EASTERN REGION TECHNICAL ATTACHMENT
NO. 91-2A
FEBRUARY, 1991

AN EVALUATION OF THE EFFECTS OF 300 YEARS OF CHANGING LAND USE ON THE PEAK FLOWS, BASE FLOW, AND FLOOD FREQUENCY OF A SMALL PENNSYLVANIAN STREAM

William B. Reed
Middle Atlantic River Forecast Center
Harrisburg, Pennsylvania

1. INTRODUCTION

Valley Creek flows through Valley Forge National Historical Park to its confluence with the Schuylkill River. Valley Creek at Schuylkill River has a watershed of 23.25 square miles. The watershed has undergone extensive land use changes resulting in changes in Valley Creek stream flow characteristics and associated fluvial processes. Within the park, between the covered bridge and the upper forge site, Valley Creek once migrated back and forth within a very narrow valley. In recent times, the stream has been confined by alternative uses of the valley floor, and now threatens these uses as it continues to adjust to changes in watershed conditions. Of particular concern is the potential for the undermining of Route 252 and underlying sewer main. Most recently the failure of a wall, located between the stream and the road at the upper forge site, brought the attention of park and Pennsylvania Department of Transportation staff to the problem of stream bank stability.

The Village of Valley Forge received its name from the iron forge built along Valley Creek in the 1740s. This forge was destroyed by the British in 1777 prior to the arrival of George Washington's army. The upper forge site may be the ruins of this historic forge. At this site, stone masonry walls were constructed (circa 1945) to protect the buried ruins and Route 252. However, the walls constrict the flow of Valley Creek, gradually reducing the channel width from 42.6 to 31.3 feet. This channel configuration and changing watershed conditions have resulted in: (1) a lowering of the stream channel (which had already been dredged during archeological investigations), (2) an undermining of the right-bank wall, and recently (3) a collapsing of a segment of the right-bank wall into the stream. The purpose of this paper is to present a qualitative evaluation of the effects of 300 years of changing land use within the Valley Creek watershed on the peak flows, base flow, and flood frequency of a small Pennsylvanian stream.

2. DESCRIPTION OF VALLEY CREEK WATERSHED

Valley Creek watershed is 20 miles west of Philadelphia, Pennsylvania. The watershed is located mainly in Chester County with a small portion (5 percent) in Montgomery County. Valley Creek flows for 11,000 feet through Valley Forge National Historical Park and is a perennial tributary to Schuylkill River. The mouth is near Washington's Headquarters within the park. At this confluence, the drainage area of the watershed is 23.25 square miles (Figure 1).

The watershed has a rectangular shape and is approximately 3 miles wide (north to south) and 8 miles long (west to east). The highest and lowest points in the watershed are 720 feet near Union Chapel (northwestern corner) and 70 feet (water surface elevation shown on USGS Valley Forge Quadrangle) at Schuylkill River (northeastern corner), respectively. Elevations are above National Geodetic Vertical Datum of 1929. Total channel length is 56,000 feet. Average channel slope is 1.2 percent. From highest point in watershed to Church Road (a distance of 25,900 feet), average channel slope is 2.0 percent. From Church Road to mouth (a distance of 30,100 feet), average channel slope is 0.4 percent.

The watershed is located in the Piedmont physiographic province of southeastern Pennsylvania and is typical of the narrow limestone valleys and the low hills of this region. The geology of the watershed consists of Ordovician and Cambrian sedimentary (shale, limestone, dolomite, and sandstone) and metamorphic (schist, serpentine, gneiss, and quartzite) rocks (Willard, 1962). Limestone and dolomite are quarried within the watershed.

The soils within the watershed are predominately, moderately well-drained silt loams derived from weathered limestone, schist, gneiss, and quartzite (Commonwealth of Pennsylvania, 1973). The hydrologic soil group classification for these soils is Group B [U.S. Soil Conservation Service (SCS), 1986]. The runoff potential for an undeveloped watershed with soils of this classification is low to moderate (Van Haveren, 1986).

3. DESCRIPTION OF HISTORICAL WATERSHED CONDITIONS

In general, the watershed has experienced five major phases of land use over the last 300 years:

(1) heavily forested--prior to significant settlement of the area by colonists (pre-1700s);

(2) the clearing of a small portion of the valley floor for agricultural use and village sites, approximately 4 to 20 percent of the watershed deforested--prior to the American Revolution (1700 to 1776);

(3) the clearing of the valley floor, rolling hills and other mild slopes for additional agriculture use and growing village sites, approximately 40 to 50 percent of the watershed deforested (1800s);

(4) the clearing of additional land for and the conversion of marginal agricultural lands to residential, commercial, and industrial areas, including planned communities (high-density residential areas), shopping centers, industrial parks, railroad yards, and quarries, approximately 60 percent of watershed deforested (1900 to 1985)--with accelerated development and major land use changes occurring essentially over a 15-year period from approximately 1970 to 1985; and

(5) the conversion of marginal and prime agricultural lands to commercial parks and isolated estates (low-density residential areas), approximately 60 percent of the watershed deforested--this is the current trend (1985 to possibly the year 2000).

The above scenario is generalized; therefore, there may be numerous exceptions to the sequence and description of events. It is beyond the scope of this report to quantify the exact pattern of historical land use within the watershed. However, the above generalizations and the following qualitative narratives are used to approximate historic and projected watershed conditions; thereby, permitting a preliminary analysis of the effects of changing land use on the peak flows, base flow, and flood frequency of Valley Creek.

Watershed condition, as defined in this paper, is the health of the watershed compared to its natural state as measured in the terms of three characteristics (1) peak flows, (2) base flows, and (3) channel morphology. Peak flow, as used here, is the largest rate of discharge expected during a given event (for floods, the peak flow is often referred to as the flood crest). Base flow is defined as the sustained or fair-weather runoff (Chow, 1964). Channel morphology, is the width, depth, and pattern (plan form) of the channel. A watershed with characteristics typical of natural conditions is considered excellent. Whereas, a watershed with characteristics typical of moderately developed conditions (without stormwater management) is considered poor. Good and fair conditions exist between these two extremes with: good representing conditions that have only been slightly impacted by development, and fair representing conditions between good and poor.

Watershed condition for phase 1: excellent. When the watershed was heavily forested, the stream flow of Valley Creek was very different than it is today. Under these conditions, soil infiltration rates were high and watershed runoff was dominated by subsurface (interflow) processes. Overland flow, which conveys precipitation to stream channels more rapidly than subsurface flow, likely was less common. Thus, peak discharges associated with precipitation were of lesser magnitude and severe flooding was less frequent than it is today. In contrast, the base flow of Valley Creek was greater, being fed by larger soil moisture and ground water reserves during dry seasons. Because the magnitude of peak flows associated with precipitation were smaller, the stream channel was presumably neither as deep nor as wide as it is today.

Watershed condition for phase 2: excellent to good. As the colonists move into the watershed they cleared a small portion of the valley floor for agriculture. An estimate of this clearing may be as high as 20 percent (Brush, 1989) or as low as 4 percent (Defries, 1986) of all available land. Such a change in land use had a relatively mild impact upon watershed condition. This is because the areas cleared probably had very mild slopes and productive soils (well-drained, highly permeable loams), and were not major sources of runoff even after clearing.

Watershed condition for phase 3: good to fair. As deforestation continued over the next century, resulting in 40 to 50 percent of the watershed deforested (Defries, 1986), the hydrology and channel morphology of Valley Creek changed noticeably. For the first time, towns--as we know them--were founded (Chester County, 1982). The main factors causing the presumed change in the hydrology and channel morphology of Valley Creek was a significant loss in vegetative and soil cover. The reduced infiltration of impacted soils would favor overland flow. This change resulted in both a significant increase in peak flows and a significant decrease in base flows. Initially, severe flooding occurred more frequently. Eventually, the stream channel increased its capacity to convey larger flows by becoming wider and deeper.

Watershed condition for phase 4: fair to poor. During this phase, the effect of continued deforestation and the conversion of marginal agricultural lands to other purposes, began to severely threaten park natural and cultural resources. The amount of developed land in Chester County doubled from 1970 to 1985 (Chester County, 1988). At least one historically perennial tributary to Valley Creek lost its base flow due to the construction of a planned community outside of the park. Such a severe response to changing land use occurs when a large percentage of the watershed becomes impervious. This change results in reduced infiltration and greater storm runoff. Also, peak flows associated with storms become larger than in the past as the watershed's response to rainfall becomes flashier due to a shorter time of concentration. Even for moderately developed watersheds, runoff volumes may be increased by more than 50 percent and time of concentrations may be decreased by as much as 50 percent--particularly if extensive drainage "improvements" are made (Schueler, 1987).

Watershed condition for phase 5: presently poor; potential for fair. In general, only the least productive soils and steeper slopes are still forested (Chester County, 1982). Although agriculture and woodlands are the two largest land use categories in Chester County, these land uses have decreased the most since 1970 (Chester County, 1988). The conversion of marginal and prime agricultural lands to corporate parks and isolated estates, may actually improve the previous watershed condition by reducing peak flows and sediment loads through best management practices. It is assumed here that best management practices will be implemented to reduce the peak flows of all events. This will likely require the use of innovative techniques--in addition to stormwater management ponds--in that stormwater management ponds are usually only designed for events equal to or less than the 25-year frequency 24-hour single-event rainfall. The watershed condition's best potential will likely only be achieved through the establishment of a watershed committee or advisory board. Without proper stormwater management, peak discharges will increase as the impervious area within the watershed increases (Sloto, 1988).

Whereas, during this phase, hydrologic conditions may improve (assuming that stormwater runoff will be better managed), channel conditions (unless otherwise altered) will decline. This decline is because the stream channel will still be adjusting to previous changes in watershed conditions (i.e., just beginning to respond to increased flows resulting from changes which occurred during the previous phase.)

4. HYDROMETEOROLOGIC SIMULATIONS FOR SELECTED WATERSHED CONDITIONS

The hydrometeorology of Valley Creek was simulated for future and representative historical conditions using the SCS unit hydrograph method (U.S. Soil Conservation Service, 1986). Specifically, the SCS TR-55 (Urban Hydrology for Small Watersheds) graphical method was used to calculate the peak discharges for 24-hour single-event rainfalls with the following return periods: 1, 2, 5, 10, 25, 50, and 100 years. Flows were calculated for Valley Creek at Schuylkill River. (These flows are specifically for Valley Creek.) The stage of Valley Creek near its mouth (approximately the reach downstream of Route 23 on Figure 1) is affected by the Schuylkill River during high flows. The flooding that occurred at this location during Hurricane Agnes (June 1972) was primarily due to the Schuylkill River with Valley Creek contributing very little to the combined stage. A Flood Preparedness Plan has been developed for this flood prone area which includes Washington's Headquarters.

The following years were subjectively selected as representative of the five major phases of land use in recent history and near future: 1685, 1776, 1885, 1985, and 1995 (projected). The rainfall amount for each storm (Table 1) was provided by the TR-55 computer program (from file COUNTY.RF), using a county and state combination of Montgomery County and Commonwealth of Pennsylvania.

FLOOD FREQUENCY	RAINFALL (inches)
1-year	2.6
2-year	3.2
5-year	4.2
10-year	5.1
25-year	5.6
50-year	6.3
100-year	7.2

Table 1. Valley Creek watershed: 24-hour single-event rainfall.

For these events, I selected a Type III rainfall distribution which is representative of Atlantic coastal areas where tropical storms bring large 24-hour rainfall amounts.

TR-55 subroutines (TCTT and RCN) were used to calculate time of concentration and runoff curve numbers. Time of concentration is the time it takes runoff to travel from the hydraulically most distant point in a watershed to the point of interest (here the mouth of Valley Creek). Time of concentrations ranged from 4.21 hours (1685 and 1776) to 3.2 hours (1885, 1985, and 1995). Curve number is a general parameter determined by several watershed properties. The major factors that determine the curve number are: hydrologic soil group, cover type, treatment, hydrologic condition, and antecedent runoff condition (U.S. Soil Conservation Service, 1986). The curve numbers used were 55 (1685), 56 (1776), 60 (1885), 67 (1985), and 66 (1995). In general, the following watershead cover descriptions were used to obtain these values:

For 1685, the entire watershed was assumed wooded.

For 1776, the watershed was assumed described by three agricultural cover descriptions including woods.

For 1885, the watershed was assumed described by four agricultural cover descriptions including woods and farmsteads.

For 1985, the watershed was described by eleven cover descriptions including urban and agricultural land uses. This land use pattern was obtained from USGS Valley Forge and Malvern Quadrangles that were photo revised in 1981 and 1983, respectively. Therefore, the full extent of urbanization in 1985 may not have been completely realized.

For 1995, the watershed was described by nine cover descriptions including urban and agricultural land uses. However, I assumed that all cultivated agricultural lands that remained in 1985 had since been converted to corporate parks and isolated estates. Additionally, I assumed that all farmsteads that remained in 1985 had since been either converted to parks (urban open space) or subdivided and subsequently converted to planned estates.

5. RESULTS

The results of the hydrometeorologic simulations for selected watershed conditions are presented in terms of peak flows for the 2-, 50-, and 100-year events; base flow; and flood frequency. Peak and base flow have been previously defined. Flood frequency, expressed as a return period (or recurrence interval), is the average time within which the given flood will be equaled or exceeded at least once. The 2-year event has a 50 percent chance of being equaled or exceeded at least once in any given year; the 50-year event has a 2 percent chance, the 100-year event has a 1 percent chance, and the 500-year event has a 0.2 percent chance.

Peak Flows: Selected hydrologic output data of the TR-55 computer simulations are presented in Table 2. The calculated peak discharges for the 2-, 50-, and 100-year 24-hour rainfall are in cubic feet per second (cfs).

Year	2-year peak	50-year peak	100-year peak
1685	350 cfs	3,100 cfs	4,200 cfs
1776	400 cfs	3,400 cfs	4,600 cfs
1885	800 cfs	5,000 cfs	6,600 cfs
1977	------	------	7,100 cfs*
1985	1,450 cfs	6,500 cfs	8,300 cfs
1995	1,350 cfs	6,300 cfs	8,100 cfs

* This value was obtained from U.S. Army Corps of Engineers (1981) and is presented here for comparison. (Note: The watershed was still being developed at the time of the Corps study.)

Table 2. Valley Creek at Schuylkill River: peak discharges for selected watershed conditions.

The 100-year peak discharge values for 1985 and 1995, although conservative, are not as high as comparable estimates made by others (Heister, 1989; Commonwealth of Pennsylvania, 1973).

Conversely, the 2-year peak discharge values for 1985 and 1995 may be high. This is because I did not take into consideration the possible cumulative effect of the small dams--throughout the watershed--on the peak flows of small floods. If these dams had any available storage prior to such events, then the resulting peak discharges would likely be less than the values presented in Table 2.

In general, over the 300-year period from 1685 to 1985, the peak discharges were doubled. This is typical of changes in stream hydrology for a moderately developed watershed, i.e., increased peak discharges about two to five times higher than pre-development conditions (Schueler, 1987). Essentially, half of the increase occurred over the 100-year period from 1785 to 1885, and half occurred over the period from 1885 to 1985, with most of this latter increase occurring since 1970. As modeled, the present trend in land use changes may actually cause a slight decrease in current (1985) peak discharges (Figure 2). This is because I assumed that in the future stormwater runoff would be better managed, i.e., I assumed that future land uses would have a lower curve number than the current land uses they replaced. If better management practices are not used, then peak flows will continue to increase. For example, without proper stormwater management, an estimate of the future 2-year peak discharge is 2,800 cfs; almost twice the 1985 peak discharge.

An analysis using the storage routine for the TR-55 computer program, indicates that even for relatively small events (e.g., the 2-year storm), the amount of storage required to reduce peak flows from projected 1995 peaks to modeled 1885 conditions would be considerable. Reducing the discharge of the 2-year event (24-hour rainfall of 3.2 inches) from 1,350 cfs to 800 cfs would require a detention basin storage volume of 205 acre-feet.

Base Flow: Over the 300-year period from 1685 to 1985, the base flow of Valley Creek within Valley Forge National Historical Park has presumably decreased. Although data have not been presented to support this supposition, it is based upon the observation that at least one formerly perennial tributary to Valley Creek no longer flows continuously during the summer. The observed drying up of the smaller stream, and the speculated reduced Valley Creek base flow, agrees well with the changes to stream hydrology expected within a moderately developed watershed (Schueler, 1987). However, the permitted discharge from a limestone quarry within the upper watershed may have offset any decrease that would have occurred in recent years.

Additionally, the growth of public water and sewer systems has resulted in significant interbasin transfers out of the Valley Creek watershed (Sloto, 1987). Sloto (1987) estimates that the net loss of water in 1984 was 630 million gallons. Such a loss could contribute to a reduction in base flow, but would likely not cause a noticeable change.

Flood Frequency: The effects of changing land use on the flood hydrology of Valley Creek at Schuylkill River has been to increase the magnitude of floods (e.g., the calculated magnitude of the 100-year flood increased from 4,200 cfs to 6,600 cfs over the 200-year period from 1685 to 1885). Another way to interpret this hydrologic trend, is that a given magnitude flow now has a more frequent (smaller) recurrence interval and thus, a higher probability of occurring. For example, a flow with a magnitude of 6,600 cfs would have been a flood with a recurrence interval slightly greater than the 500-year flood in 1776, but would have been a 100-year flood in 1885. And if a flood of this magnitude was to occur today, it would be only a 50-year flood. One result of this trend is that although the covered bridge (located approximately

2000 feet upstream of the upper forge site) may have been designed (by chance or on purpose) for the 100-year flood at the time of its construction (1851), it now has a conveyance (below low steel) roughly equal to the 50-year flood.

6. CONCLUSIONS

The effects of changing land use between 1685 and 1885 on the hydrology and channel morphology of Valley Creek may have complemented the changes in the historical uses of the stream. Inadvertently, the smaller, gentler stream of the colonial era was gradually changed to the larger, powerful stream of the industrial era.

The effects of changing land use between 1970 and 1985 on the hydrology and channel morphology of Valley Creek have resulted in an impaired fluvial system that may not yet be in equilibrium with existing watershed conditions. Without effective stormwater management, additional urbanization in the Eastern U. S. will likely continue to adversely impact stream hydrology.

In general, it appears that present-day changes in land use from agriculture to low-density residential areas and corporate centers (the trend since approximately 1985) may have less impact on the hydrology of Valley Creek than did the previous transition from agriculture to high-density residential areas and industrial parks. However, if proper stormwater management is not implemented, then peak flows may again increase. If the current trend continues, then Valley Creek streamflow characteristics will deviate very little from existing conditions. Therefore, it may be appropriate to design slope protection and erosion control efforts for current streamflow conditions.

7. ACKNOWLEDGMENTS

The assistance provided to the author by Brian Lambert, Natural Resource Specialist, Valley Forge National Historical Park, contributed to the preparation of this report. Thanks also to Jacqueline V. Nolan, Water Operations Branch, National Park Service for drafting the figures.

REFERENCES

Brush, G.S., 1989: Abstract: A History of Sediment and Metal Influxes in Some Mid-Atlantic, USA Estruaries. EOS, October 24, 1989.

Chester County, 1982: Chester County Open Space and Recreation Study. Chester County Planning Commission and Chester County Parks & Recreation Department, West Chester, PA.

Chester County, 1988: Chester County Land Use Plan. Chester County Planning Commission, West Chester, PA.

Chow, V.T., 1964: Handbook of Applied Hydrology, A Compendium Of Water-Resources Technology. McGraw-Hill Book Company, New York, NY.

Commonwealth of Pennsylvania, 1973: Hydrologic Study of Valley Creek at Valley Forge State Park. Department of Environmental Resources, Harrisburg, PA.

Defries, R.S., 1986: Effects Of Land-Use History on Sedimentation in the Potomac Estuary, Maryland: A Water-Quality Study of the Tidal Potomac River and Estuary. U.S. Geological Survey Water-Supply Paper 2234-K.

Heister, R.D., 1989: Impact of Urbanization on a Small Stream. Conestoga High School, Berwyn, PA.

Schueler, T.R., 1987: Controlling Urban Runoff: A Practical Manual for Planning and Deisigning Urban BMPS. Metropolitan Washington Council of Governments, Washington, D.C.

Sloto, R.A., 1987: Effects of Urbanization on the Water Resources of Eastern Chester County, Pennsylvania. U.S. Geological Survey Water-Resources Investigations Report 87-4098.

Sloto, R.A., 1988: Effects of Urbanization on Storm-Runoff Volume and Peak Discharge of Valley Creek, Eastern Chester County, Pennsylvania. U.S. Geological Survey Water-Resources Investigations Report 87-4196.

U.S. Army Corps of Engineers, 1981: Flood Preparedness Plan Outline, George Washington's Headquarters, Valley Forge National Historical Park.

U.S. Soil Conservation Service, 1986: Urban Hydrology For Small Watersheads. Technical Release 55.

Van Haveren, B.P., 1986: Water Resources Measurements, A Handbook For Hydrologists and Engineers. American Water Works Association, Denver, CO.

Willard, B., 1962: Pennsylvania Geology Summarized. Pennsylvania Geological Survey Educational Series No. 4.

SITE DESCRIPTIONS

1a. Valley Creek at Morehall Road
1b. Valley Creek at Church Road
1d. Valley Creek at Le Boutillier Road
1e. Valley Creek near Mill Road (100 feet upstream of confluence with Little Valley Creek
1f. Valley Creek at USGS gaing station (100 feet upstream of Pennsylvania Turnpike Bridge
2a. Tributary to Valley Creek at Morehall Road
2b. Tributary to Valley Creek at Church Road
3c. Little Valley Creek at North Valley Road
3e. Little Valley Creek near Mill valley Road (50 feet upstream of confluence with Valley Creek
4c. Small Tributary to Little Valley Creek at North Valley Road

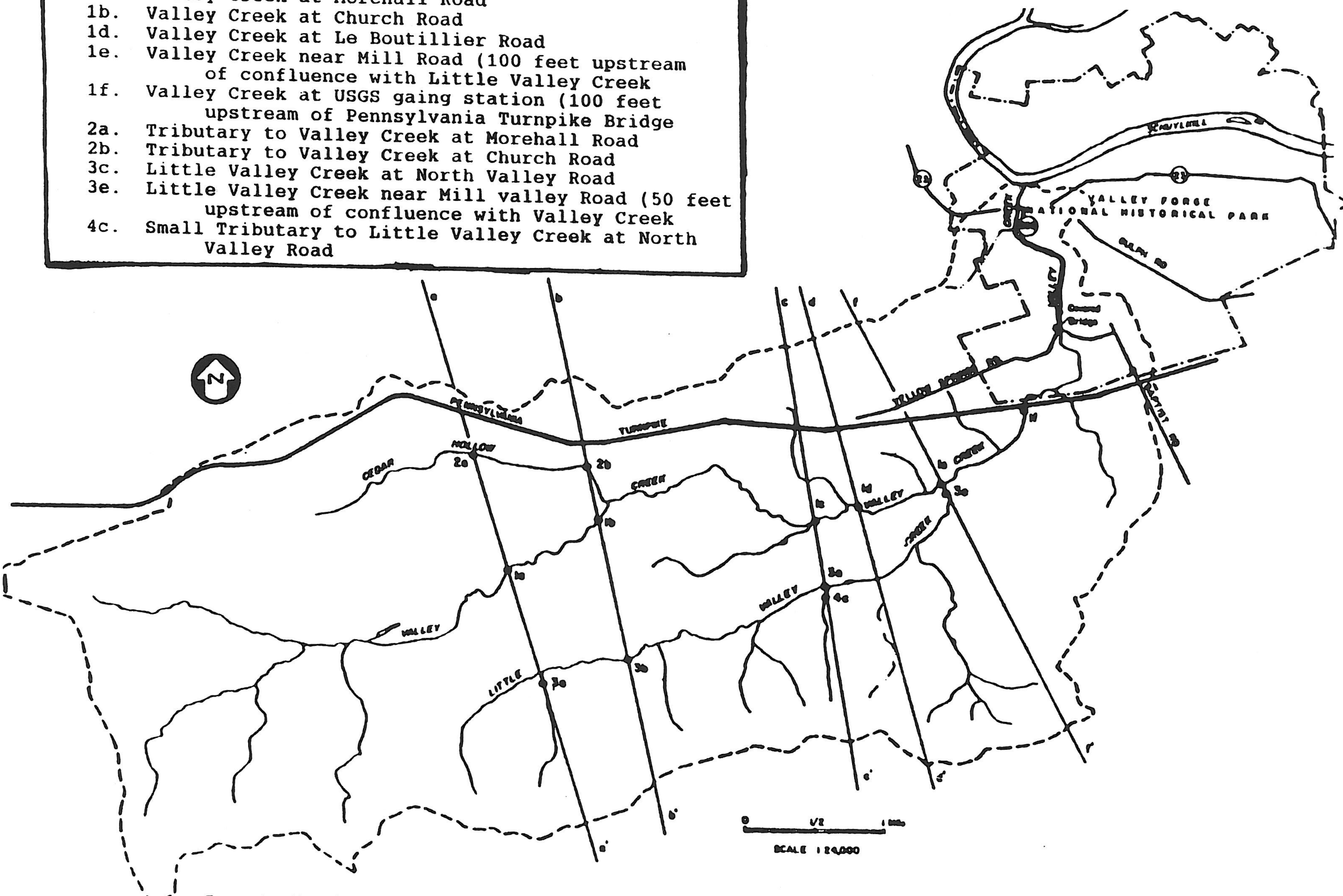

Figure I. VALLEY CREEK WATERSHED--MALVERN AND VALLEY FORGE QUADRANGLES, PENNSYLVANIA

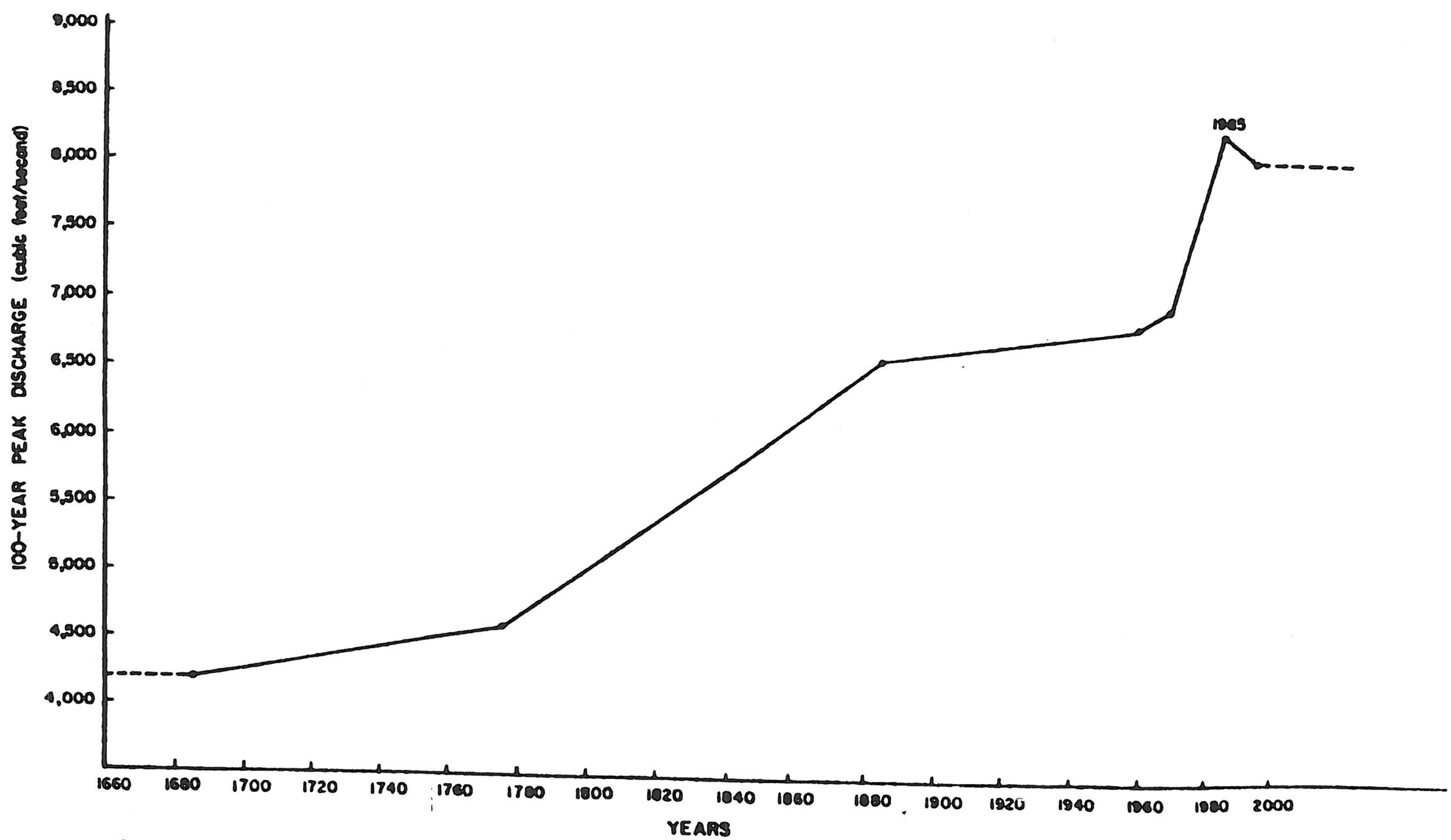

Figure 2 100-YEAR PEAK DISCHARGES -- 1685 to 1995, VALLEY CREEK at SCHUYLKILL RIVER, VALLEY FORGE NHP