. Using monthly data, this was not considered to be an assumption of major significance in the final results.

Third, it was assumed that no unmeasured diversions or releases of water occurred within the basin south of Trenton and that consumptive use of water is generally small. While most of the interbasin transfers generally cancel out, one interbasin transfer does occur which is hardly inconsequential. This transfer is the water flow through the Chesapeake and Delaware Canal located just south of Wilmington, Delaware and just north of Reedy Point. The canal has been in existence for well over one hundred years. While there is a net flow of generally fresh water from the Chesapeake into the Delaware in all seasons of the year, the exact amount of this flow is unknown. Over the years, the canal has undergone deepening and widening and this has, of course, resulted in significant changes in the flow of water in the canal but always with the net flow being from the Chesapeake to the Delaware because of the height difference in the water levels in the two water bodies.

The only estimate of the flow of water in the canal in recent years is included in a 1939 report by the U. S. Corps of Engineers which indicates an average annual value of somewhat over 2,000 cfs through the canal from the Chesapeake to the Delaware Bay. During the 20-year period of investigation in this study, the monthly flow at Trenton dipped to 2,000 cfs or below on 12 occasions or about 5 percent of the time. The average discharge of the Schuylkill River at Philadelphia, draining over half of the basin seaward of Trenton is 2,975 cfs; the Chesapeake and Delaware canal contributes nearly as much water to the Delaware estuary as the Schuylkill River or as much as one half of the whole basin seaward of Trenton. Viewed in this light, this unknown quantity becomes quite significant. The water transfer by the canal was not considered in the present study because of the lack of any real quantitative values.

Two significant assumptions were made in evaluating precipitation over the estuary surface. First, it was assumed that values of precipitation as measured by perimeter stations are representative of the values of precipitation actually falling in the water surface. Second, it was assumed that it was possible to extrapolate from the point observations of precipitation to the wider area between observing stations with little loss of accuracy.

Actually both assumptions are questionable although climatologists have had to live with them both for a long time. We have already discussed in more detail the question of using data from perimeter stations to represent over-water precipitation. The second assumption concerning the reliability of extrapolating from point values may be more questionable. In an earlier study (Mather, 1969), the ratio of the monthly precipitation at Dover and Milford, located on the relatively flat Delmarva peninsula and less than 20 miles apart, was shown to vary from 0.74 to 2.00 in January with a relative error (the standard deviation of the ratio over the average value of the ratio) of 23.4 percent. This would indicate that if Dover had a 4-inch January precipitation total, the Milford precipitation could be estimated only within ±1 inch. With the greater variability in summertime precipitation, the relative error increased to 31 percent. Similar variations may exist over the water so that the actual value of precipitation at any spot over the water cannot be estimated with any great degree of precision. However, it has always been assumed that extrapolation from point values is possible and that the errors that exist because of actual but unmeasured variations in precipitation from place to place will balance out. The relatively few measured values must be accepted as representative of the whole area.

Again, two significant assumptions were made in evaluating evaporation over the estuary surface. First, it was assumed that evaporation from a water surface can be approximated by the potential evapotranspiration as computed from temperature data and, second, it was assumed that potential evapotranspiration at perimeter stations would be representative of evaporation from a water body whose temperature might be different from the surface and air temperature at the perimeter stations. Both of these assumptions have been discussed in some detail in an earlier section.

Finally, it must be re-emphasized that to obtain the values of net outflow given in table 3, the runoff for the past month at Trenton, from the basin seaward of Trenton, and from precipitation and evaporation over the estuary were all combined. The net figures, thus, are based on the assumption that all this water flows out of the mouth of the estuary by the end of the month. This, we know, is not the case and some delay or lag especially in the figures for runoff must be considered. Thus, the figures for net outflow should be adjusted to lag, at least, the runoff values slightly, since it will take an appreciable amount of time for the water to flow through the estuary system to the ocean. The actual monthly values of each of the factors involved are included in table 3 so that other assumptions for lagging can be included by other investigators.

V. SUMMARY AND CONCLUSIONS

The foregoing analyses cover two-thirds of the program outlined in the whole research proposal. The third aspect is covered in Part II. The present report provides a number of significant conclusions, not the least of which is that it is possible to determine net flow at the mouth of a body of water such as an estuary by means of evaluating all the input and withdrawal terms in the hydrologic equation.

In addition this study has:

a) provided quantitative values of the monthly outflow of water at the mouth of the Delaware estuary which had previously only been roughly estimated;

b) suggested the importance of the relative contribution of runoff from various areas of the basin, of precipitation, and of evaporation to the overall water flow in the estuary;

c) shown that significant correlations between flow values and water quality (specific conductance) at several places in the estuary do exist and thus, that the water balance of the area has a significant role to play in the quality of estuary waters of importance to shellfish and to man; and

d) provided estimates of the nature of the lag in the various terms of the hydrologic balance to account for the slow movement of water from the land, through the estuary, to the ocean.

The study did not actually provide figures of net flow at any selected point within the estuary system but rather only at the mouth of the estuary. It is clear that the same technique could be utilized to provide realistic flow values at any particular place. This ability should have applicability in many other hydrologic studies involving the influence of watershed changes, the movement of the salt front in the estuary, and the rate of disposal of pollutants or other substances in the waters of the estuary.

In the Lower Bay area, where sizeable volumes of runoff enter through ungaged streams, the water balance method should prove extremely useful in estimating the fresh water input vital to the maintenance of the salinity, temperature, and water quality balance needed to sustain a viable ecosystem. Even minor changes in the amount of runoff flowing into Delaware Bay and its adjacent tidal marshes could drastically change the environment in an unfavorable way.

REFERENCES

Blust, F. A. and B. G. DeCooke, 1960: Comparison of precipitation on islands of Lake Michigan with precipitation on the perimeter of the lake, J. Geophys. Res., 65(5):1565-1572.

Carter, D. B., 1958: The average water balance of the Delaware Basin, Publications in Climatology, Laboratory of Climatology, Vol. 11, No. 3, pp. 249-269.

Cohen, B., 1957: Salinity of the Delaware estuary, Delaware Geological Survey, Rept. of Investigations No. 1, Newark, Del., 86 p.

Corps of Engineers, U. S. Army, 1954: Delaware River model study, salinity tests of existing channel, WES Report No. 2, Tech. Memo. No. 2-337, Vicksburg, Miss., 38 p.

Corps of Engineers, U. S. Army, 1956: Delaware River model study hydraulic and salinity verification, WES Report No. 1, Tech. Memo. No. 2-337, Vicksburg, Miss., 25 p.

Cronin, L. E., J. C. Daiber and E. M. Hulbert, 1962: Quantitative seasonal aspects of zooplankton in the Delaware River estuary, Chesapeake Science, 3(2):63-93.

Durfor, C. N. and W. B. Keighton, 1954: Chemical characteristics of Delaware River water, U. S. Geol. Survey Water-Supply Paper 1262, U. S. Dept. of Interior, Washington.

Freeman, J. R., 1926: Regulation of Elevation and Discharge of the Great Lakes, (A Report to the Chicago Sanitary District) Chicago, Ill., 548 p.

Governor's Task Force, 1972: The Coastal Zone of Delaware: A Plan for Action in Delaware, Final Report of the Governor's Task Force on Marine and Coastal Affairs, College of Marine Studies, University of Delaware.

Horton, R. E. and C. E. Grunsky, 1927: Hydrology of the Great Lakes, Pt. III, Appendix II, Report Engineering Div., Sanitary District, Chicago, Ill., 432 p.

Hunt, I. A., 1958: A Technique for Forecasting Observed Runoff from Large Areas, U. S. Lake Survey, Corps of Engineers, U. S. Army

Ketchum, B. H., 1952: The distribution of salinity in the estuary of the Delaware River, Woods Hole Ocean. Inst., Mass., Ref. No. 53-31.

Mather, J. R. (ed.), 1954: The measurement of potential evapotranspiration, Publications in Climatology, Laboratory of Climatology, Vol. 7, No. 1, 225 p.

Mather, J. R., 1969: Factors of the climatic water balance over the Delmarva peninsula, Publications in Climatology, Laboratory of Climatology, Vol. 22, No. 3, 129 p.

Muller, R. A., 1966: The effects of reforestation on water yield: A case study using energy and water balance models for the Allegheny Plateau, New York, Publications in Climatology, Laboratory of Climatology, Vol. 19, No. 3, pp. 251-304.

Sanderson, M., 1966: A climatic water balance of the Lake Erie basin, 1958-1963, Publications in Climatology, Laboratory of Climatology, Vol. 19, No. 1, 87 p.

Thornthwaite, C. W., 1948: An approach toward a rational classification of climate, Geogr. Rev., 38(1):55-94.

Thornthwaite, C. W. and J. R. Mather, 1955: The water balance, Publications in Climatology, Laboratory of Climatology, Vol. 8, No. 1, 104 p.

U. S. Dept. of Interior, 1952-1962: Surface water supply of the United States, 1949-1960, Part I, North Atlantic Slope Basins, Water-Supply Paper, Geological Survey, Nos. 1141, 1171, 1202, 1232, 1272, 1332, 1382, 1432, 1502, 1552, 1622, 1702, U. S. Govt. Printg. Off., Washington.

U. S. Dept. of Interior, 1962-1969: Surface Water Records of Pennsylvania, 1961-1968, Water Resources Division, Geological Survey (in 1966, became entitled Water Resources Data for Pennsylvania).

U. S. Geological Survey, 1954: Water loss investigations: Lake Hefner studies, Geol. Survey Prof. Paper 269, U. S. Dept. of Interior, Washington.

U. S. Geological Survey, 1958: Water loss investigations: Lake Mead studies, Geol. Survey Prof. Paper 298, U. S. Dept. of Interior, Washington.

PART II[1]

THE EFFECT OF URBANIZATION ON ANNUAL WATER YIELD

by

Bruce J. Hartmann

I. INTRODUCTION

As our population grows, our cities continue to expand. Although many groups of people desire to escape the unpleasant urban environment, few are successful. As great numbers of people abandon the large cities to settle in suburban areas, industry follows, capitalizing on lower land costs while maintaining adequate manpower supplies. Thus, suburban areas are transformed into high density population centers, sterilizing larger and larger areas of the natural environment. In 1950, 56 percent of the American population occupied only 7 percent of the land area (Jens and McPherson, 1964). This trend will continue since an ever-increasing percentage of our population is settling in urban and suburban areas (Mumford, 1956).

In essence, urban centers have exceeded all natural limits. Man has forced changes upon his environment. He has covered large portions of the earth's surface with concrete and asphalt. He has replaced trees and vegetation with buildings. He has introduced large numbers of foreign particles into the air and water. He has allowed so many people to occupy such a small area that their physical, mental, and emotional health is deteriorating.

One of the more subtle effects of urbanization is that of modifying the processes involved in the hydrologic cycle. This change is, perhaps, most evident in the runoff process. The quantity, quality and time distribution of runoff are all materially affected by urbanization. Because of increased water usage now and in the future, perhaps the most important effect is related to the quantity of runoff from a given area, the water yield. The annual water yield from an area is determined by many factors. These factors are usually divided into the two major groups of: (a) climatic factors; and (b) physiographic factors. The climatic factors are: amount of precipitation, form of precipitation, temperature, wind velocity, humidity, and solar radiation. The physiographic factors are: elevation of watershed, soil type, and land use (Chow, 1964).

Although urbanization modifies most of the above factors (Landsberg, 1956), land use is altered the most. Urban areas have grown and transformed forests and fields into residential and industrial areas at an alarming rate. Between 1942 and 1956, about 230,000 acres of forest and agricultural land in New England and 1,150,000 acres in the Middle Atlantic States were converted to nonagricultural uses (Lull and Sopper, 1969). About

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[1] The material included in Part II and Appendix I is from a thesis prepared by the author and submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Master of Civil Engineering, June 1971. Mr. Hartmann was employed as a Research Fellow on the present Sea Grant project.

238 acres of forest and farm lands are converted for every increase of 1,000 in urban population (Lull and Sopper, 1969) or over one million acres a year in the United States (Lull and Storey, 1957).

The purpose of this paper is to investigate the long-range effect that urbanization has upon annual water yield. Because both the elevation of the watershed and the basin soil type will remain essentially unchanged during the period of analysis, land use will be the only physiographic factor that will change. Thus, it should be possible to investigate the problem indirectly in the following three steps: (1) estimation of the long-term trend in actual annual water yield which will reflect changes in both climate and land use; (2) estimation of the long-term trend in a synthesized annual water yield which will reflect changes in climate only; and (3) comparison of these long-term trends and determination of the difference. This difference will be the change in annual water yield caused by land use changes or, in other words, by urbanization.

Actual annual water yield can be estimated from stream gaging, diversion, and reservoir storage records. However, some analytical technique must be used to synthesize annual water yield values which reflect only climatic variation. The technique used here for this purpose is the climatic water balance model which was developed by Thornthwaite and Mather (1955, 1957). This model is essentially a bookkeeping system of evaluating the water supplied to and lost from the soil or land surface. Through this method, the soil moisture storage, the soil moisture deficit or surplus, and the amount of runoff from any surface can be calculated for any particular climatic and soil moisture holding conditions. Values of annual water yield can be calculated from the appropriate climatic data, based on the land use or degree of urbanization that existed at any given period of time. These calculated water yield values will reflect changes only in climate and, therefore will approximate the annual yield which would have occurred if the basin had not been urbanized.

II. BACKGROUND

The influence of land use on streamflow has occupied an increasing amount of attention from investigators for the past century. During most of this time, the effect upon streamflow of changing forest to pasture or cultivated fields has been studied. Recently, however, the change in streamflow due to converting rural areas into urban and suburban areas has received increased attention.

The Physical and Hydrometric Methods

In the past, most land use and streamflow investigations have followed one of two research approaches. The first of these is called the physical method. Using this approach, changes in runoff yield are inferred from independent measurements of one or more climatic variables or hydrologic processes (Muller, 1966). Problems such as the effect of land use on snow accumulation, snow evaporation and melting, interception and evapotranspiration, all of which are intimately related to streamflow, can be studied by this approach. This method is used to study the relationship between land use changes and particular processes involved in the hydrologic cycle. Although relationships based on the physical method alone are sometimes inaccurate, since total runoff yield is not measured, the results can provide information as to the direction and general magnitude of the changes in the annual streamflow as a result of specific modifications of the basin itself (Muller, 1966).

The second approach, the hydrometric method, is quite different from the physical approach. Hydrometric investigations involve the study of water yield from entire watersheds (Muller, 1966). In general, the method consists of comparing measured runoff yields from selected watersheds which have similar climates and physical characteristics but different land uses. Hence, any significant differences in measured yields are caused by land use differences.

Usually, analysis of land use effects upon streamflow by the hydrometric method is based on either the "control basin" or the "paired basin" technique. If the "control" or "index" watershed technique is used, one or more watersheds are given a particular land use treatment, while another is left unchanged. The unchanged watershed is the index or control and it is not changed throughout the period of analysis. During the time before the experimental basins are treated, the runoff yield from the various basins are calibrated with respect to the control basin. After an accurate correlation has been attained, the experimental basins are altered. Upon completion of the treatments, the corrected differences between measured runoff yield from the treated and control basins represents the change in runoff yield caused by land use modification only. This technique is based on the following two requirements: (a) the calibration period has been of a sufficient length to ensure accurate prediction of runoff from experimental basins by means of control watershed runoff values; (b) the control basin reflects variations in runoff yield caused only by climatic variations.

The "paired watershed" technique is very similar to the "control watershed" analysis. When using this technique, the runoff totals from two adjacent basins with similar climates and physical characteristics, except land use, are compared. Because all of the factors affecting annual runoff yield (except land use) are very nearly identical, all differences between watershed runoff yields are assumed to be caused by inequality in the land usage. For this technique to be acurate, the watersheds under consideration must be identical or nearly so. This is a difficult condition to satisfy and is the major reason why so few investigators have used this technique.

Probably the greatest advantage in using the hydrometric method instead of the physical approach is that the former integrates the effects of land use on the various hydrologic processes over the entire area of each of the watersheds studied (Muller, 1966). On the other hand, the effect of land use change on each of the hydrologic processes cannot be evaluated separately. Hydrometric analysis is a more direct approach but it requires a longer length of time to reveal significant changes in runoff; after such results are obtained, they can be applied to only the area studied, or, at least, only to a watershed with the same climate and physical characteristics (Muller, 1966). The analysis presented in this paper will be basically of the hydrometric type.

Recent Results Using the Water Balance Approach

In 1961, an investigation of the effect of reforestation in New York State was presented by Schneider and Ayer (1961). The Shackham Brook basin occupying about 3.12 square miles and located on the Allegheny Plateau in central New York State was studied from 1939 to 1957 using the control basin procedure. Albright Creek, draining 7.08 square miles and located about 10 miles northeast of Shackham Brook, was used as the index basin. Both areas were between 1,200 to 2,200 feet elevation and composed of silty to sandy loam soils. This region was previously farmland, but coniferous trees, mostly pine and spruce, were planted and reforestion began about 1930. Although the Shackham Brook area was 58 percent reforested by 1957, the Albright Creek basin remained unchanged at a land use level of 20 percent deciduous trees and 80 percent pasture and cropland. This afforestation caused an average annual decrease in the Shackham Brook streamflow of 0.36 inches or a 22 percent reduction in annual flow.

Muller (1966) used these same two basins along with the Sage Brook and Cold Spring Brook watersheds located in central New York State in a study of the effect of land use changes. All four watersheds received about 45 inches of precipitation annually, were composed of silt loam soils, and drained from 0.7 to 7.08 square miles of land. In his investigation, the climatic water balance model was used to evaluate runoff variations caused by climatic influences, while measured yield reflected variations due to both climatic and land use modifications. The Shackham Brook, Sage Brook and Cold Spring Brook annual streamflows were reduced 0.42, 0.22 and 0.13 inches respectively during the period 1935 to 1957. The Albright Creek yield decreased 0.4 inches per year from 1941 to 1957.

Lull and Sopper (1969) also employed the climatic water balance model to analyze runoff yield from three increasingly urbanized watersheds over periods of 24 to 35 years. The first watershed, Weasel Brook, located in New Jersey, drained 4.45 square miles of area of which 98 percent was urban. The second area, Second River basin in New Jersey was 11.6 square miles in area and also 98 percent urbanized. Rock Creek, Maryland was the third watershed investigated. It covered 62.2 square miles in area but was only urbanized to the 25 percent level. The following results were obtained from this investigation: Weasel Brook, annual runoff yield increased 0.93 inches per year between 1938 and 1962; Second River, streamflow increased by 0.18 inches annually between 1938 and 1964; Rock Creek, streamflow increased by an average of 0.07 inches every year from 1930 to 1965. All of these increases were actually the differences between actual measured annual streamflow and that predicted from the water balance model when land use was artificially held constant.

Past watershed studies indicate that land use has a definite influence on annual runoff yield, but that the magnitude and the direction of this effect depends on the physiographic and climatic characteristics of the watershed and the type and extent of the land use modification. Deforestation, the removal of the natural forest cover, increases the annual streamflow. This increase has ranged from 17 inches at Coweeta Experimental Forest in North Carolina to less than one inch at Fernow Experimental Forest in West Virginia. Similarly, cultivated watersheds yield up to 5 inches more water annually than pasture areas. Urbanization has also increased annual streamflow. From two completely urbanized basins in New Jersey, the annual increase was .93 and .18 inches, while a basin in Maryland, which was urbanized to only the 25 percent level, yielded an increase of 0.07 inches yearly.

III. DESCRIPTION OF THE EXPERIMENTAL WATERSHED

Physiography

The Chester Creek watershed is located in southeastern Pennsylvania. The creek itself originates about four miles north of West Chester, Pennsylvania in the Piedmont Province of the Appalachian Highlands, and flows in a southeasterly direction to the Atlantic Coastal Plain at Chester, Pennsylvania where it empties into the Delaware River. Portions of Chester and Delaware Counties, Pennsylvania are drained by this creek.

Only that portion of the watershed located upstream from the United States Geological Survey stream gaging station situated at Dutton Mill Bridge, about 3 miles northwest of Chester, will be considered (U.S. Dept. of Interior, 1960). This 61.1 square mile area ranges in elevation from 40 feet at the gaging station to 500 feet at the creek's source. Characterized by shallow valleys and narrow flood plains, this basin has relief ranging from nearly level to steep (Kunkle and others, 1963). Most of the region is composed of soils from the Glenelg-Manor-Chester and Neshaminy-Glenelg soil associations, while a small part of the basin belongs to the Neshaminy-Chrome-Conowingo group. Thus, nearly all of the area is shallow to deep silt loam, underlain by mostly gabbro, gneiss, granite, and schist (Kunkle and others, 1963). Maps showing the location and drainage channels of the basin are included in figures 1 and 2.

Climate

This basin has a humid, temperature climate with relatively mild winters because of the influence of the nearby Atlantic Ocean. The prevailing winds are from the northwest in the winter and from the southwest during the summer months.

The only U.S. Weather Bureau station situated in the basin is located at West Chester. It has been operated continuously since 1936 at an elevation of 440 feet above sea level (U.S. Dept. of Commerce, 1958). From the West Chester records, the average annual temperature during the 1936 to 1968 period is 53.4 F, ranging from a maximum of 55.7 F in 1949 to a minimum of 50.8 F in 1958. The area has an average frost-free period of 190 days from April 16 to October 23. The maximum, minimum and mean monthly average temperatures are given in figure 3.

During the study period, the mean annual precipitation totaled 43.69 inches. In 1952, 57.41 inches fell while only 30.86 inches fell during the entire year of 1941. As can be seen in figure 4, precipitation is relatively evenly distributed throughout the year, but is usually greater during the growing season. About 27 inches of snow falls on the watershed annually of which 74 percent comes in the winter months of December, January and February (Kunkle and others, 1963).

Annual Water Yield

Since both West Chester and Media, Pennsylvania have diverted water from Chester Creek and three reservoirs have been operated on the creek over

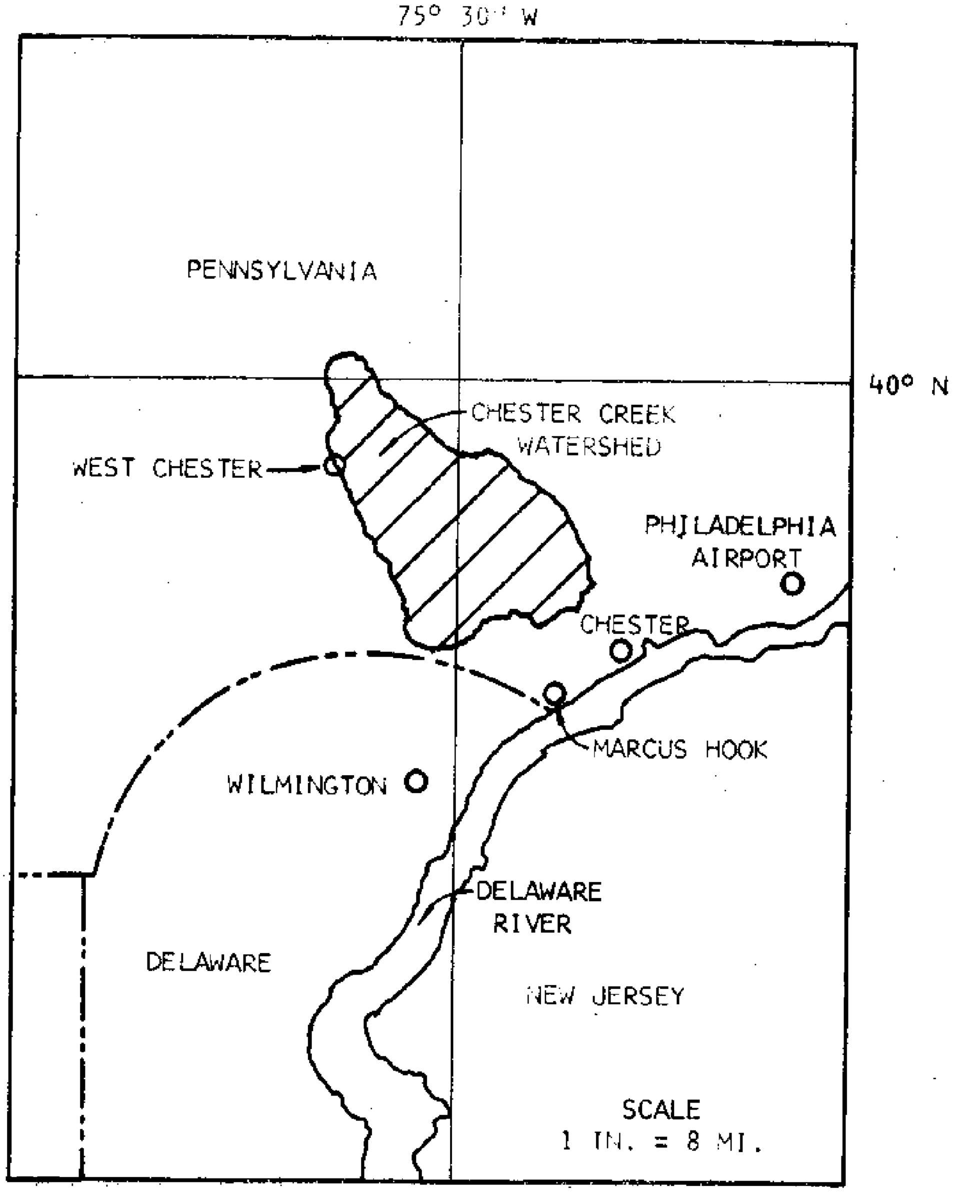

Figure 1. Map Showing the Location of the Chester Creek Watershed and Nearby U. S. Weather Bureau Weather Stations.

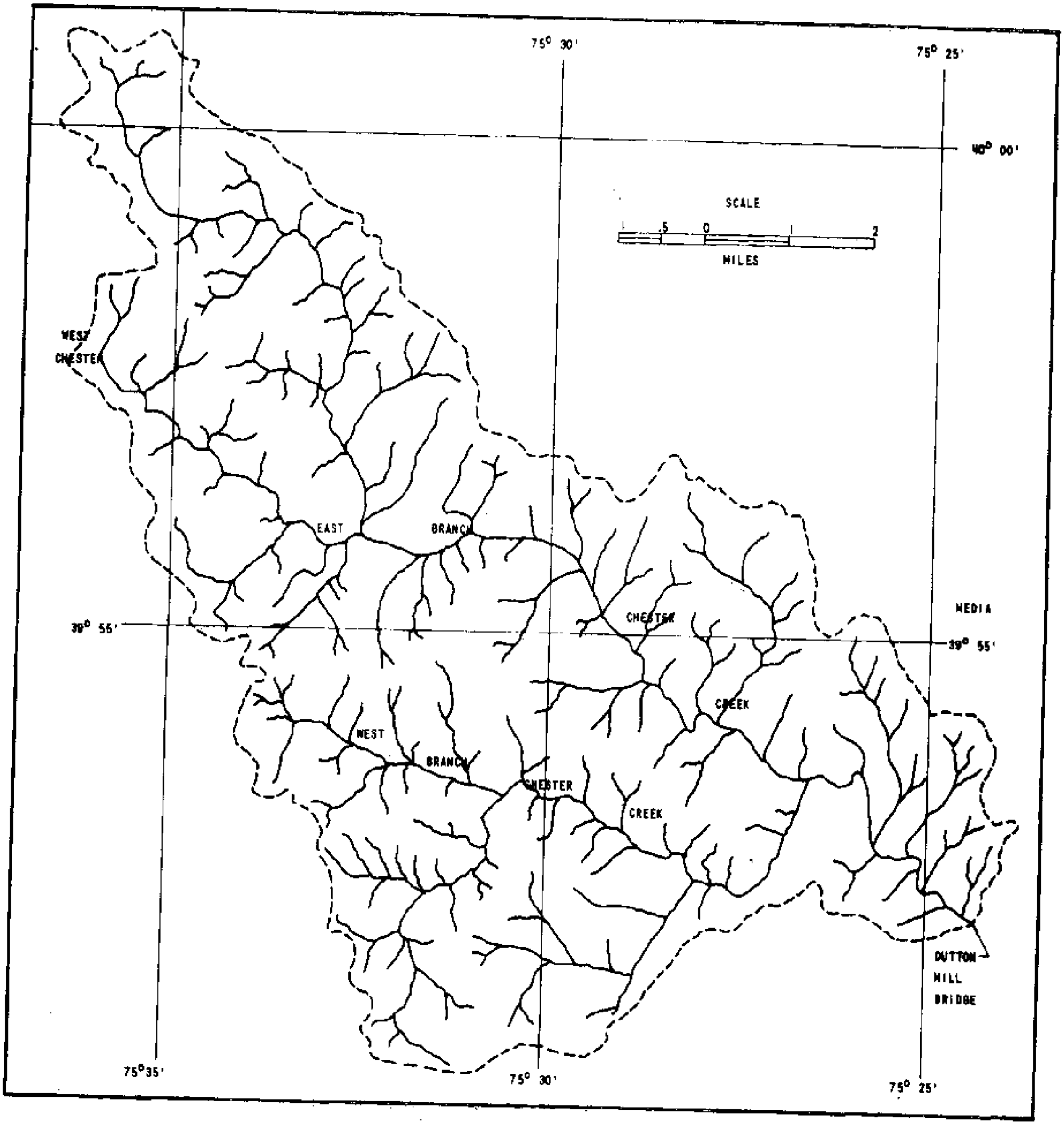

Figure 2. Map of the Chester Creek Watershed

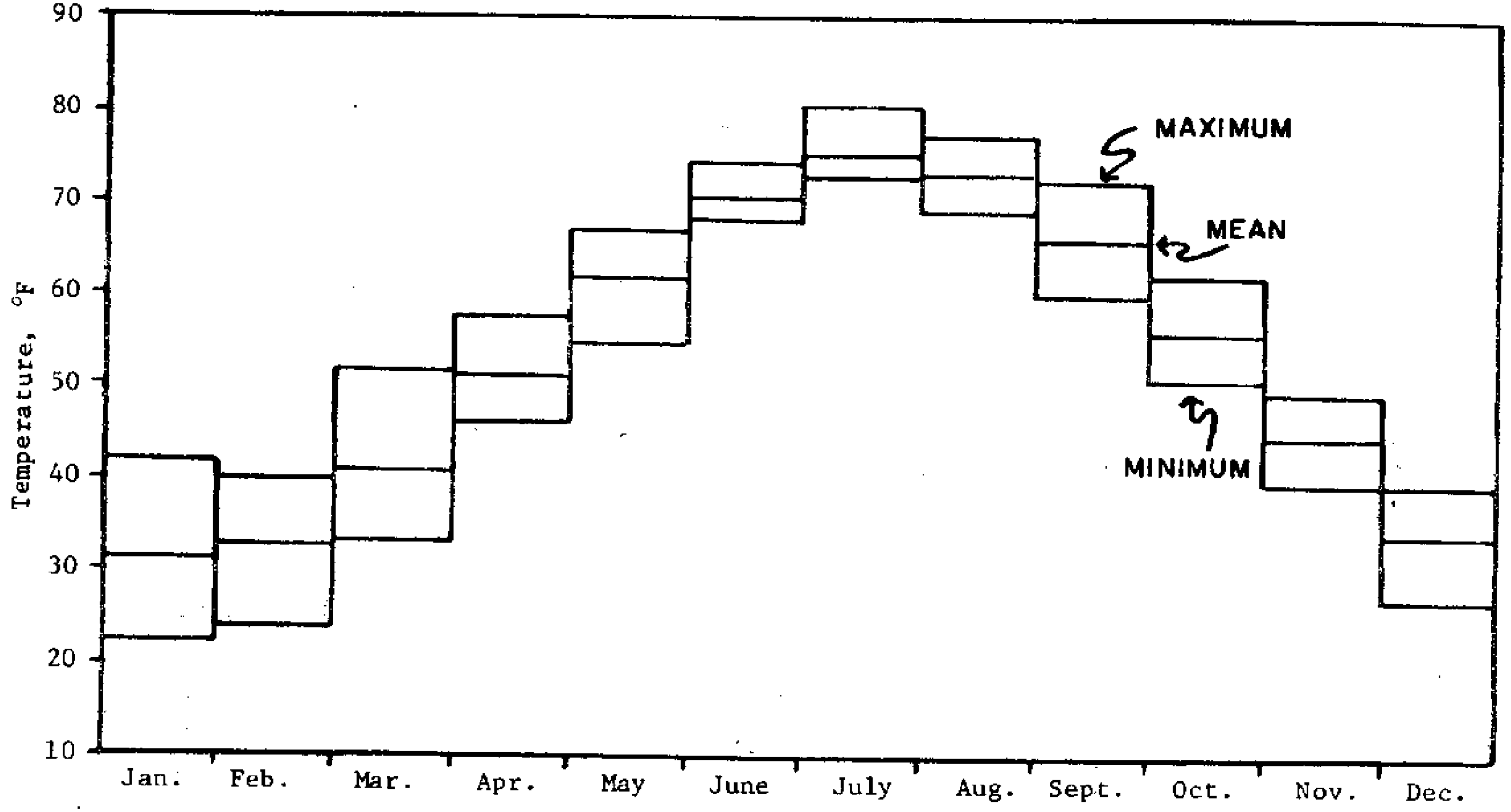

Figure 3. Maximum, Mean, and Minimum Average Monthly Temperature at West Chester, Pennsylvania, 1936 - 1968.

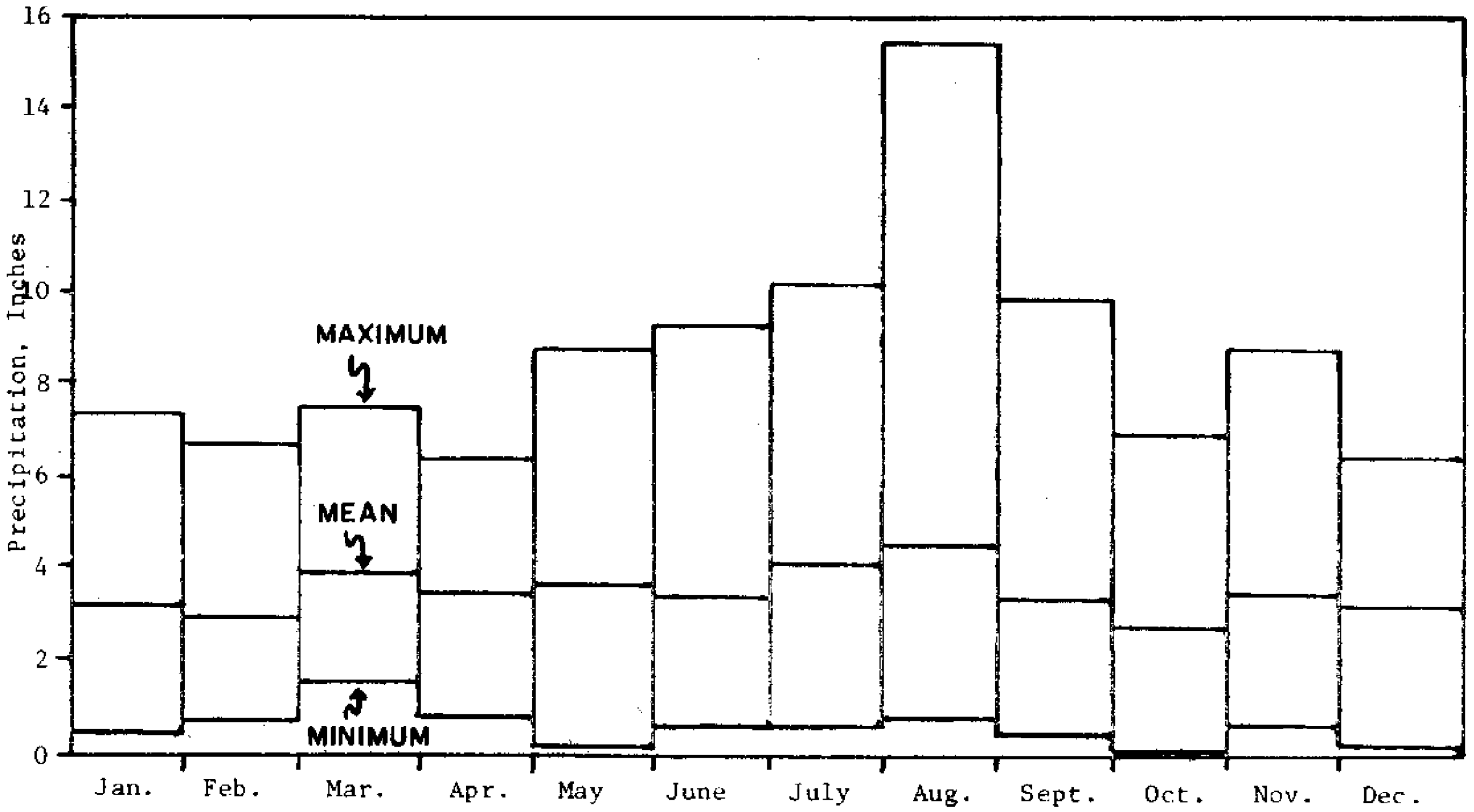

Figure 4. Maximum, Mean, and Minimum Total Monthly Precipitation at West Chester, Pennsylvania, 1936 - 1968.

the 33-year period of the present study (1936-1968), the annual water yield from the basin will be the sum of the annual diversions, the yearly changes in storage in the reservoirs, and the amount of water leaving the basin anually as streamflow.

According to measurements by the United States Geological Survey, the average annual streamflow at Dutton Mill Bridge for the period from 1936 to 1968 is 17.59 inches. Values of runoff at the gaging station range from a maximum of 27.28 inches in 1952 to a minimum of 10.32 inches during the drought year of 1965. The measured values of streamflow for each of the years from 1936 to 1968 are given in table 1. During this period, most of the streamflow came during the first six months of the year, as can be seen from the monthly march of runoff in figure 5.

In addition to the water leaving the basin as streamflow, a significant amount of water was diverted from the basin by West Chester and Media for their domestic water supplies[1]. West Chester had diverted water for its use prior to 1936. As shown in figure 6, Township Line Reservoir, Milltown Reservoir, and Westtown Reservoir, are used to store water. Water from these reservoirs is pumped to a central water treatment plant and pumping station below Milltown Reservoir, and it is then pumped to West Chester for domestic use. Part of this water, after use, is returned to the Chester Creek watershed via a sewage treatment plant located southeast of the borough on Goose Creek, a tributary of the Chester Creek. A portion of the supply is diverted into the Brandywine Creek watershed via a sewage treatment plant located northwest of the borough, on Taylor Run, a tributary of the eastern branch of the Brandywine Creek. The remainder of the water supplied to West Chester is either lost by evaporation or returned to the Chester or Brandywine Creeks by means of leaky water mains or sewer lines or through septic tanks. Probably only about 1 percent of the untreated water is lost by evaporation, while the other 99 percent is either diverted from or returned to the Chester Creek basin. Since most of the heavy water users and water users who do not discharge their effluent into the West Chester sewer system are located east or southeast of the borough, most of the untreated water appears to be returned to the Chester Creek. Although actual data are not available on the percentage of the untreated water which is returned, it has been assumed that about one half of this water is returned. The remaining portion of the water which is neither discharged at the Goose Creek or Taylor Run plants is ultimately diverted to the Brandywine Creek basin. Based on the above assumptions, about 25 percent of the untreated water is diverted annually. The total amount of water diverted in terms of both millions of gallons and inches of runoff is shown in table 2.

Since values of the returns to Goose Creek or diversions to Taylor Run are not available before 1955, the average percentage of the supply diverted from 1955 to 1968, 41 percent, was also used for the years prior to 1955.

During the dry years of 1963, 1964 and 1966, the borough of Media found it necessary to supplement their usually adequate supply from Ridley Creek by diverting water from Chester Creek. The diversions were made during

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[1] Personal communications with E. B. Bayliss, Director of Public Works, Borough of West Chester, and with T. G. Mooney, Chief Operator, Media Water Works.

Table 1

Annual Streamflow, Diversions, and Water Yield from the Chester Creek Watershed, 1936-1968

(All values in inches depth over the watershed)

	Streamflow	Diversion West Chester	Diversion Media	Total Water Yield
1936	21.13	0.20		21.33
37	14.40	0.20		14.60
38	20.46	0.20		20.66
39	21.18	0.20		21.38
1940	18.23	0.20		18.43
41	12.00	0.20		12.20
42	13.57	0.20		13.77
43	16.55	0.21		16.76
44	14.87	0.21		15.08
1945	22.98	0.22		23.20
46	17.97	0.24		18.21
47	14.76	0.26		15.02
48	21.96	0.25		22.21
49	17.74	0.25		17.99
1950	19.31	0.24		19.55
51	17.97	0.28		18.25
52	27.28	0.31		27.59
53	25.19	0.30		25.49
54	11.26	0.29		11.55
1955	13.75	0.34		14.10
56	17.93	0.27		18.20
57	13.96	0.28		14.24
58	27.07	0.30		27.37
59	15.52	0.32		15.84
1960	24.72	0.33		25.05
61	22.23	0.32		22.55
62	14.81	0.31		15.12
63	11.69	0.31	0.03	12.03
64	14.26	0.33	0.03	14.62
1965	10.32	0.34		10.66
66	11.63	0.34	0.03	12.00
67	19.18	0.37		19.55
68	16.79	0.37		17.16

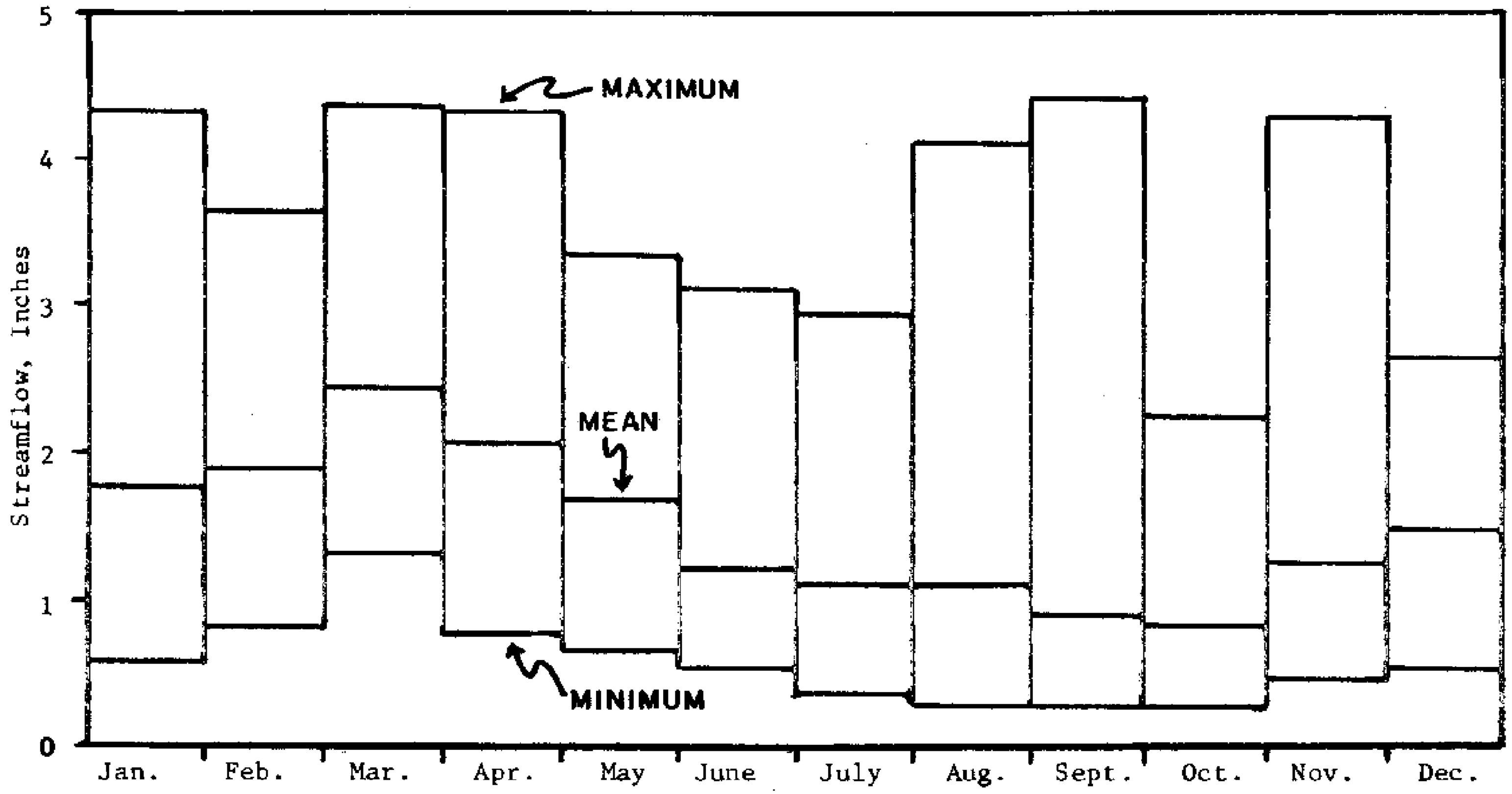

Figure 5. Maximum, Mean, and Minimum Total Monthly Streamflow from the Chester Creek Watershed, 1936-1968.

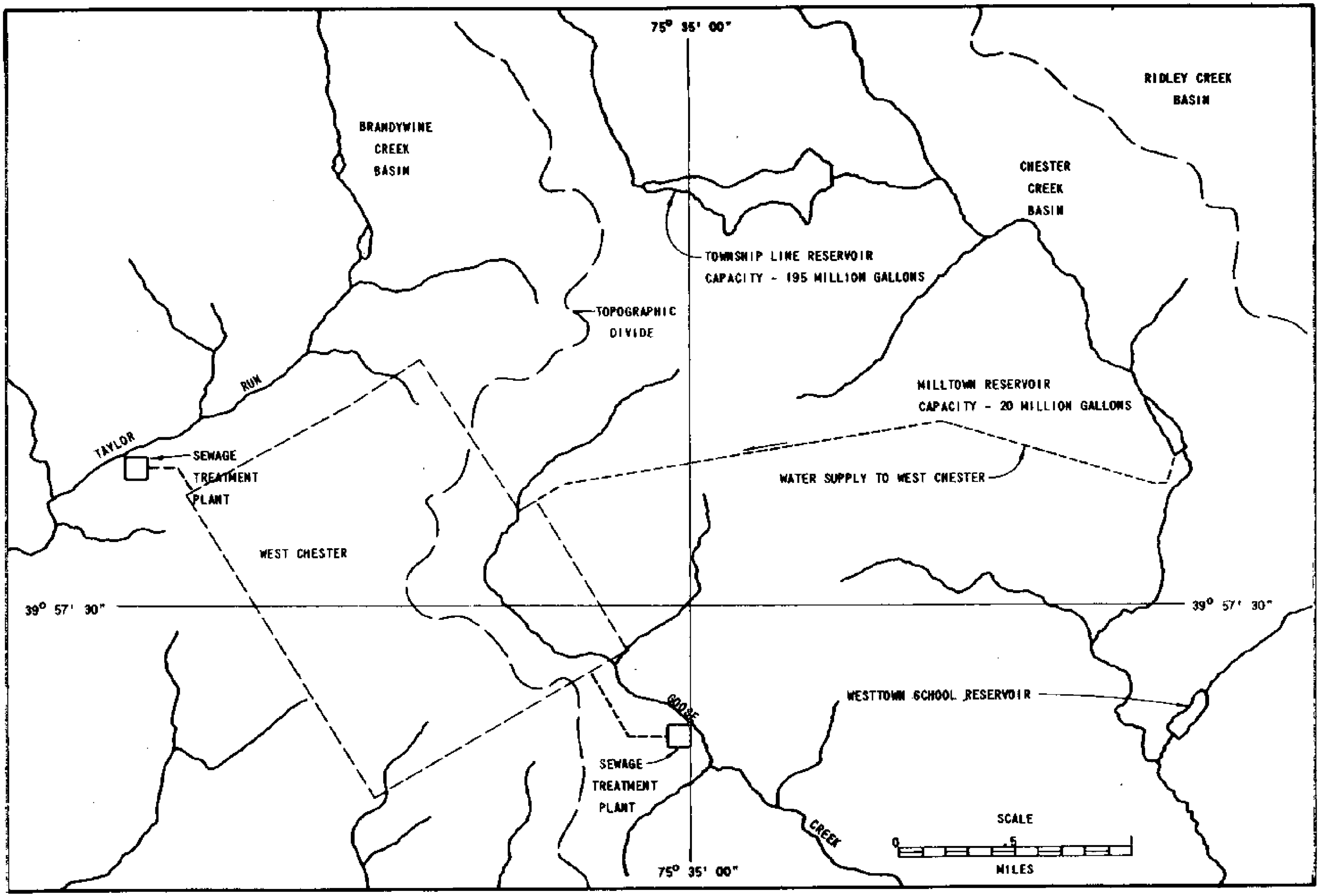

Figure 6. Map of the West Chester, Pennsylvania Area Showing the Water Supply and Sewage Treatment Facilities of the Borough.

Table 2

Annual Diversion of Water from the Chester Creek Watershed at West Chester, Pennsylvania, 1936-1968

Year	Supply to West Chester (10^6 gals)	Return to Goose Creek (10^6 gals)	Diversion to Taylor Run (10^6 gals)	Miscellaneous Losses and Returns (10^6 gals)	Other Diversions to Brandywine Basin (10^6 gals)	Total Diversion (10^6 gals)	Percent of Supply Diverted	Total Diversion, inches
1936	521.680					213.889	41	0.20
1937	522.000					314.020	41	0.20
1938	512.120					209.969	41	0.20
1939	514.910					211.113	41	0.20
1940	511.290					209.629	41	0.20
1941	526.780					215.980	41	0.20
1942	513.950					210.720	41	0.20
1943	547.730					224.569	41	0.21
1944	555.380					227.706	41	0.21
1945	557.580					228.608	41	0.22
1946	614.300					251.863	41	0.24
1947	662.040					271.436	41	0.26
1948	655.780					268.870	41	0.25
1949	655.820					268.886	41	0.25
1950	634.600					260.186	41	0.24
1951	727.650					298.337	41	0.28
1952	804.620					329.894	41	0.31
1953	771.320					316.241	41	0.30

Table 2

(Continued)

Year	Supply to West Chester (10^6 gals)	Return to Goose Creek (10^6 gals)	Diversion to Taylor Run (10^6 gals)	Miscellaneous Losses and Returns (10^6 gals)	Other Diversions to Brandywine Basin (10^6 gals)	Total Diversion (10^6 gals)	Percent of Supply Diverted	Total Diversion, inches
1954	742.070					304.249	41	0.29
1955	716.380	281.383	335.590	99.407	24.852	360.442	50	0.34
1956	736.730	323.867	239.612	173.251	43.313	282.925	38	0.27
1957	783.820	352.843	255.499	175.478	43.870	299.369	38	0.28
1958	831.170	391.946	279.286	159.938	39.985	319.271	38	0.30
1959	836.782	377.636	298.351	160.795	40.199	338.550	40	0.32
1960	873.820	389.150	305.105	179.565	44.891	349.996	40	0.33
1961	815.000	388.712	317.771	108.517	27.129	344.900	42	0.32
1962	824.070	341.411	284.814	197.845	49.461	334.275	40	0.31
1963	835.130	373.475	289.855	171.800	42.950	332.805	40	0.31
1964	877.180	324.611	285.174	267.395	66.849	352.023	40	0.33
1965	912.860	305.246	278.538	329.076	82.269	360.807	40	0.34
1966	908.130	331.465	284.087	292.578	73.019	357.106	39	0.34
1967	934.010	352.075	325.627	256.308	64.077	389.704	42	0.37
1968	982.310	393.872	322.280	266.158	66.504	388.784	40	0.37

the dry months of August, September, and October and totaled about 29 to 30 million gallons yearly. Since none of the water was returned to the basin after use, these diversions account for about 0.03 inches of runoff[1].

Although information on the yearly change in storage of the three storage reservoirs is not available, the change from one year to the next is probably very small. Even if the maximum storage change occurs, 240 million gallons, the error in annual water yield will only be about .23 inches. Thus, any contribution to annual water yield by storage change is probably negligible.

Based on the above assumptions and data, the average annual water yield from the Chester Creek watershed from 1936 to 1968 is found to be 17.87 inches. As shown in figure 7, the maximum annual yield is 27.59 inches in 1952, and the minimum is 10.66 in 1965. The values plotted in figure 7 are also included in tabular form in the right-hand column of table 2.

IV. EVALUATION OF LAND USE CHANGES

Land Use Sampling

In the past, many land use studies involved individual survey of all points inside the study area. This procedure is time-consuming and, because of human error, may result in inaccurate estimates of land use. A possibly better approach is by means of statistical sampling of only a portion of the whole area. By using this method, the time and cost of the study is reduced, the scope of the study can be increased, and the accuracy of the land use estimates is often improved (Berry, 1962). The estimates resulting from sampling are still subject to errors of two types: sampling error and sample bias. Sampling errors are unavoidable when sampling is used. However, sample bias is introduced when the surveyor deliberately selects typical cases for analysis, uses convenient sampling units, or fails to examine the whole of a chosen sample (Berry, 1962).

Bias can be eliminated from estimates, if "probability" sampling is used. When using this type of sampling, samples are drawn on the basis of rigorous mathematical theory, and after a sampling method is adopted, individual observations are drawn from the whole by established rules (Haggett, 1965). One advantage of probability sampling is that the probability of the occurrence of an error of a given size can be derived from information obtained in the sample (Berry, 1962). Probability sampling can be used quickly and efficiently to obtain precise estimates of land usage.

To sample a two-dimensional space such as a watershed, either random, stratified random, or systematic sampling techniques can be applied in either direction (Quenouille, 1949). All three techniques are based upon the characteristic of randomness, but to varying degrees.

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[1] Personal communications, T. G. Mooney, Chief Operator, Media Water Works, Media, Pennsylvania.

Simple random sampling, as its name implies, is completely random. With such a technique, every point in the population has an equal and independent chance of being selected. If one direction of an areal sample is sampled randomly, the x or y coordinates (whichever corresponds to the axis randomly sampled) of all points within the sample will be determined randomly. If both directions of an areal sample are randomly sampled, each point will be chosen by randomly selecting its two coordinates. All other things being equal, when using a random areal sample, the more points sampled, the smaller the sampling error.

Stratified random sampling is similar to simple random sampling except that the stratified case provides a more even distribution of points over the sample space at the cost of being only partly random. In the one dimensional case, the axis is divided into segments and one point is sampled at random from each segment. If a two-dimensional space is sampled in this way, the area is divided into subareas, and a separate random areal sample is taken in each subarea. Usually, such subdivisions are areas which have similar characteristics (Haggett, 1965).

Systematic samples are both stratified and random to a certain degree. In a linear space, the axis is divided into segments and one point is sampled in each segment. The coordinate of the first point is randomly selected while the remaining points are located on the basis of a regular interval (Berry, 1962). When using an areal systematic sample, the sample space is subdivided into small subareas by a grid system, and one point is sampled per cell. All the points in any one row or column of cells will have the same horizontal or vertical coordinate, respectively. This design combines the theoretical advantages of randomization and stratification with the practical, systematic selection of sample points inherent to systematic sampling (Haggett, 1965).

Each of the above three sampling techniques can be modified as to the way in which sample points are arranged in any one direction. Points can be aligned with one another or can be independently determined (Quenouille, 1949). If an aligned sample is taken in the horizontal direction but not in the vertical direction, points will be aligned with one another in the vertical direction.

Optimal Land Use Sampling Method

A great deal of theoretical and empirical analysis has been devoted to research concerning which of the many possible types of areal samples is the most preferred. A test of the relative efficiency of the various sampling methods was conducted by Burton (1962) on the Coon Creek watershed located in Vernon County, Wisconsin. He found that systematic unaligned areal sampling yields a more precise estimate of land use values and has a smaller variation associated with it than either simple random or stratified random areal samples of the same size, a conclusion verified by others (Berry, 1962; Cochran, 1946).

Figure 7. Measured Annual Water Yield from the Chester Creek Watershed, 1936-1968.

Experimental Watershed Land Use Changes

After considering other alternatives, aerial photographs were selected as the medium for sampling, since the photographs can be handled easily and provide an accurate basis for land use surveys. Photographs from 1937 and 1965 were chosen for sampling in order to determine the land use changes over this period. Point sampling units were used in a systematic unaligned areal sampling design to estimate the percentage of the basin covered with forests, pastures, croplands, and impervious surfaces. The possibility of sample points falling on streams and lakes was anticipated, and a separate land use classification, water, was adopted.

Prior to sampling, the Chester Creek watershed was partitioned into 100 cells, 0.88 miles long and 0.89 miles wide. Both axes of the cells were divided into 100 parts, thus separating each cell into a grid of 10,000 points. Accurate positioning of the cells was attained by using printed latitudinal and longitudinal lines on the aerial photographs as references.

Following this division of the watershed into cells, 8 systematic unaligned samples consisting of 100 points each were taken. The same points, 8 within each cell, were located and sampled on each of the two sets of photographs. The manner in which each of the samples was obtained is illustrated in figure 8. First, the horizontal coordinate, X_a, and the vertical coordinate, Y_a, of point A were randomly chosen from a table of random numbers. X_a was then used as the horizontal coordinate for all points in the cells along the bottom row (points B, C, D, E, F, G, and H). Similarly, Y_a was used as the vertical coordinate for all points in the first column of cells (points I, J, K, L, and M). Next, the horizontal coordinate of point I was selected from the random number table and used as the horizontal coordinate for all points in that row of cells. In a similar fashion, the vertical coordinate of point B was randomly selected and used for all points in the second column of cells. This process was continued until one point was located in each cell. The finished pattern was a well distributed areal sample such as that in figure 8.

Each of the eight 100-point samples were obtained in this fashion, and the number of points falling in each of the various land use classes in 1937 and 1965 were recorded (table 3). A graph of the corresponding percentage estimates, as a function of sample size, for the 1937 survey is given in figure 9 and for the 1965 investigation in figure 10. After some initial fluctuation, the sample estimates tend to stabilize. After 800 observations, the land use estimates were: 19.0, 44.6, 31.3, and 4.9 percent forest, pasture, cultivated land and impervious surface, respectively, in 1937; and 27.8, 38.3, 21.8, and 12.1 percent, respectively, in 1965.

Assuming these estimates are accurate, the amount of forest cover over the Chester Creek watershed has increased by 8.8 percent from 1937 to 1965, pastured areas have decreased 6.4 percent, cultivated land has decreased 9.5 percent, and impervious areas have increased by 7.3 percent. Vaughn (1970), using a different technique, has determined the change in land use in each of the three counties in Delaware. Since the northernmost county, New Castle County, is adjacent to both Chester and Delaware Counties, Pennsylvania, both areas have developed somewhat similarly. Thus, a comparison of the land use

Table 3

Actual Count of Land Usage in the Chester Creek Basin as a Result of Eight 100-point Samples, 1937 and 1965

1937					
Sample No.	Impervious	Cultivated	Pasture	Forest	Water
1	6	32	44	17	1
2	2	33	44	21	0
3	7	31	42	20	0
4	8	27	46	19	0
5	4	31	40	25	0
6	1	30	43	26	0
7	5	29	52	14	0
8	6	37	46	10	1
Total	39	250	357	152	2

1965					
Sample No.	Impervious	Cultivated	Pasture	Forest	Water
1	17	22	39	22	0
2	13	20	33	34	0
3	10	19	41	30	0
4	10	32	36	22	0
5	15	18	34	33	0
6	11	18	43	28	0
7	11	19	42	28	0
8	10	26	38	25	1
Total	97	174	306	222	1

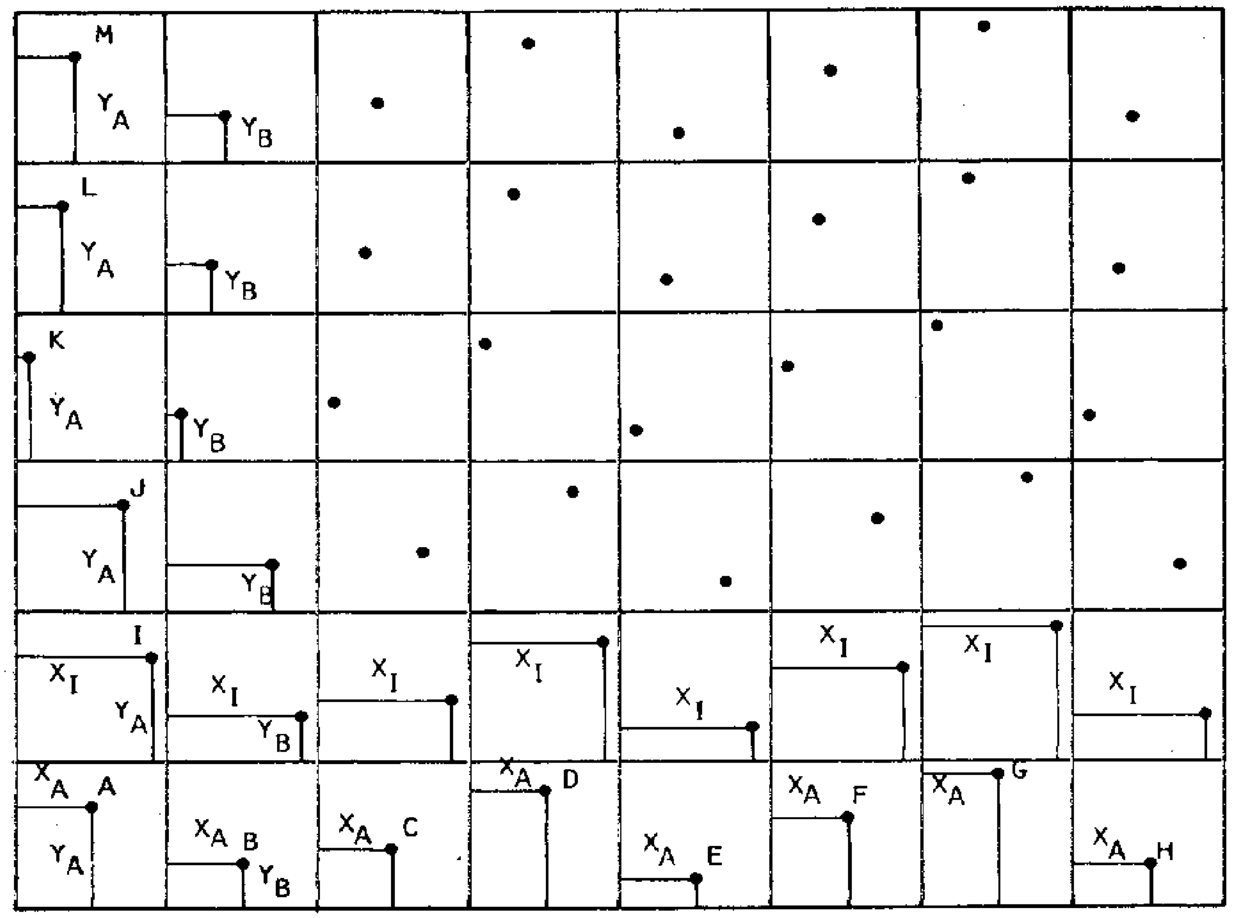

Figure 8. Method of Constructing a Systematic Unaligned Areal Point Sample.
(From figure 5, Berry, 1962)

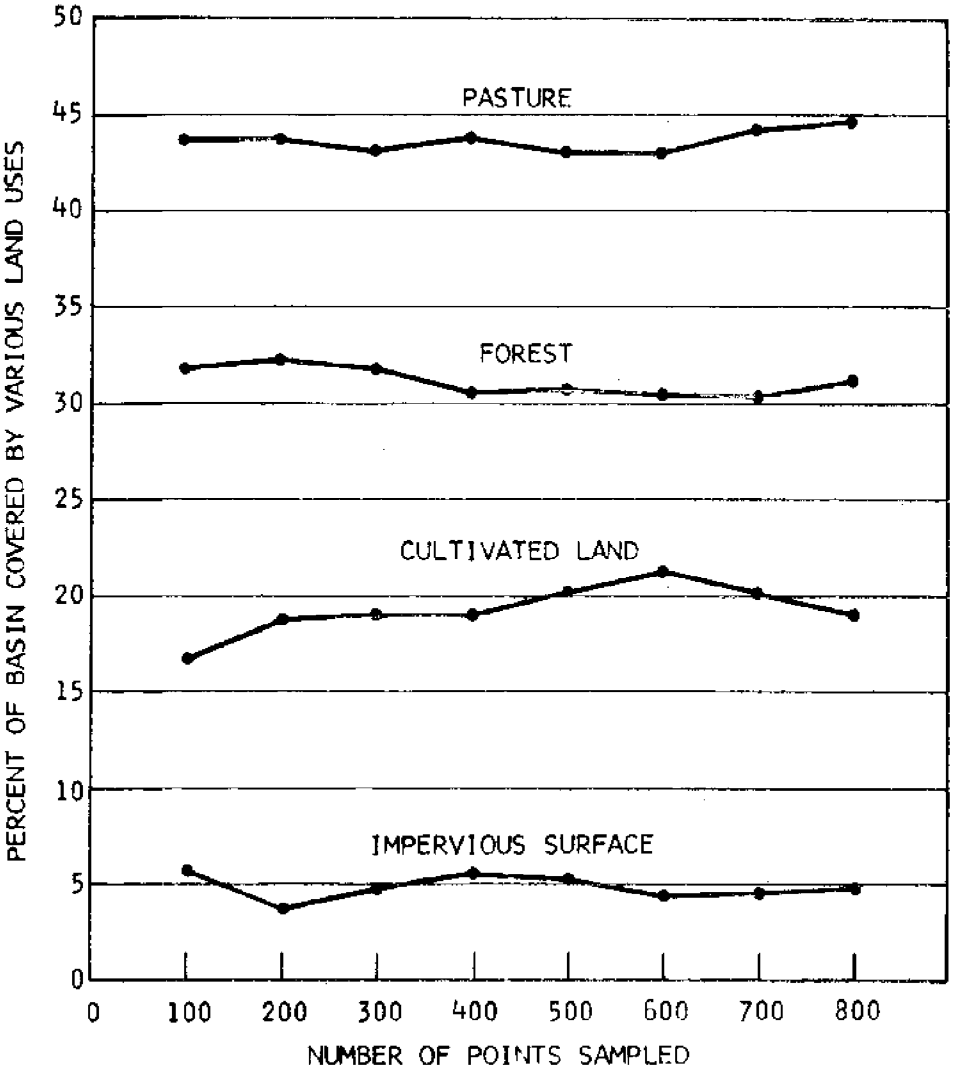

Figure 9. Graph of the Estimated Percentage of the Chester Creek Watershed in Various Land Uses during 1937 as a Function of Sample Size.

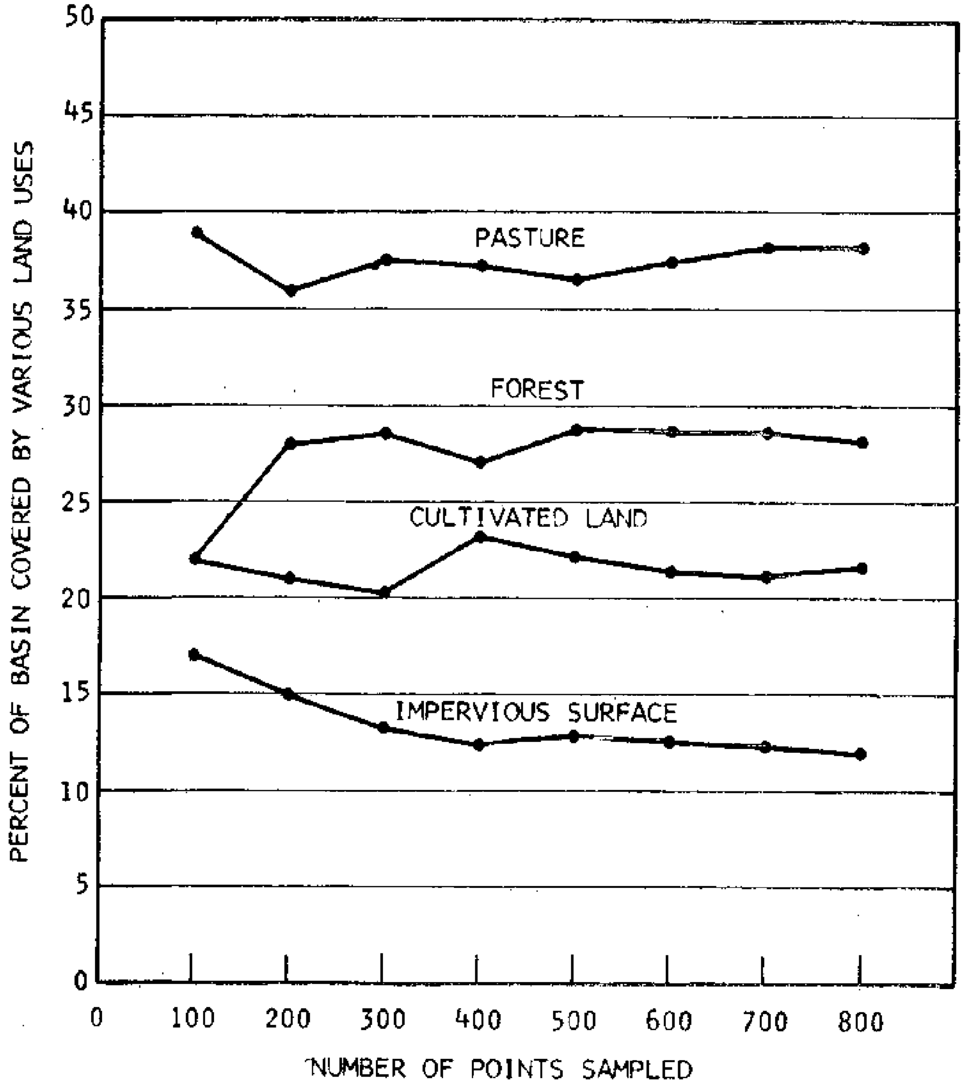

Figure 10. Graph of the Estimated Percentage of the Chester Creek Watershed in Various Land Uses during 1965 as a Function of Sample Size.

changes, over similar periods, in both areas can provide a check on the accuracy of the estimated land use changes over the Chester Creek watershed. Although New Castle County was more urbanized at the beginning of the survey, both areas had almost identical land use changes. Forest land increased in New Castle County by 7.2 percent from 1930 to 1964, while pasture land decreased 7.2 percent, cultivated land decreased 9.4 percent, and impervious surfaces increased 9.4 percent. Not only were the trends in land use change similar in both areas, the extent of these changes was almost identical.

V. WATER YIELD CHANGES CAUSED BY CLIMATIC VARIATION

In the past, most of the investigations of land use changes and streamflow have been conducted by the control or index watershed technique. This type of analysis, while accurate compared to most other techniques, has two serious weaknesses. First, the control and experimental watersheds may differ so greatly in size, location, elevation, land use, and climate that any accurate prediction of runoff from the experimental basin based on the control watershed runoff is impossible. Second, the control basin may have been altered during the study period, so that the runoff from the basin reflects changes in both land use and climate rather than only climate.

Both of these weaknesses can be eliminated if the climatic water balance is used to generate "control" runoff. Using data representative of climatic conditions over the entire basin, the land use in the experimental basin can be artificially held constant for the entire study period; annual streamflow values will be generated which reflect changes in climate only.

The Climatic Water Balance

The climatic water balance is simply a monthly or daily comparison of the climatic supply of water by precipitation with the climatic demand for water (potential evapotranspiration). During periods when the climatic supply is greater than the climatic demand, the soil moisture storage will increase, and if the water holding capacity of the soil is surpassed, a surplus or runoff of water will occur. In those periods when the demand for water exceeds the precipitation, the soil moisture storage will be depleted and a soil moisture deficit will result. Thus, through comparison of monthly or daily values of precipitation and potential evapotranspiration, knowing the water holding capacity of the soil, it is possible to secure quantitative information about: (a) the amount of water stored in the soil, the storage; (b) the amount by which climatic demand exceeds climatic supply, the water deficit; (c) the amount by which climatic supply less climatic demand exceeds the water holding capacity of the soil, the water surplus; and (d) the amount of water available for streamflow, the runoff. The actual steps necessary for evaluating the climatic water balance are included in Appendix I.

Prediction of Annual Water Yield Using the Climatic Water Balance

The climatic water balance has been used in many different areas in recent years, but, perhaps, it has been used most effectively in the field of hydrology for predicting and synthesizing streamflow. After determining the proper water holding capacity and detention factor, the runoff computed by means of the water balance approximates very closely the actual runoff. However, this agreement seems to be better on a yearly basis than on a monthly basis.

In 1969, as part of a study of the water resources of the Delmarva Peninsula, Mather (1969) compared computed and measured annual streamflow from 19 streams and rivers over the peninsula for the 1949 to 1964 period. A list of correlation coefficients between measured runoff and that computed by the water balance using climatic data from nearby weather stations is given in table 4. The average correlation coefficient is +0.866, with a high of +0.944 in the case of the relation between computed runoff at Newark, Delaware and measured runoff in the Christina River at Cooches Bridge, Delaware, and a low of +0.685 between computed runoff at Vienna, Maryland and measured runoff of the Chicamacomico River.

Table 4

Correlation Between Measured Annual Runoff and Computed
Annual Station Runoff Over the Delmarva Peninsula
(Adapted from: Table 13, Mather, 1969)

Stream	Area Sq. Mi.	Weather Station	Correlation Coefficient
Marshy Hope Creek	44.8	Bridgeville	0.844
Nanticoke	75.8	Bridgeville	0.902
Choptank River	113.0	Dover	0.948
Beaverdam Branch	5.9	Easton	0.841
Stockley Branch	5.2	Georgetown	0.866
Unicorn Branch	22.3	Millington	0.881
Christina River	20.5	Newark	0.944
White Clay Creek	87.8	Newark	0.934
Big Elk Creek	52.6	Newark	0.941
Faulkner Branch	7.1	Preston	0.862
Manokin Branch	5.8	Princess Anne	0.837
Choptank River	113.0	Ridgely	0.804
Beaverdam Creek	19.5	Salisbury	0.798
Pocomoke River	60.5	Salisbury	0.878
Nassawango Creek	44.9	Snow Hill	0.907
Chicamacomico River	15.0	Vienna	0.685
Red Clay Creek	47.0	Wilm. (Porter)	0.878
Brandywine Creek	314.0	Wilm. (Porter)	0.889
Shellpot Creek	7.5	Wilm. (Porter)	0.916

A similar high correlation was found by Thornthwaite and Mather (1955) for three large watersheds of the Muskingum drainage basin near Coshocton, Ohio. The Killbuck Creek, 466 square miles, was studied from 1930 to 1942, while the Licking River, 622 square miles, and the Wills Creek, 730 square miles, were studied between 1934 and 1942, and 1930 and 1936, respectively. As can be seen in table 5, the average computed annual runoff over the respective study periods was consistently higher than the observed values, however, by only 0.70, 0.14 and 0.54 inches, or 6.8, 1,1, and 4.4 percent, respectively.

Table 5

Comparison of Observed Annual Runoff and Computed Annual Station Runoff
For Three Large Watersheds Near Coshocton, Ohio
(Adapted from: Table 4.1, Thornthwaite and Mather, 1955)

Watershed	Area Sq. Mi.	Weather Bureau Station	Computed Runoff, In.	Observed Runoff, In.
Killbuck Creek	466	Wooster	10.94	10.24
Licking River	672	Newark	12.94	12.80
Wills Creek	730	Cambridge	12.95	12.41

Predicted Annual Water Yield From the Experimental Watershed

Since the climatic water balance is an accurate method of predicting yearly runoff, this method was used to determine the volume of water which would have drained from the Chester Creek watershed yearly, if the land usage throughout the basin had not been altered. Annual runoff values, based on the 1937 land usage, were generated for each year from 1936 to 1968. This runoff is called the "control" runoff since it is essentially the same as control watershed runoff, if the control watershed technique had been used. Such annual values reflect changes in climate only, since the land use was held constant at the level in 1937. Yearly streamflow from 1936 to 1968 was also computed, based on the 1965 values of land use. These values are used as a check on the accuracy of the resulting difference in measured and control runoff. To calculate the water balance for each type of land use, representative climatic data and accurate values of water holding capacities and detention factors had to be obtained.

The following United States Weather Bureau meteorological stations are located in and around the Chester Creek basin: Chester, Marcus Hook, Philadelphia and West Chester, Pennsylvania and Wilmington, Delaware (figure 1). Both the Chester and Marcus Hook stations yielded questionable weather data because of poor exposure of the recording instruments. The Chester station was on the roof of a three-story building, while the station in Marcus Hook was located near large industrial buildings (U.S. Dept. of Commerce, 1958). Although the Philadelphia and Wilmington weather data seemed accurate, when water balances at these locations were computed, the resulting annual surpluses did not correlate well with measured annual streamflow. For this reason, only the Wester Chester meteorological data (the only station situated inside the basin) was used to compute the monthly climatic water balance and yearly runoff from the entire Chester Creek watershed.

Next, the proper values of water holding capacity for each of the major land uses, impervious surface, cultivated land, pasture, and forest, were determined. The land use classification of water was not considered since less than one-quarter of a percent of the watershed was used in this manner. A water holding capacity of one inch was used for impervious areas. Normally, only a fraction of an inch is used, but since most of the areas were small and probably had cracks in them, precipitation could flow through the cracks or flow laterally from surrounding areas to supply the underlying soil and increase the moisture content of these areas. Cultivated areas were given a six-inch water holding capacity as suggested by Thornthwaite and Mather (1957). Pastured areas were assumed to hold nine inches of water at field capacity while a value of twelve inches was used for forested areas. All of these values seem realistic, with, perhaps, the exception of the 12-inch value for forests. As will be seen later, if this value had been increased to 16 inches as suggested by Thornthwaite and Mather, the decrease in annual runoff from the entire basin would have been very small.

The percentage of monthly surplus which actually reaches the drainage channels, the runoff factor, has been assumed to be 100, 50, 30, and 20 percent for impervious, cultivated, pastured, and forested plots, respectively. Precipitation which falls on impermeable areas will runoff immediately. Because of the frequent disturbance and compaction of croplands by tillage, the hydraulic conductivity of these areas is impaired and only about half of the water available for runoff in any one month actually does runoff. Pastures are generally less frequently disturbed and any compaction of the soil is usually done by grazing animals. Thus, these areas permit more infiltration and slower runoff. Runoff from forest covered areas is by far the slowest. The soils in these areas are rarely disturbed and natural vegetation and burrowing animals increase the vertical permeability by making holes in the soil profile. Surface runoff from such areas is infrequent.

The average monthly climatic water balances for each of the types of land use, based on the 1936-1968 average monthly climatic data from the West Chester weather station and the above water holding capacities and runoff factors, are tabulated in tables 6 to 9. Annual values of runoff from each of these land use types were also obtained for each year from 1936 to 1968 using the actual monthly climatic data. By averaging the computed yearly runoff values for each type of land use, the average annual runoff from impervious, cultivated, pastured, and forested areas in the basin are found to be 20.67, 17.74, 17.02, and 16.57 inches, respectively. Annual runoff is 0.72 inches greater from cultivated areas than from pastured areas, and pastures produce 0.45 inches more water than forests. If forested areas are assumed to have a

Table 6

Average Monthly Climatic Water Balance for Impervious Areas at West Chester, Pennsylvania, 1936-1968*

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Temp., °F	31.4	32.8	41.3	51.8	62.1	71.0	75.5	73.5	66.5	56.2	44.9	34.2	53.43
Pot. Evapo.	0.00	0.00	0.62	2.00	3.35	4.88	6.10	5.31	3.43	2.02	0.75	0.00	28.46
Precipitation	3.29	2.96	3.99	3.49	3.83	3.57	4.24	4.63	3.60	2.94	3.69	3.46	43.69
Prec. - Pot. Ev.	3.29	2.96	3.37	1.49	0.48	-1.31	-1.86	-0.68	0.17	0.92	2.94	3.46	
Storage	1.00	1.00	1.00	1.00	1.00	0.23	0.03	0.00	0.17	1.00	1.00	1.00	
Change in Storage						-0.77	-0.20	-0.03	+0.17	+0.83			
Actual Evapo.			0.62	2.00	3.35	4.34	4.44	4.66	3.43	2.02	0.75		25.61
Deficit						0.54	1.66	0.65					2.85
Surplus	3.29	2.96	3.37	1.49	0.48					0.09	2.94	3.46	18.08

Table 7

Average Monthly Climatic Water Balance for Cultivated Land at West Chester, Pennsylvania, 1936-1968*

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Temp., °F	31.4	32.8	41.3	51.8	62.1	71.0	75.5	73.5	66.5	56.2	44.9	34.2	53.43
Pot. Evapo.	0.00	0.00	0.62	2.00	3.35	4.88	6.10	5.31	3.43	2.02	0.75	0.00	28.46
Precipitation	3.29	2.96	3.99	3.49	3.83	3.57	4.24	4.63	3.60	2.94	3.69	3.46	43.69
Prec. - Pot. Ev.	3.29	2.96	3.37	1.49	0.48	-1.31	-1.86	-0.68	0.17	0.92	2.94	3.46	
Storage	6.00	6.00	6.00	6.00	6.00	4.80	3.50	3.13	3.30	4.22	6.00	6.00	
Change in Storage						-1.20	-1.30	-0.37	+0.17	+0.92	+1.78		
Actual Evapo.			0.62	2.00	3.35	4.77	5.54	5.00	3.43	2.02	0.75		27.48
Deficit						0.11	0.56	0.31					0.98
Surplus	3.29	2.96	3.37	1.49	0.48						1.16	3.46	16.21

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*All values except temperature given in inches

Table 8

Average Monthly Climatic Water Balance for Pastures at West Chester, Pennsylvania, 1936-1968*

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Temp., ^{o}F	31.4	32.8	41.3	51.8	62.1	71.0	75.5	73.5	66.5	56.2	44.9	34.2	53.43
Pot. Evapo.	0.00	0.00	0.62	2.00	3.35	4.88	6.10	5.31	3.43	2.02	0.75	0.00	28.46
Precipitation	3.29	2.96	3.99	3.49	3.83	3.57	4.24	4.63	3.60	2.94	3.69	3.46	43.69
Prec. - Pot. Ev.	3.29	2.96	3.37	1.49	0.48	-1.31	-1.86	-0.68	0.17	0.92	2.94	3.46	
Storage	9.00	9.00	9.00	9.00	9.00	7.79	6.34	5.89	6.06	6.98	9.00	9.00	
Change in Storage						-1.21	-1.45	-0.45	+0.17	+0.92	+2.02		
Actual Evapo.			0.62	2.00	3.35	4.78	5.69	5.08	3.43	2.02	0.75		27.72
Deficit						0.10	0.41	0.23					0.74
Surplus	3.29	2.96	3.37	1.49	0.48						0.92	3.46	15.97

Table 9

Average Monthly Climatic Water Balance for Forests at West Chester, Pennsylvania, 1936-1968*

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Temp., ^{o}F	31.4	32.8	41.3	51.8	62.1	71.0	75.5	73.5	66.5	56.2	44.9	34.2	53.43
Pot. Evapo.	0.00	0.00	0.62	2.00	3.35	4.88	6.10	5.31	3.43	2.02	0.75	0.00	28.46
Precipitation	3.29	2.96	3.99	3.49	3.83	3.57	4.24	4.63	3.60	2.94	3.69	3.46	43.69
Prec. - Pot. Ev.	3.29	2.96	3.37	1.49	0.48	-1.31	-1.86	-0.68	0.17	0.92	2.94	3.46	
Storage	12.00	12.00	12.00	12.00	12.00	10.76	9.21	8.70	8.87	9.79	12.00	12.00	
Change in Storage						-1.24	-1.55	-0.51	+0.17	+0.92	+2.21		
Actual Evapo.			0.62	2.00	3.35	4.81	5.79	5.14	3.43	2.02	0.75		27.91
Deficit						0.07	0.31	0.17					0.55
Surplus	3.29	2.96	3.37	1.49	0.48						0.73	3.46	15.78

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*All values except temperature given in inches water holding capacity of 16 inches instead of 12 inches, the expected yearly runoff would be about 16.27 inches, 0.30 inches per year less than obtained using a 12-inch storage capacity. Since only about 23 percent of the whole watershed is forested between 1937 and 1965, the decrease in computed runoff is about 0.07 inches annually, a negligible amount.

Based on the 1937 and 1965 estimates of land use in table 3, and the appropriate computed yearly runoff value, an annual runoff figure was computed for the entire Chester Creek watershed. Annual runoff values based on the 1937 land usage from 1936 to 1968, the control runoff, are graphed in figure 11, along with yearly values from 1956 to 1968, based on the 1965 land use.

VI. WATER YIELD CHANGES CAUSED BY LAND USE MODIFICATION

Between 1937 and 1965, some of the land in the Chester Creek watershed which had been previously used for crops and pastures was converted to forests and impervious areas such as buildings, roads, and parking lots. Although the increase in impervious areas is typical of regions being urbanized, the increase in the amount of forest seems to indicate a trend toward ruralization. Since this basin is situated about 20 miles west of Philadelphia, Pennsylvania and about 10 miles north of Wilmington, Delaware, it is clear that the overall trend is toward urbanization and that this increase in the area covered by forest can be explained as an intermediate step in the urbanization process. Regions surrounding large urban centers such as Philadelphia are used initially for farming and agricultural production in order to supply these centers with food and other raw materials. As these urban centers and their encircling suburbs grow, these once agricultural regions are transformed into residential developments. The early migrants, to insure personal privacy which was not available in the city, construct their homes on large tracts of farmland and allow much of their land to return to forest. Hence, farmland is converted to both impervious and forest areas, during this intermediate step of urbanization. It seems that the Chester Creek watershed experienced this phase of urbanization between 1936 and 1968.

Analysis of Data

The effect of this change in land use on annual runoff yield will be determined by comparing the observed values of annual yield with the predicted values computed by using the climatic water balance. However, before comparing these annual values, it will be useful to compare five-year running means of observed and computed annual water yield as a preliminary check of accuracy. Much of the large year to year variation in annual yield will be eliminated by this procedure. These five-year mean values are plotted for the middle year of the five-year period under consideration. For example, the mean annual yield for the 1936-1937-1938-1939-1940 period is plotted for 1938. Five-year running means for the measured annual yield and the computed yield for both the 1937 land use and 1965 land use are plotted in figure 12 for the 1938 to 1966 period.

The measured and computed means correlate very well during the late 1930's and 1940's, except in 1938 where the predicted value is 2 inches higher. Prior to 1946, the computed values are higher than the corresponding measured values every year except 1940. After 1946, however, the computed means fall further and further below the measured means until 1963. Between 1963 and 1965, the difference decreases markedly. In 1966, the trend reverses itself again and the computed means rise above the observed means once again. Thus, as was anticipated, the two means correlated very well in the earlier years of the study but differed significantly throughout most of the later years.

As a check on the validity of this deviation in the later part of the study, a five-year running mean, based on the 1965 land usage, was calculated from 1958 to 1966 and compared with the 1937-based means and the measured values. As had been anticipated, the 1965-based values were better estimates of observed yield than the corresponding 1937-based values during this period. These values were better estimates 6 out of 9 years or 67 percent of the years. Thus, it seems that the relationship between the measured and computed values of yield is very similar to that anticipated and that the climatic water balance has produced representative values of yield.

Straight lines were fitted to the annual values of measured and computed yield by the method of least-squares (figure 13). For the measured yield, the equation of the line is $y_m = 22.50 - .0878\,x$, while it is $y_c = 26.94 - .1856\,x$ for the computed yield. Since the measured and computed annual yields should be identical in 1937, these two lines should intersect in 1937. However, the line fitted to the computed values is about 0.8 inches higher than the measured value line. This value is about 4 percent higher than the corresponding measured line.

This deviation from the real case may be caused by the measured yields being low, the computed values being high, or a combination of the two. Regardless of the cause for this, this bias should remain constant throughout the study period, and therefore, it can be artificially corrected.

If it is assumed that these lines do intersect in 1937, as they should, the effect of urbanizing the Chester Creek watershed on the annual yield from that area will be represented by the difference in the slopes of the straight lines. Since measured annual yield decreases .0878 inches a year on the average and computed annual yield decreases .1856 inches a year, urbanization has produced an average yearly increase in yield of .0978 inches or a total increase of 3.13 inches in annual water yield between 1937 and 1968. This value of runoff increase agrees quite well with the figure of 0.07 inches per year found in the previously mentioned study of urbanization of the 62.2 square mile Rock Creek watershed near Washington, D.C. The similarity in the runoff changes lends confidence to the results achieved in the present study.

Assumptions and Errors of Analysis

The analysis of the effect of urbanization upon annual water yield was based on the following two fundamental assumptions:

(1) The annual water yield from the basin was measured and computed with such accuracy that these values represent the actual annual yield.

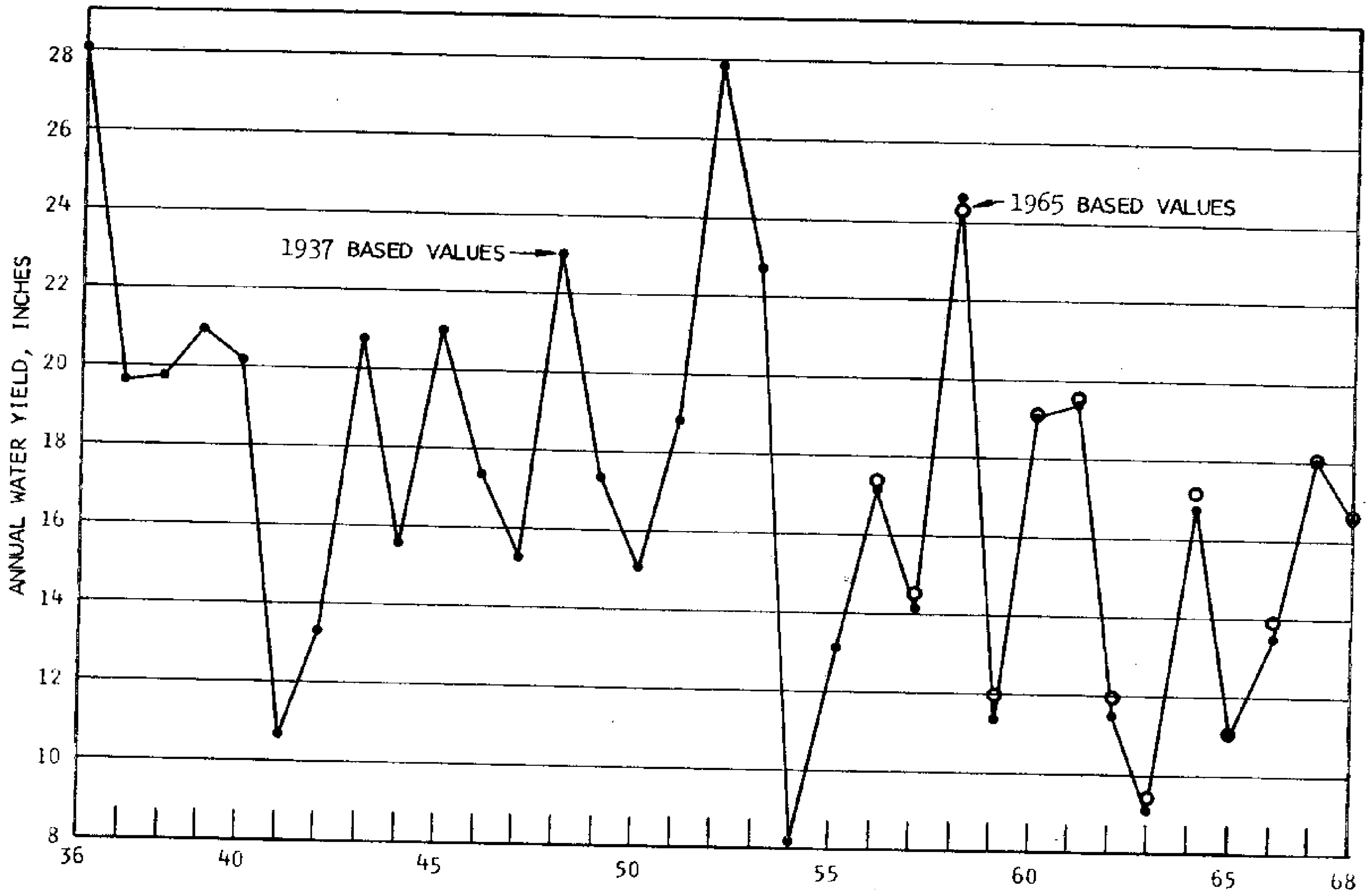

Figure 11. Computed Annual Water Yield from the Chester Creek Watershed Based on the 1937 and the 1965 Land Use, 1936-1968.

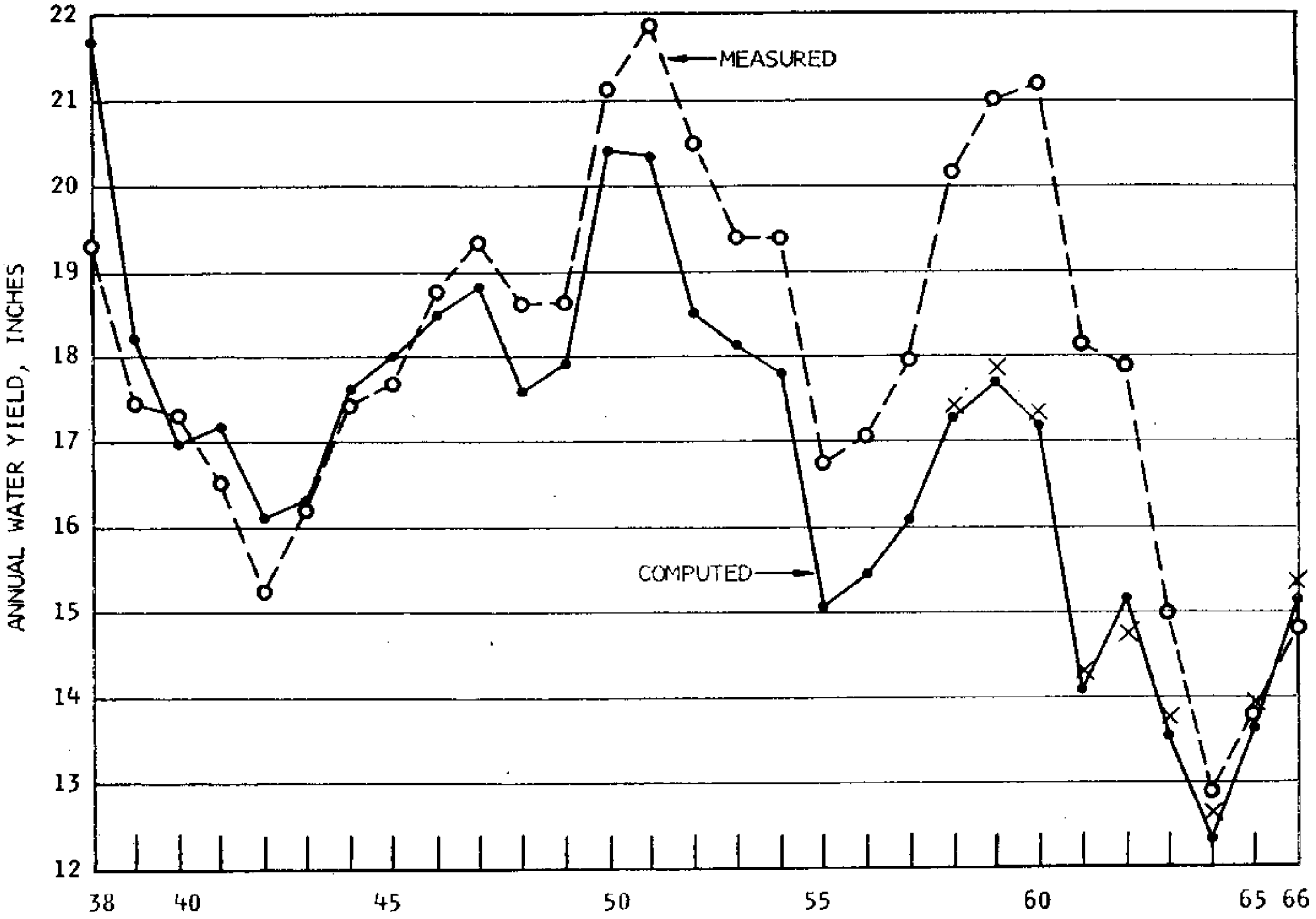

Figure 12. Five-Year Running Means of Measured Annual Water Yield and Computed Annual Water Yield Based on the 1937 and the 1965 Land Use of the Basin, 1938-1966.

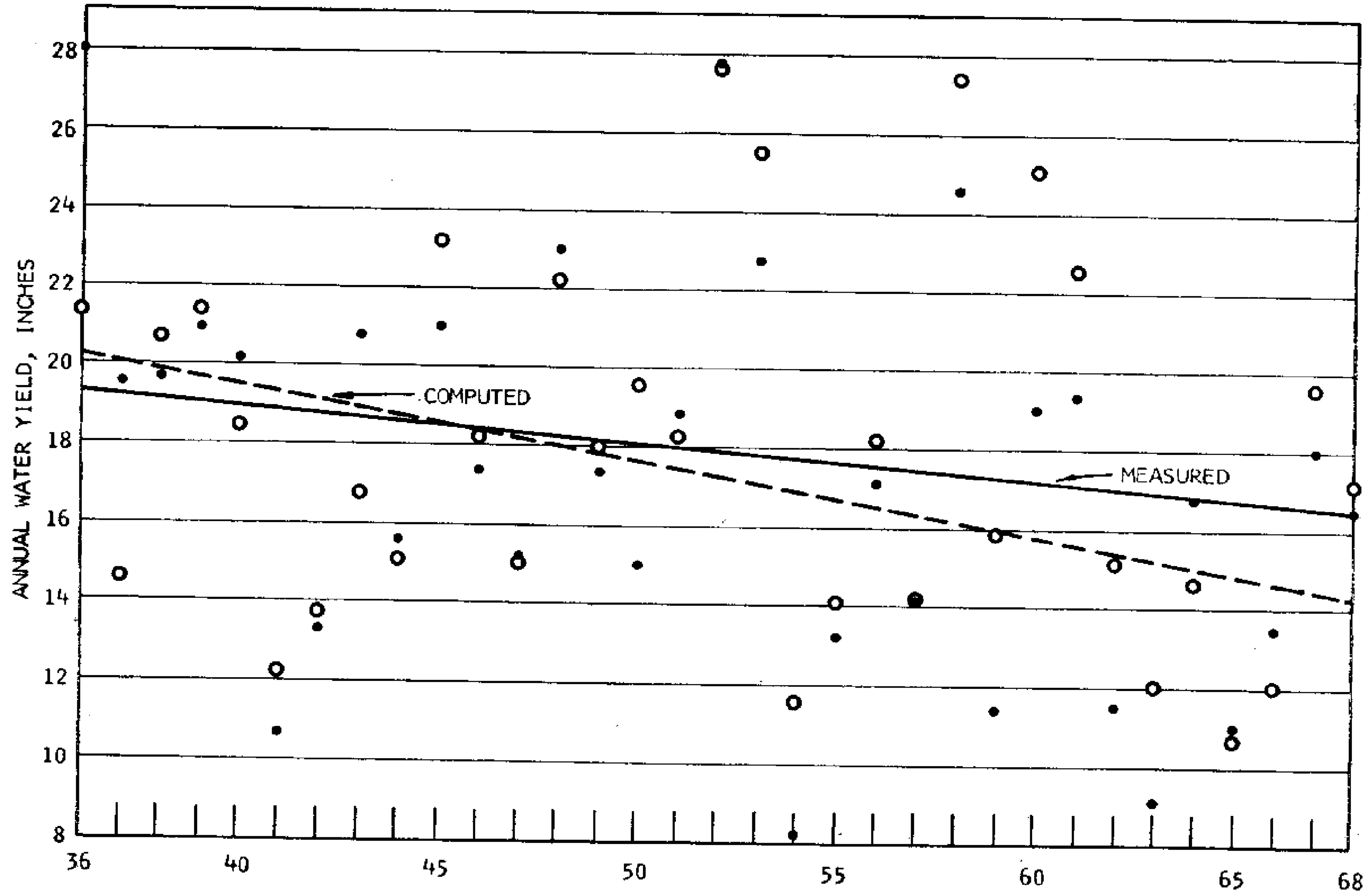

Figure 13. Long-Term Trends in Measured Annual Water Yield and Computed Annual Water Yield Based on the 1937 Land Use, 1936-1968.

(2) The annual water yield, which was computed by means of the climatic water balance procedure, approximated very accurately the water yield which would have taken place yearly if land use in the basin had remained unchanged.

Actual annual water yield is the volume of water which does runoff or is available for runoff from a watershed, yearly. This value can be thought of as the total volume of water which a) leaves the basin as natural streamflow; b) is artificially diverted from the watershed; or c) increases the storage in the basin over a one-year period. Thus, the accuracy with which measured yield approximates actual yield depends upon the accuracy with which these three components are measured or computed.

As stated previously, streamflow from the Chester Creek watershed was measured by the U.S.G.S. at Dutton Mill Bridge. These measurements have been made with an automatic water stage recorder, since 1931. According to the U.S.G.S., the observed values are within 10 percent of the actual values for every year except 1966, 1967 and 1968 (U.S. Dept. of Interior, 1938-1962; 1962-70). In these three years, the measurements are only within 15 percent of the actual values. These rather large errors resulted from the occurrence of ice in the stream during the winter months which rendered the stage-discharge relationship meaningless.

The annual diversion of water from the basin was measured for some years, but usually it had to be computed after making some simplifying assumptions. In the case of the diversion by West Chester, accurate measurement of the annual diversion of water into the Brandywine Creek basin through the borough's sewage treatment plant on Taylor Run was made only after 1954. In addition to this diversion, a portion of the water supplied to West Chester was diverted by other means to the Brandywine basin. As an estimate of this secondary diversion, it was assumed that 25 percent of the annual supply which was neither treated at the Taylor Run nor the Goose Creek sewage treatment plants was ultimately diverted from the basin to the Brandywine. Based on this reasonable assumption, the total diversion from the Chester Creek at West Chester from 1955 to 1968 averaged 41 percent of the annual domestic supply to the borough. Consequently, since only values of annual water supply are available before 1955, the total annual diversion during these years is also assumed to be 41 percent of that annual supply. This assumption appears valid; even in the years of greatest supply to the borough, the error introduced into the actual water yield value would be only about .19 inches or about one percent of the average water yield of 18 inches.

The only other significant diversions were made by the borough of Media in 1963, 1964, and 1966. These annual diversions are very small, about 0.03 inches, and seem to have been measured accurately. Thus, no error was introduced into the actual annual water yield values by measurement or computation of these diversions.

Since no data on the yearly change in storage in the three reservoirs located in the basin are available, an assumption as to the storage change was made. Storage from year to year is assumed to remain constant throughout the study period. This assumption seems to be reasonable, and since the change from one year to the next is probably small, the error introduced into each actual annual value of water yield should be negligible. Even if all three storage reservoirs went from completely full to empty from one year to the next, the measured water yield for that year would only be 135 million gallons or 0.27 inches higher than the actual water yield. This error corresponds to only a 1.5 percent error in the annual water yield.

From the above, it can be seen that the maximum error in estimating the actual annual yield will be approximately 18 percent. Although this maximum error is quite significant, the actual error will probably be well below this. The error can be either positive or negative throughout the entire study period; it should not significantly influence the accuracy of the estimated long-range trend in the actual annual yield.

The annual water yield from the watershed if urbanization had not occurred is called the control annual water yield. Although this quantity is imaginary, since every watershed is altered to some degree through time, control yield can be estimated by using the climatic water balance after some initial assumptions have been made. First, urbanization was assumed not to influence the climate over the basin. This assumption is justifiable since, although the basin has been changed since 1937, the change was only from a rural to a suburban environment. Since only concentrated urban and industrial areas have been found to influence local climate significantly (Landsberg, 1956), the climate over the Chester Creek was probably little affected. Second, accurate estimates of the land usage over the basin were assumed to be obtained by sampling the 1937 and 1965 aerial photographs of the area. This assumption seems reasonable since a systematic unaligned areal sample was used; this is the most accurate method for determining land use over a large area. Even if the actual area of impervious surfaces was 5 percent higher than the estimate and the actual forested area was 5 percent lower than the estimate, the resultant error in annual computed water yield would only be about 1 percent.

Since the above two assumptions appear valid, the climatic water balance can be used to estimate the control yield precisely, provided representative weather data and accurate water holding capacities are available.

In this analysis, monthly weather data from the West Chester weather station were used exclusively. The West Chester temperature values are probably quite representative of the average monthly temperature over the entire basin. However, since precipitation is highly variable over an area, the West Chester precipitation values are probably much less representative. To illustrate this point, average annual temperature and precipitation values for 1950 to 1960 at West Chester, Philadelphia and Wilmington were compared. The variance in temperature at these three locations was 0.28 F, while the variance in precipitation was 5.29 inches. Consequently, the West Chester precipitation data were probably not completely representative of the entire basin, and some error may have been introduced into the annual control yield values. This error was, however, random in nature, so that the values at West Chester for any given year could be either higher or lower than the actual basin value. The magnitude of this error is probably much less than the deviation between the annual means at West Chester and Philadelphia which is 4.54 inches or about 28 percent of the average annual computed yield.

From the above, it appears that most of the error in computed annual water yield is caused by the unrepresentative precipitation data used. Furthermore, the estimated control yield will be either higher or lower than the actual control yield for any given year; over the study period, these variations will tend to offset each other, and thus, the rate of decrease in actual control water yield should be just about 0.1856 inches a year, as estimated.

VII. CONCLUSIONS

Many interesting conclusions result from the present study. Probability sampling was used to determine the land usage in the basin in 1937 and was found to be an accurate, efficient, and effective method of determining land use over a large area.

The climatic water balance was used to generate the computed or "control" annual water yield. This mathematical model was found to be a precise procedure for estimating imaginary annual water yield, such as "control" water yield.

The change in land use in the Chester Creek watershed was determined between 1937 and 1965. Although this watershed is located outside of two large urban centers, Philadelphia, Pennsylvania and Wilmington, Delaware, the area of the basin covered by forest increased over the period of study. Evidently, the basin experienced an intermediate step in the urbanization process whereby rural farm land was transformed into low-density residential areas, and hence, the extent of forest increased.

In comparing the long term trends in measured and predicted annual water yield, urbanization was found to increase annual water yield approximately 0.1 inches (1/2 percent) per year, or 3.13 inches (17 percent) from 1936 to 1968. In other words, urbanization has increased annual water yield by about 100,000,000 gallons per year. In the future, the rate of urbanization of this watershed will probably increase much more rapidly, and therefore, annual water yield will probably increase as much as 1 or 2 percent per year.

Because of the great differences in the climate and physiography of watersheds around the world, these results apply only to basins which have characteristics similar to the Chester Creek watershed and which are being urbanized at a similar rate.

Much additional work must be devoted to the study of urbanization and runoff. The effect of urbanization on annual water yield from basins with different climates, soil types, elevations, and land uses must be investigated. Also, the effect of urbanization on monthly water yield from various basins should be studied. The portion of annual and monthly yield coming from surface runoff and from subsurface runoff should be investigated. Furthermore, the effect of urbanization upon stream overflow and flooding needs to be studied.

In essence, future work is needed to investigate the effect of urbanization on the quantity, quality, and time distribution of runoff. Perhaps, through future research into the effect of urbanization on the process of runoff, more may be learned about all of the processes involved in the hydrologic cycle; through a deeper understanding of the hydrologic processes, man may ultimately learn to work in harmony with his surrounding natural environment.

REFERENCES

Berry, B. J. L., 1962: Sampling, coding and storing flood plain data. Agriculture Handbook, Economic Research Service, U.S. Dept. Agriculture, No. 237, 27 p.

Burton, I., 1962: Types of agricultural occupance of flood plains in the United States. Research Paper, Dept. of Geography, Univ. of Chicago, No. 75, 167 p.

Chow, V. T., 1964: Runoff, in Handbook of Applied Hydrology. McGraw-Hill Book Co., New York, p. 14-1 to 14-54.

Cochran, W. G., 1946: Relative accuracy of systematic and stratified random samples for a certain class of population. Annals of Mathematical Statistics, Vol. 17, pp. 164-177.

Haggett, P., 1965: Locational Analysis in Human Geography. Edward Arnold Publishers, Ltd., London, 310 p.

Jens, S. W. and M. B. McPherson, 1964: Hydrology of urban areas, in Chow, V. T., Handbook of Applied Hydrology, McGraw-Hill Book Co., New York, p. 20-1 to 20-45.

Kunkle, W. M. and others, 1963: Soil survey of Chester and Delaware Counties, Pennsylvania. Soil Survey, U. S. Dept. Agriculture, No. 19, 125 p.

Landsberg, H. E., 1956: The climate of towns, in Thomas, W. L. Jr., Man's Role in Changing the Face of the Earth. Univ. of Chicago Press, Chicago, pp. 584-606.

Lull, H. W. and W. E. Sopper, 1969: Hydrologic effects from urbanization of forested watersheds in the Northeast. Research Paper, Forest Service, U.S. Dept. Agriculture, No. NE-146, 31 p.

Lull, H. W. and H. C. Storey, 1957: Factors influencing streamflow from two watersheds in northeastern Pennsylvania. Journ. of Forestry, Vol. 55, No. 3, pp. 198-200.

Mather, J. R., 1969: Factors of the climatic water balance over the Delmarva Peninsula. Publications in Climatology, Laboratory of Climatology, Vol. 22, No. 3, 129 p.

Muller, R. A., 1966: The effect of reforestation on water yield. Publications in Climatology, Laboratory of Climatology, Vol. 19, No. 3, 53 p.

Mumford, L., 1956: The natural history of urbanization, in Thomas, W. L. Jr., Man's Role in Changing the Face of the Earth, Univ. of Chicago Press, Chicago, pp. 382-398.

Quenouille, M. H., 1949: Problems in plane sampling. Annals of Mathematical Statistics, Vol. 20, pp. 355-375.

Schneider, W. J. and G. R. Ayer, 1961: Effect of reforestation on streamflow in central New York. Water-Supply Paper, Geological Survey, U.S. Dept. Interior, No. 1602, 61 p.

Thornthwaite, C. W. and J. R. Mather, 1955: The water balance. Publications in Climatology, Laboratory of Climatology, Vol. 8, No. 1, 86 p.

Thornthwaite, C. W. and J. R. Mather, 1957: Instructions and tables for computing potential evapotranspiration and the water balance. Publications in Climatology, Laboratory of Climatology, Vol. 10, No. 3, pp. 185-311.

U. S. Dept. of Commerce, 1958: Substation history, Pennsylvania. Key to Meteorological Records Documentation, Weather Bureau, No. 11, 133 p.

U. S. Dept. of Interior, 1960: Compilation of records of surface waters of the United States through September 1950, Part 1-B, North Atlantic slope basins, New York to York River. Water-Supply Paper, Geological Survey, No. 1302, pp. 342-343.

U. S. Dept. of Interior, 1938-1962: Surface water supply of the United States, 1936-1960, Part 1, North Atlantic slope basins. Water-Supply Paper, Geological Survey, Nos. 801, 821, 851, 871, 891, 921, 951, 971, 1001, 1031, 1051, 1081, 1111, 1141, 1171, 1202, 1232, 1272, 1332, 1382, 1432, 1502, 1552, 1622, 1702.

U. S. Dept. of Interior, 1962-70: Surface Water Records of Pennsylvania, 1961-1969. Water Resources Division Geological Survey (in 1966 became entitled Water Resources Data for Pennsylvania).

Vaughn, G. F., 1970: Land use change in Delaware, 1930-1980. Extension Circular, Univ. of Delaware, No. 130, 4 p.

APPENDIX I

COMPUTATION OF THE MONTHLY CLIMATIC WATER BALANCE

In order to compute the monthly climatic water balance at a location, the following information is needed:

(a) Mean monthly air temperature at the particular location.

(b) Total monthly precipitation at the location.

(c) Necessary conversion and computational tables.

(d) Information on the water holding capacity of the depth of soil under consideration.

Air temperature and precipitation (items a and b) are measured by the National Weather Service at many thousands of stations over the United States. There are more than 15,000 such stations around the world. All of the tables needed for the computations (item c) are presented in Thornthwaite and Mather (1957). The water holding capacity of the soil (item d) can be determined if: (a) the soil type and structure; and, (b) the type of vegetation growing on the surface, are known. A listing of suggested water holding capacities for various combinations of soil and vegetation is available in table 10 of Thornthwaite and Mather (1957).

To illustrate the computational steps in calculating the monthly climatic water balance, the 1950 water balance for West Chester, Pennsylvania is presented in table 1. Based on a water holding capacity of 6.00 inches and a runoff detention factor of 50 percent, the balance for this station can be calculated in the following steps:

Line 1: T°F - Temperature in Degrees Fahrenheit

The mean monthly air temperature at a particular location can be obtained from National Weather Service records in the area. For the water balance of West Chester, the records for 1950 at the West Chester weather station were used. The average monthly values appear in line 1 of table 1.

Lines 2-4: Adj. PE - Adjusted Potential Evapotranspiration

Potential evapotranspiration at a particular location can be calculated in the following steps, if the latitude of the station is known. First, the Heat Index, I, must be calculated by summing the twelve monthly values of _i_ which are a function of the mean monthly temperatures. The individual i values can be obtained from table 1 of Thornthwaite and Mather (1957). Second, the unadjusted daily potential evapotranspiration values are obtained from table 3 of Thornthwaite and Mather (1957) for the various mean temperatures, knowing the Heat Index, I. Third, the unadjusted daily potential evapotranspiration

Table 1

1950 Monthly Climatic Water Balance at West Chester, Pennsylvania
(Water Holding Capacity = 6.00 Inches, Detention Factor = 50%)

		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
T°F	(1)	42.1	32.9	37.5	48.9	60.7	70.2	73.9	72.0	63.4	58.5	46.0	32.5	53.2
I	(2)	1.19	0.03	0.47	2.60	5.79	8.92	10.26	9.57	6.62	5.13	1.95	0.01	52.54
UNADJ. PE	(3)	0.02	0.00	0.01	0.05	0.09	0.13	0.15	0.14	0.10	0.08	0.04	0.00	
PE	(4)	0.50	0.00	0.31	1.67	3.35	4.88	5.72	4.96	3.12	2.50	1.00	0.00	28.0
P	(5)	1.81	3.24	4.77	1.49	4.52	2.62	3.19	6.54	4.93	3.16	7.91	3.23	47.41
P-PE	(6)	1.31	3.24	4.46	-0.18	1.17	-2.26	-2.53	1.58	1.81	0.66	6.91	3.23	
ACC. PO. WL	(7)	0.00	0.00	0.00	-0.18	0.00	-2.26	-4.79	0.00	0.00	0.00	0.00	0.00	
ST	(8)	6.00	6.00	6.00	5.82	6.00	4.10	2.66	4.24	6.00	6.00	6.00	6.00	
ΔST	(9)	0.00	0.00	0.00	-0.18	+0.18	-1.90	-1.44	+1.58	+1.76	0.00	0.00	0.00	
AE	(10)	0.50	0.00	0.31	1.67	3.35	4.52	4.63	4.96	3.12	2.50	1.00	0.00	26.56
D	(11)	0.00	0.00	0.00	0.00	0.00	0.36	1.09	0.00	0.00	0.00	0.00	0.00	1.45
S	(12)	1.31	3.24	4.46	0.00	0.99	0.00	0.00	0.00	0.05	0.66	6.91	3.23	20.85
RO	(13)	2.37	2.81	3.63	1.82	1.40	0.70	0.35	0.18	0.11	0.39	3.65	3.44	20.85

values are adjusted for month and day length by multiplying by the appropriate correction factors given in table 6 of Thornthwaite and Mather (1957). These adjusted potential evapotranspiration values are entered in line 4 of the tabulation.

In line 2 of table 1, the monthly values of i are entered, and according to these values, the Heat Index at West Chester for 1950 is 52.54. The unadjusted values of PE corresponding to the various monthly temperatures and the Heat Index are entered in line 3. These unadjusted values are then adjusted by multiplying by the appropriate correction factors and entered in line 4 of table 1.

Line 5: P - Precipitation

The total monthly precipitation at a particular location is obtained from National Weather Service records in the area. For the water balance of West Chester shown in table 1, the precipitation records for 1950 at the West Chester weather station were used and entered in line 5.

Line 6: P-PE - Precipitation Minus Potential Evapotranspiration

The difference between the supply to the soil, P, and the potential demand from the soil, PE, indicates months of moisture excess, when this value is positive, or months of moisture deficiency, when this value is negative. As indicated in table 1, West Chester in 1950 only had three months of moisture deficiency. In these months, April, June, and July, P-PE was negative, while this value was positive for the other months of the year.

Line 7: Acc. Pot. WL - Accumulated Potential Water Loss

The negative values of P-PE in line 6 should be summed month by month for successive months of moisture deficiency and be entered in line 7 as an aid in the computational steps to follow. For West Chester, as shown in table 1, an accumulated potential water loss was entered in April, June, and July. These were the months of moisture deficiency.

Line 8: ST - Soil Moisture Storage

This line represents the amount of moisture stored in the soil during any given month. Normally, the soil is assumed to be at field capacity at the beginning of the first year of computation. The soil moisture storage will continue to be at this level until the first month with a moisture deficiency, negative P-PE, is encountered. During any series of months of moisture deficiency, the storage level of the soil is determined from the accumulated potential water loss for each month using tables 11 to 22 of Thornthwaite and Mather (1957). Periods of moisture deficiency are usually followed by periods of moisture excess where P-PE is positive again, and the soil moisture is restored. Normally, in an area such as West Chester, the soil is again at field capacity by December and our original assumption of having the soil at field capacity at the beginning of the year is valid.

In 1950 at West Chester, the soil stayed at field capacity until April when P-PE was negative. In April, the storage was reduced, but because of the excess moisture available in May, the soil was brought up to field capacity again. However, during June and July, the soil moisture storage value dropped because of the moisture deficiency in these months. Following this dry period, precipitation again exceeded potential evapotranspiration and the soil was brought back up to field capacity in September and remained there until the end of the year.

Line 9: ΔST - Change in Soil Moisture Storage

The change in soil moisture storage from one month to the next is needed for later computations. Since storage cannot exceed field capacity, when field capacity is reached, any additional moisture (P-PE) is assumed to become surplus (and entered into line 12). The change in soil moisture storage becomes zero.

Line 10: AE - Actual Evapotranspiration

During periods of moisture excess (positive P-PE), the actual evapotranspiration will equal the potential evapotranspiration. However, when precipitation drops below potential evapotranspiration, the soil moisture content decreases, making it more difficult for plants to obtain water for evapotranspiration. During these periods, actual evapotranspiration is less than potential evapotranspiration and is equal to the sum of precipitation and the change in soil moisture storage in line 9 (without regard to sign).

Line 11: D - Moisture Deficit

The difference between actual and potential evapotranspiration for any month is the moisture deficit for that month. As shown in table 1, there was a moisture deficit only in June and July at West Chester. In April, there was no deficit, since actual and potential evapotranspiration were the same.

Line 12; S - Moisture Surplus

Any precipitation over the amount needed to replenish soil moisture is surplus for that month and is available for runoff. For September, at West Chester in table 1, P-PE was 1.81 inches. Only 1.76 inches were needed to bring the soil up to field capacity. The other 0.05 inches of water was surplus and is shown in line 12.

Line 13: RO - Runoff

During months of moisture excess, a portion of the moisture surplus finds its way to creeks and streams as runoff, while the remaining portion of the surplus is held and made available for runoff in the following months. The percentage of the monthly moisture surplus which does not runoff is called the detention factor. This percentage is approximately 50 percent for moderate to large watersheds although it may vary considerably for smaller watersheds. Thus, monthly runoff or water yield values are computed from monthly surplus values and entered in line 13 of the water balance.

In our sample computation for West Chester shown in table 1, the surplus in January was found to be 1.31 inches. This computed value is lower than the actual value since a portion of the surplus water available for runoff in December 1949 should have been carried over into the surplus available for runoff in January 1950. In order to obtain the correct value of carry-over from 1949, the water balance for 1949 should first be worked out. Thus, if only one year's record is needed, it may be necessary to evaluate at least two years of data to insure that the proper values of storage and surplus are carried over to the year of interest.

In all climatic water balance computations, all of the lines except lines 1 and 2 have the dimensions of length. In our example computation, line 1 is in degrees Fahrenheit, line 2 is dimensionless, and all of the other lines are in inches.

As the last step in any computation, it is usually wise to check the foregoing calculations. In the case of the monthly climatic water balance, the calculations can be checked by noting: (a) if the sum of the monthly actual evapotranspiration, AE, and the monthly deficit, D, values equal the total yearly potential evapotranspiration value; and, (b) if the sum of the monthly actual evapotranspiration, AE, and the monthly surplus, S, values equal the total yearly precipitation value.

The preceding is only an introduction to the computation of the monthly climatic water balance. Further information on the uses and computational procedure can be obtained from Thornthwaite and Mather (1955, 1957).

REFERENCES

Thornthwaite, C. W. and J. R. Mather, 1955: The water balance, Publications in Climatology, Laboratory of Climatology, Vol. 8, No. 1, 86 p.

Thornthwaite, C. W. and J. R. Mather, 1957: Instructions and tables for computing potential evapotranspiration and the water balance, Publications in Climatology, Laboratory of Climatology, Vol. 10, No. 3, pp. 185-311.

APPENDIX II

LIST OF STATIONS USED IN ANALYSIS OF RUNOFF, PRECIPITATION AND EVAPOTRANSPIRATION DATA

Stations Used for Geographic Analysis of Runoff from the Basin Below Trenton

a) Stations in basin below Trenton

Coatesville, Penn.
George School, Penn.
Marcus Hook, Penn.
Philadelphia, Penn.
Phoenixville, Penn.
Port Clinton, Penn.
Reading, Penn.
West Chester, Penn.
Cape May, N. J.
Millville, N. J.
Pemberton, N. J.
Dover, Del.
Lewes, Del.
Milford, Del.
Newark, Del.
Wilmington (Porter Res.), Del.

b) Stations located just outside basin

Allentown, Penn.
Hawley, Penn.
Holtwood, Penn.
Lancaster, Penn.
Palmerton, Penn.
Stroudsburg, Penn.
Belvidere, N. J.
Flemington, N. J.
Hightstown, N. J.
Indian Mills, N. J.
Lambertville, N. J.
Layton, N. J.
Long Valley, N. J.
Newton, N. J.
Pleasantville, N. J.
Georgetown, Del.
Denton, Md.
Millington, Md.

Stations Used for Geographic Analysis of Over-Water Precipitation and Evapotranspiration, Delaware Estuary

Coatesville, Penn.
George School, Penn.
Marcus Hook, Penn.
Philadelphia, Penn.
Phoenixville, Penn.
West Chester, Penn.
Cape May, N. J.
Indian Mills, N. J.
Millville, N. J.
Pemberton, N. J.
Pleasantville, N. J.
Dover, Del.
Georgetown, Del.
Lewes, Del.
Milford, Del.
Newark, Del.
Wilmington (Porter Res.), Del.
Denton, Md.
Millington, Md.