

## The Role of Snowmelt in the January 1996 Floods in the Northeastern United States

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### ABSTRACT

Intense rainfall and rapid snowmelt on January 18 and 19, 1996, resulted in major flooding on coastal rivers from Virginia to New Jersey and in the upper reaches of the Ohio River drainage. Record flood crests were set in Pennsylvania, New York, West Virginia, and Maryland. The Ohio River at Pittsburgh, the Susquehanna River at Wilkes-Barre, and the Potomac River at Little Falls, Virginia, all crested at the highest stages since Hurricane Agnes in 1972. The large snowmelt contribution to the flood event was the result of much above-average snow cover over the region and high melt rates produced by latent and sensible heat exchange. During the peak of the snowmelt, air temperatures ranged from 13-17°C, relative humidity was above 90 percent, and winds at open sites were over 10 m/s. It is estimated that snowmelt generated about half of the water that produced the flood.

### INTRODUCTION

A succession of snowstorms brought significant and widespread snow accumulation across much of the Northeastern United States by January 17, 1996. Snow depths of 60 to 90 cm were common from central Pennsylvania into New York State. From southern Pennsylvania across Maryland and West Virginia into Virginia, snow depths averaged 30 cm or more, with significantly higher amounts in the

mountains. A strong storm system then moved through the Eastern United States on January 18-19, 1996, bringing heavy precipitation as well as high temperatures, humidity, and winds into the Ohio, Susquehanna, and mid-Atlantic drainages. Mean areal watershed rainfall varied from 30 mm to slightly over 75 mm, with some individual gages reporting over 100 mm. At most locations, the intense rain lasted only for about 6 hours. Figure 1 shows a map of estimated storm rainfall. The heavy rains combined with significant snowmelt, and in some cases ice jams, to produce major flooding in Pennsylvania, West Virginia, New York, Virginia, Maryland, Vermont, Ohio, and New Jersey.

The magnitude of the flooding varied between basins, but it was a major event throughout the area. Over 70,000 people were evacuated in the Wyoming Valley region of the Susquehanna River Basin. The entire town of Marlinton, West Virginia (1,100 people) on the Greenbrier River was evacuated. Many evacuations also took place in the Allegheny, Susquehanna, and Finger Lakes drainages in Pennsylvania and New York. The Ohio River at Pittsburgh had its highest crest since Hurricane Agnes in 1972 (Table 1). On the Susquehanna River at Wilkes-Barre, the crest of 34.5 feet (10.5 m) on January 21 exceeded all past floods except Agnes in 1972. Record floods occurred on Loyalsock Creek at Loyalsock, Pennsylvania; Schoharie Creek at Burtonsville, New York; Beaver Kill Creek at Cooks Fall, New York; the Greenbrier River at Marlinton,

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**Table 1. Selected Northeast Flood Crests - January 1996**

Location	Flood Stage - ft (m)	Crest - ft (m)	Comment
Ohio River @ Pittsburgh	25 (7.6)	34.6 (10.5)	Highest Since Agnes, 1972
Susquehanna River @ Wilkes-Barre	22 (6.7)	34.5 (10.5)	Highest Since Agnes, 1972
Susquehanna River @ Harrisburg	17 (5.2)	24.7 (7.5)	Highest Since Eloise, 1975
Delaware River @ Trenton	20 (6.1)	22.2 (6.8)	Highest Since Connie, 1955
Potomac River @ Little Falls	10 (3.0)	19.0 (5.8)	Highest Since Agnes, 1972
James River @ Richmond	12 (3.7)	20.6 (6.3)	Highest Since 1987
Hudson River @ Albany	11 (3.4)	15.5 (4.7)	Highest Since 1948

West Virginia; Wills Creek at Cumberland, Maryland; and Opequon Creek at Martinsburg, West Virginia. Record crests were also observed on the Lower Conemaugh River, Lower Mahoning River, West Branch Clarion River, Aughwick Creek, Towonda Creek, and Tunkhannock Creek, all in Pennsylvania.

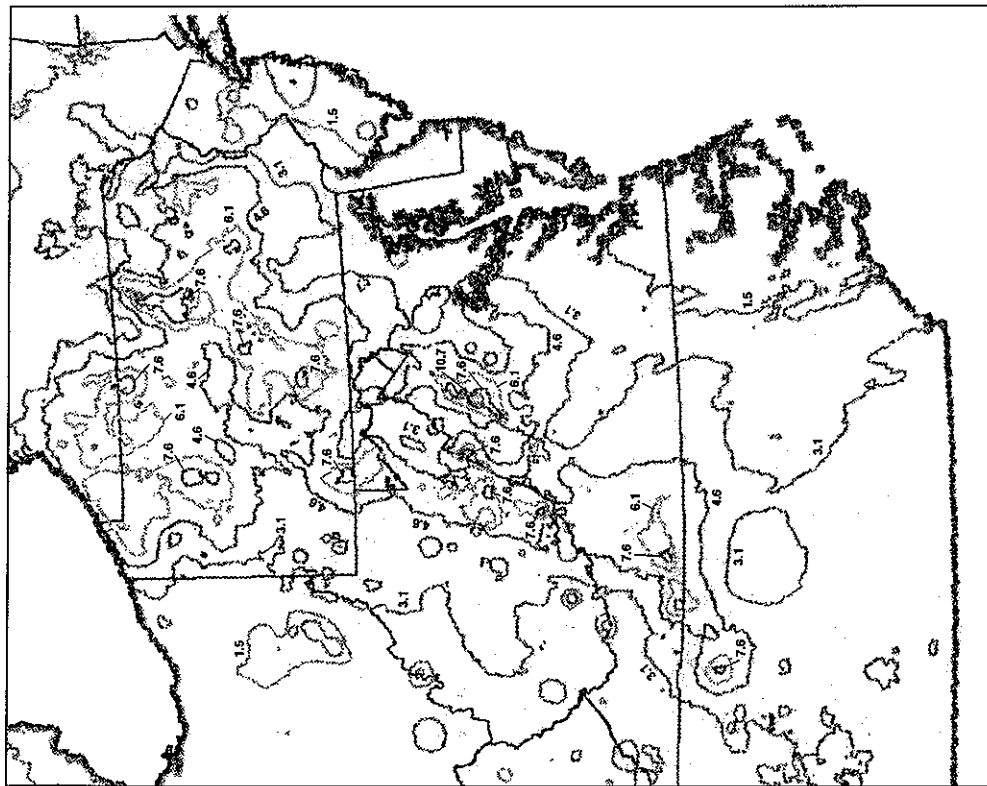
As flood waters began to recede, there were reports of flood-related deaths. Unofficially, 30 deaths were reported with 15 in Pennsylvania, 10 in New York, 1 in West Virginia, 3 in Virginia, and 1 in Vermont. Based on the widespread nature of the flooding and comparisons to historical floods, it is estimated that total flood-related damages exceeded \$1.5 billion dollars.

#### **SNOW COVER PRIOR TO THE EVENT**

The abnormally large snow cover that accumulated over the Northeastern United States in the weeks prior to the flood event was the result of a number of storms. The "Blizzard of 96" which occurred from January 6 to January 8, 1996, was a major contributor to the snow cover from Virginia, across Maryland, and through much of Pennsylvania and New Jersey. During the period before the flood event, January 14-17, above freezing temperatures occurred over most of the area. Significant snowmelt

occurred west of the Appalachian mountains. The snow cover was also partly depleted in parts of Virginia and eastern Maryland prior to the flood event. Over portions of Pennsylvania, New York, and New Jersey, this warming period caused some ripening of the snow cover, but there was little reduction in the water equivalent.

Figure 2 represents an estimate of the water equivalent of the snow cover over the primary flood area on the morning of January 18. Water equivalents ranged from zero in the far southeastern portion of the area to over 125 mm (5 inches) in areas from south-central Pennsylvania to the Catskill Mountains of New York. The map represents the general trend in values and not the small scale variations that may exist in any individual watershed. The figure was constructed using all available snow data. The major type of snow data in this part of the United States is snow depth. All available snow depth reports that were sent by National Weather Service (NWS) offices were used. Point water-equivalent measurements were available from some NWS synoptic stations and at some locations in the upper Ohio River drainage. The NWS National Operational Hydrologic Remote Sensing Center (NOHRSC) measured water equivalent from airborne natural gamma radiation surveys over the upper Ohio River drainage during the period from January 11 to



January 15. Since there was significant melt over this area between these dates and January 18, the airborne data were only used in a subjective manner in preparing the map. Water-equivalent data were also available from the U.S. Army Corps of Engineers (COE) and the U.S. Geological Survey (USGS). The Baltimore District of the COE makes periodic multiple-point surveys to determine the average water equivalent above 14 of their projects in the Susquehanna and Potomac drainages. Measurements were available for the 16th and 17th of January. Measurements made by the USGS from January 10 to January 12 were available for seven locations in the Delaware basin. At locations with both depth and water-equivalent values, snow density could be computed and used to convert other depth values into an estimate of water equivalent. Snow density ranged from less than .20 in areas where the snow cover had not yet ripened, to slightly over .30 in western and southern areas where significant melt had occurred in previous days. Areal snow coverage, as determined from satellite observations by the NOHRSC, was used to determine areas in the southeastern part of the area that were not covered by snow at this time. The water-equivalent analysis shown in Figure 2 used topographic information to help extrapolate the available data. It was especially important to take terrain information into account along the crest of the Appalachian Mountains.

### SNOWMELT DURING THE FLOOD EVENT

Significant snowmelt occurred over the area beginning on the morning of the 18th in the western part and continued through the afternoon of the 19th in the eastern portion of the region. Generally, any given area experienced between 18 and 30 hours of high snowmelt rates. The rapid snowmelt was primarily caused by the turbulent transfer of latent and sensible heat due to the high temperatures, dew-points, and wind speeds.

Figures 3a through 3d show calculated snowmelt rates and key data values during January 18-19 at four synoptic stations across the region. The figures also show the breakdown of the melt into each of the energy exchange components whenever the hourly melt rate exceeds about 1 mm. Snowmelt rates shown

in Figure 3 were computed using equations from Anderson (1976). Solar radiation, which was a minor factor since the sky was heavily overcast during the intense melt period, was estimated from percent sunshine (Hamon et al. 1954) or sky cover (Thompson 1976), and the albedo of the snow surface was assumed to be 75 percent. Longwave radiation exchange was computed by taking the difference between incoming longwave, calculated from the air temperature along with an estimate of the emissivity of the atmosphere (Anderson and Baker 1967), and the outgoing longwave from the snow surface at 0°C. Sensible (convective) and latent (condensation) heat exchange, which were dominant during this event, were computed using an empirical wind function with a coefficient of  $0.002 \text{ mm} \cdot \text{mb}^{-1} \cdot \text{km}^{-1}$ . This coefficient is for wind at a height of about 1 meter above the snow surface. The wind speed data were reduced to the 1 meter level by using a factor of 0.5 at all stations, even though there is some variation in anemometer heights. Rain melt was computed by assuming that the temperature of the rain drops are equal to the wet-bulb temperature. Data values for each hour were obtained by averaging the synoptic observations at the beginning and end of the hour.

An empirical wind function was used to compute the turbulent heat exchange components because the quality and quantity of the data did not justify the use of a theoretical function. The coefficient used in the empirical wind function was the one that gave the best overall results at the NOAA snow research station in Vermont (Anderson 1976). In this case, the only way to determine if the computed melt rates are reasonable is to compare them to the measured depletion of the snow cover. In Figure 3, the melt rates are labeled as potential melt rates since, at some of the sites, the snow was gone well before the melt period was over. At those sites with significant snow cover, the computed melt rates agree quite closely with the depletion of the snow cover. At Binghamton, just over 3 inches (75 mm) of water equivalent was reported before the event and the snow was gone at the site about mid-morning on the 19th, as expected based on the melt calculations. Middletown (Harrisburg) was the only one of the sites not to lose all of its snow cover during the event. The snow depth dropped from 23 inches (58 cm) to 9 inches (23

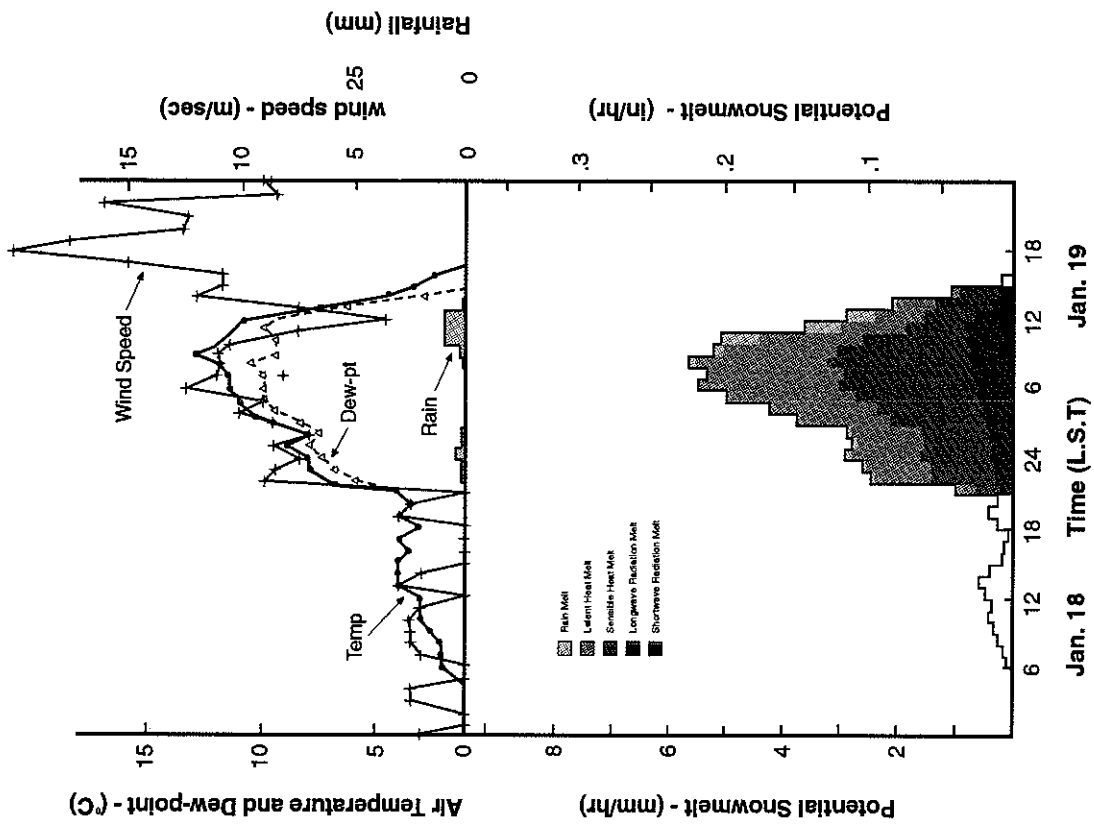


Figure 3a - Energy Balance Snowmelt Estimates - Binghamton, NY (BGM). Total Snowmelt is 4.0 inches (102 mm).

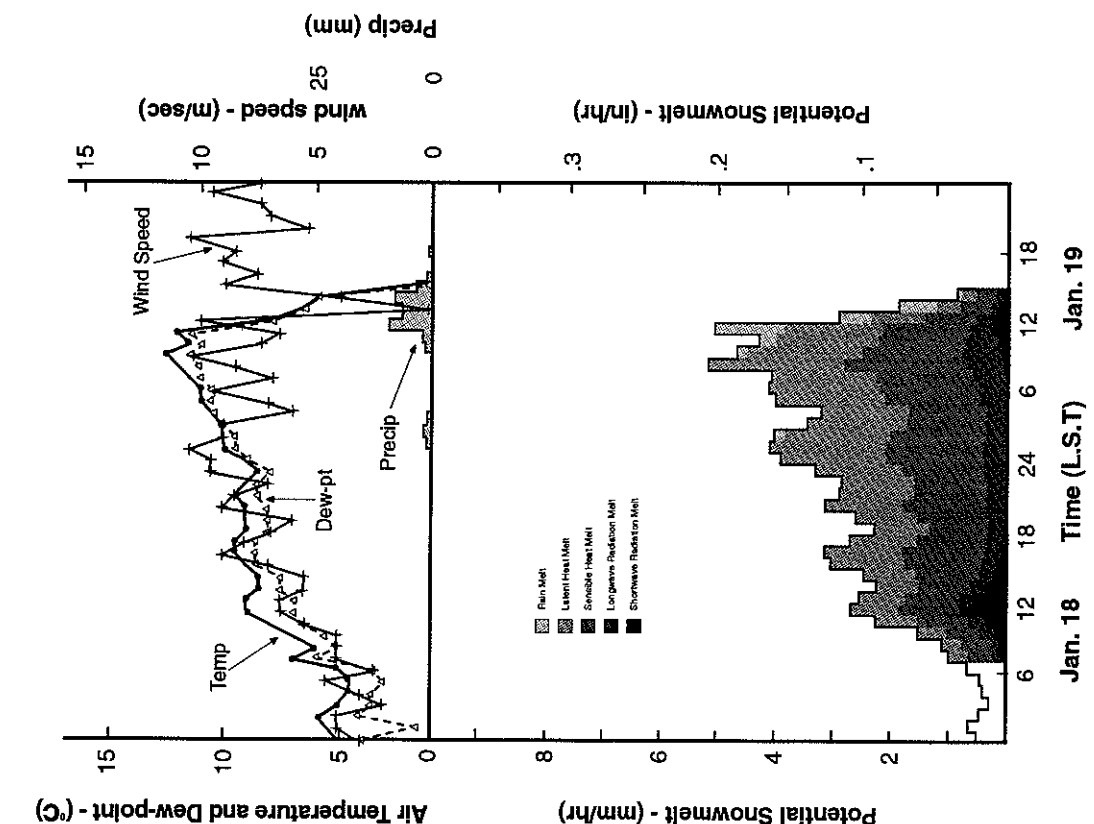


Figure 3b - Energy Balance Snowmelt Estimates - Middletown (Harrisburg), PA (MDL). Total Snowmelt is 2.7 inches (69 mm).

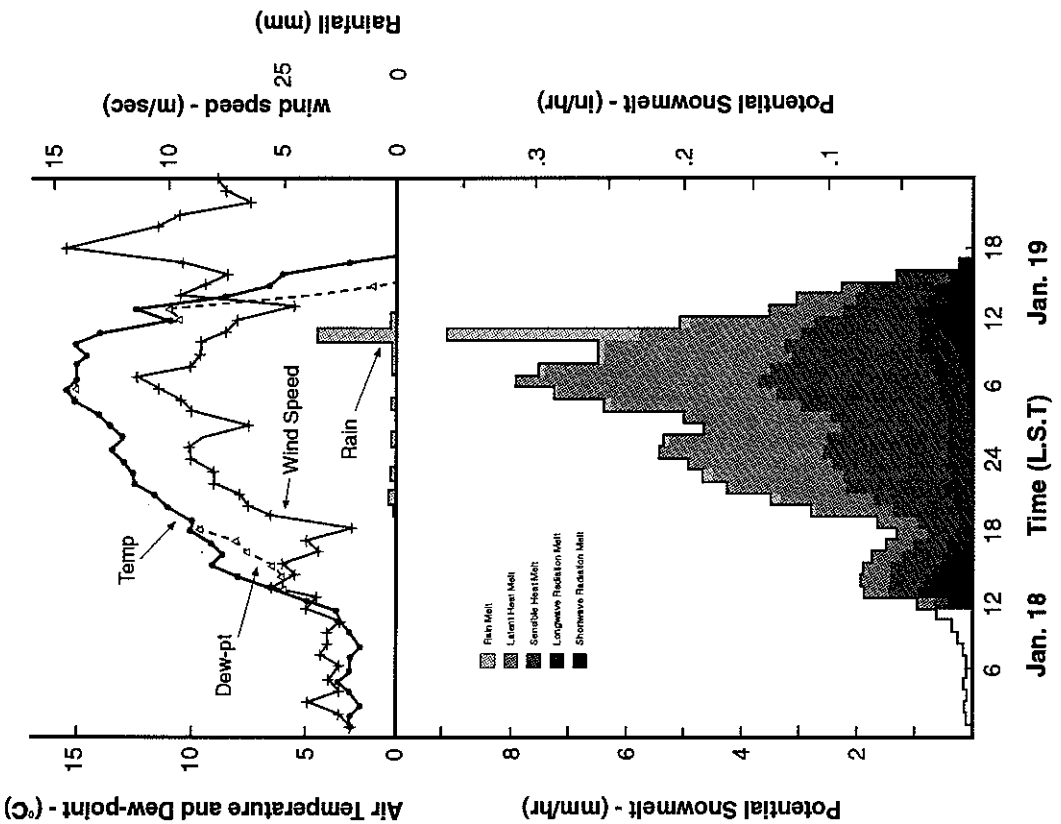


Figure 3c - Energy Balance Snowmelt Estimates - Washington National Airport (DCA). Total Snowmelt is 4.8 inches (121 mm).

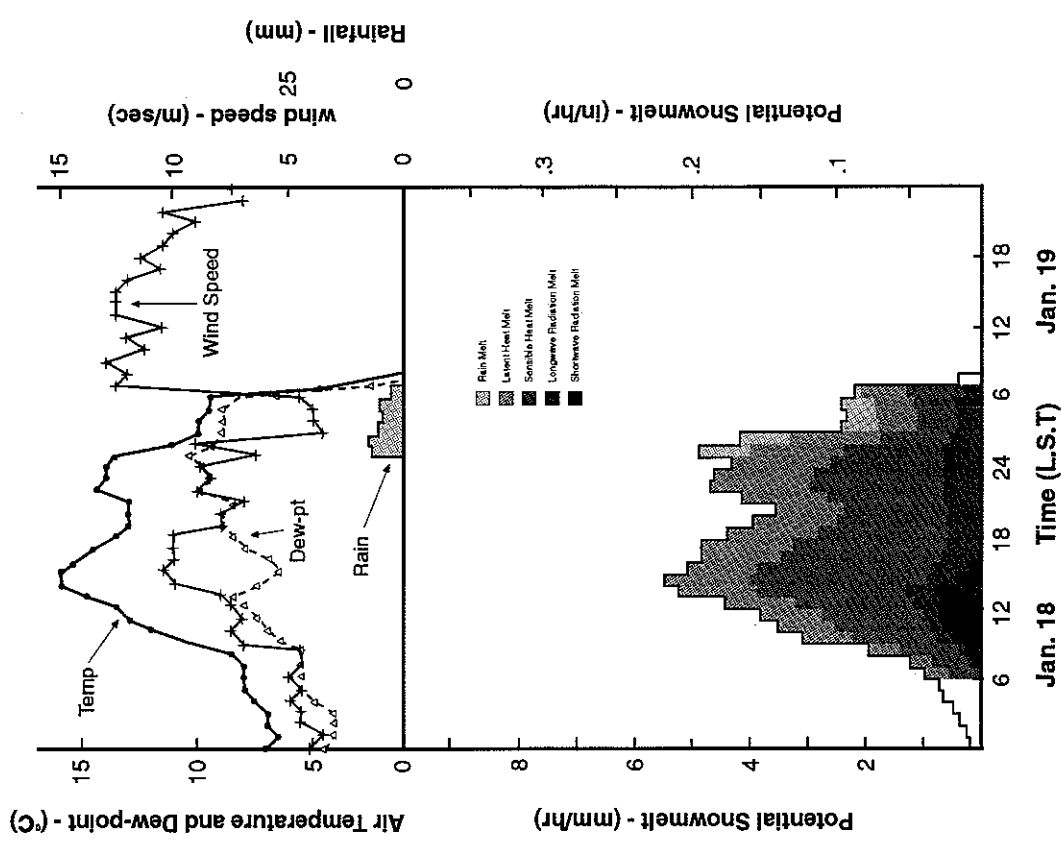


Figure 3d - Energy Balance Snowmelt Estimates - Pittsburgh International Airport (PIT). Total Snowmelt is 3.8 inches (96 mm).

cm) during the intense snowmelt period. No water-equivalent measurements were available at the site. The drop in depth is reasonably consistent with the computed melt. Above the COE projects, changes in water equivalent of 3 inches (75 mm) to 5 inches (125 mm) were typical at open sites lending further evidence that the computed melt rates shown in Figure 3 are realistic for this event.

The energy budget computations of snowmelt indicate that at these open sites the total potential melt ranged from about 65 to 125 mm during the flood period. Melt rates of this magnitude are quite rare, especially in the middle of the winter. For example, the maximum daily melt computed at the NOAA snow research station (Anderson 1976) over a 7-year period from 1969 to 1975 was just over 40 mm. This value occurred on a sunny day in late April. Snowmelt during this event for areas that were protected from the high winds out of the south, such as forested areas and locations north of wind barriers, would be less. Most of the stations that are east of the Appalachian crest had similar melt patterns. Generally there was a period of low melt rates during the day on the January 18, with a rapid increase in snowmelt late in the evening as the temperatures, and especially the wind speed, increased dramatically. The exception was the northeastern part of the area, represented by Binghamton, where melt rates in excess of 2 mm/hr began in the late morning of the 18th and continued throughout the afternoon and into the evening due to more moderate winds and temperatures. This resulted in more total melt at Binghamton than at other sites in the central and northern parts of the area. West of the divide, there was considerable snowmelt occurring throughout the day and into the evening on the 18th, in addition to the high rates overnight.

#### **SNOW COVER AFTER THE EVENT**

Even with the very high snowmelt rates that occurred during the flood event, there was still significant snow remaining after the event over portions of the area, especially in western Maryland, much of Pennsylvania, northern New Jersey, and portions of New York. Figure 4 depicts an estimate of the water equivalent remaining after the flood event.

Again, this figure attempts to represent the general trend in water equivalents and not all the localized variations. Local variations were accentuated by the time the event was over due to local variability in melt rates. This figure utilizes data similar to that used to construct Figure 2. The relative geographical variation in melt rates depicted in Figure 3 was factored into the analysis, as was topography. The snow remaining after the event was very ripe with densities around 0.3 or greater. It was recognized that many of the depth reporting stations are in exposed locations which would have less snow than the surrounding area after a significant melt period. Especially valuable in constructing Figure 4 were the data from the Baltimore District COE. A survey was made shortly after the event on January 22 and 23. The difference between the average watershed water equivalents before and after the event, generally in the range of 35 to 75 mm, were very useful and given significant weight in the analysis. Runoff data from selected watersheds was also used to estimate the areal average snowmelt contributions. The mean areal rainfall was subtracted from the total runoff (including an estimate of the increase in baseflow storage) to get an estimate of the snowmelt contribution. A local snow network maintained by the Binghamton weather office provided much detail on snow conditions in that area. Again, satellite observations from the NOHRSC were used to define the areas with little or no snow cover. An effort was made not to include the light snow that occurred after the frontal passage on the January 19 in the western and northern parts of the area.

#### **SUMMARY**

Figure 5 contains an estimate of the total snowmelt contribution to the flood event. This figure was constructed by subtracting Figure 4 from Figure 2. Figure 5 indicates that, over the area of major flooding, snowmelt contributed about 40 mm to over 65 mm of water. This is very similar to the amount of rain that was measured.

In some parts of the area, the amount of available snow controlled the contribution. This was especially true in the upper Ohio River drainage, much of Virginia, along the eastern edge of the area, and in

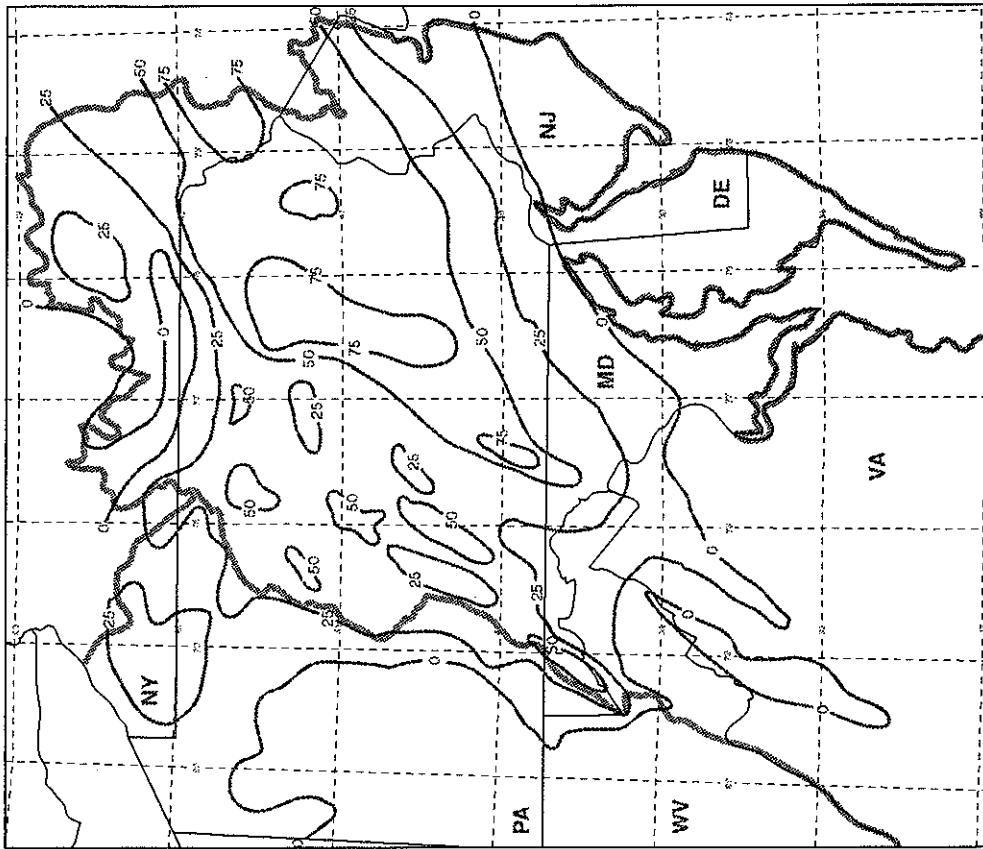


Figure 4 - Estimated Water Equivalent of the Snow Cover After the end of Melt (units are millimeters).

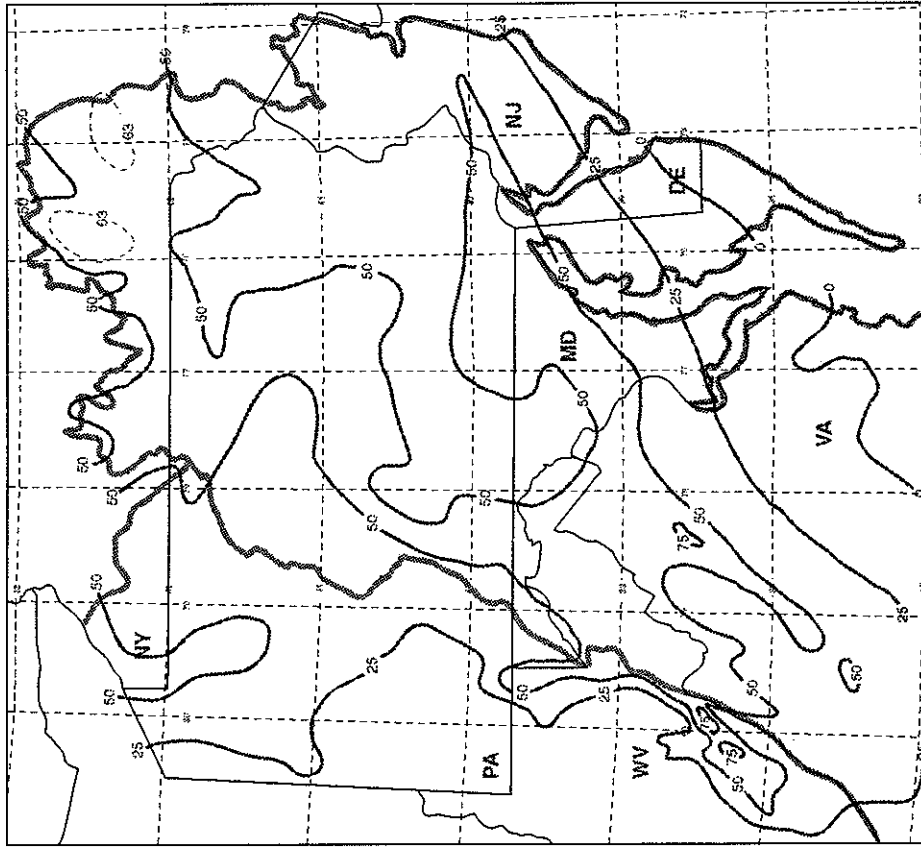


Figure 5 - Estimated Snowmelt Contribution to the Flood Event on January 18 and 19, 1996 (difference between figures 2 and 4) (units are millimeters).



portions of New York. Over the rest of the area, the snowmelt rates during the event determined the amount of water generated from the snow cover.

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