SECTION 2. METEOROLOGY AND PRECIPITATION

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SECTION 2. METEOROLOGY AND PRECIPITATION

2.1 Introduction

Precipitation and meteorological data are primary forcing functions in the Chesapeake Bay Phase 5.3 Community Watershed Model. Simulated flow and nonpoint source loads primarily depend on the continuous hourly input of precipitation, temperature, evaporation, and solar radiation. In addition, many reaction rates in the model such as denitrification, ammonia volatilization, and others are dependant on temperature inputs. Consequently, great care was used to develop the precipitation and meteorological database.

The Phase 5.3 Model uses a 20-year continuous time series of hourly precipitation data developed from a statistical analysis of rainfall data from observation at numerous measurement stations in the region (Hay et al. 1991, 2000a, 2000b). The complete time series of information on precipitation and meteorological data as applied in the Phase 5.3 Model from 1985 to 2005 is at the Chesapeake Community Modeling Program's (CCMP) Phase 5.3 data library on the web at http://ches.communitymodeling.org/models/CBPhase5/datalibrary.php.

2.2 HOURLY PRECIPITATION DATA

2.2.1 Development of a Precipitation Time Series

The foundation of any hydrological simulation is the input precipitation data. HSPF (Bicknell et al. 1997; 2001; Donigian et al. 1984; Johanson et al. 1980) uses an hourly time series of precipitation, and the Watershed Model requires continuous hourly input data for the 1984 to 2005 simulation. Developing decades of an hourly precipitation time series is a challenge. The decadal time frame of the simulated precipitation data and the ongoing addition of new years to the simulation produce gaps and other problems in the derived data record as new precipitation monitoring stations became operative and older stations are discontinued (Figure 2-1). A method for generating the Phase 5.3 precipitation data sets have to account for the changing spatial distribution of observed stations over the simulation period. To do that, a precipitation model was used to incorporate the greatest number of precipitation stations in each of the simulation years.

Lauren Hay of the U.S. Geological Survey (USGS) National Research Program has developed a methodology for estimating the spatial distribution of precipitation and other meteorological variables (Hay et al. 1991, 2000a, 2000b, 2006). Observed meteorological data of precipitation and temperature are interpolated across the Phase 5.3 domain by fitting a multiple regression equation that relates the observed data to latitude, longitude, and elevation. In the case of the Phase 5.3 Model, the Chesapeake Bay basin was divided into six subregions, and a separate regression equation was fitted by month for each subregion. The fitted equations were then interpolated onto a 5-kilometer (km) grid and then averaged over land-segments. That procedure was used to estimate both precipitation and temperature inputs.

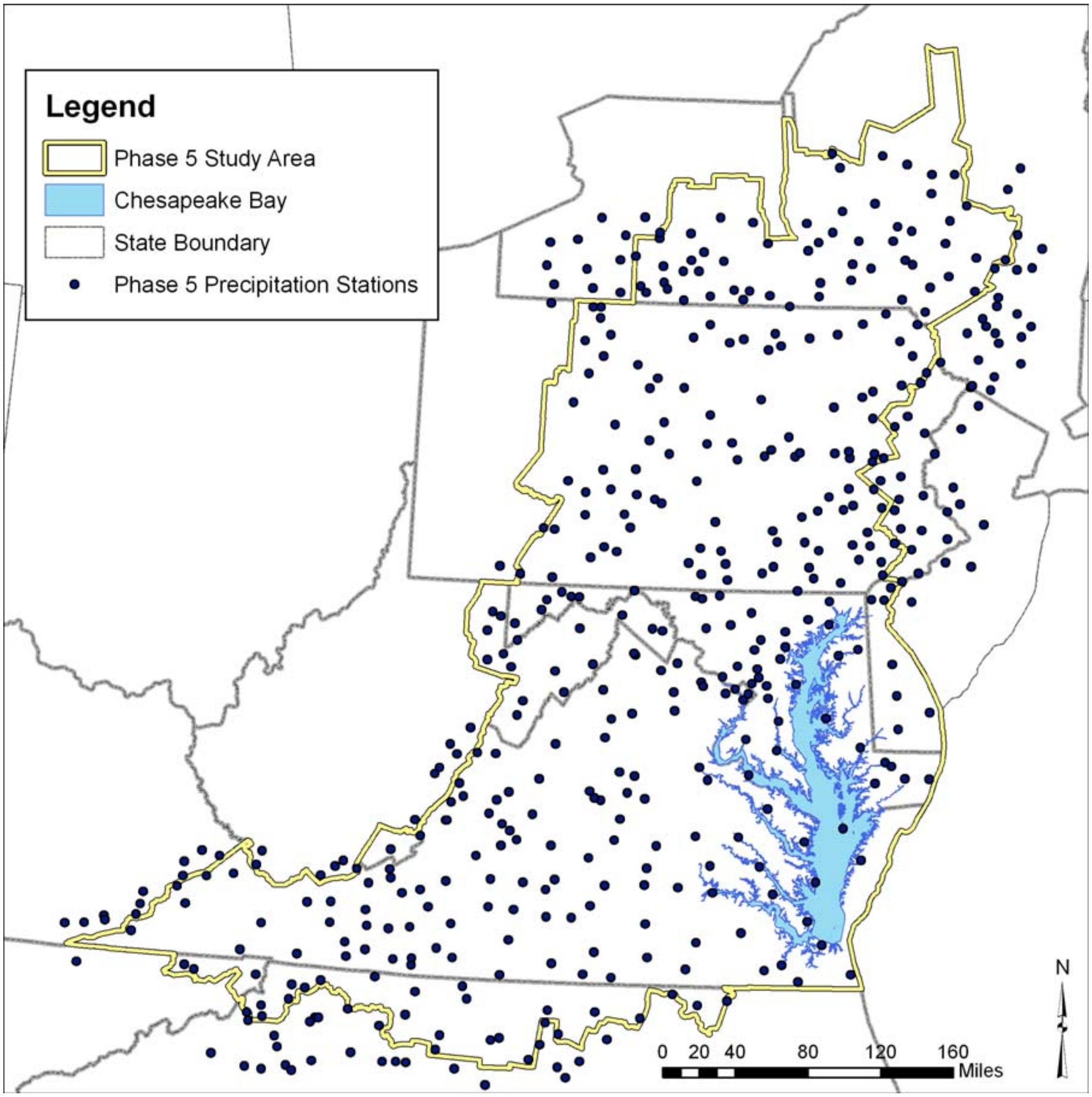


Figure 2-1. Daily and hourly precipitation stations used in the Phase 5.3 Watershed Model.

As the Next Generation Weather Radar (NEXRAD) or the North American Reanalysis continues to evolve and improve, future versions of the Watershed Model could use data from these sources for estimated precipitation inputs (Over et al. 2007, Mesinger et al. 2006).

2.2.2 Generation of Daily Rainfall Records

HSPF uses estimates of hourly precipitation and other meteorological variables for each model segment. To compute reliable estimates of these quantities, researchers at the USGS National Research Program in Denver have developed a method of interpolation of observed data across a basin to better represent basin climate variability. Significant physical factors affecting the spatial distribution of climate variables in a river basin are latitude (x), longitude (y), and elevation (z). In the method, multiple linear regression

(MLR) equations are developed for each dependent climate variable (e.g., precipitation) using the independent variables of x, y, and z from the climate stations. The general form of the MLR equation for daily precipitation (p) is

$$p = b_0 + b_1 x + b_2 y + b_3 z$$

The resulting fit from the above equation describes a plane in three-dimensional space with slopes b_1, b_2, and b_3 intersecting the p axis at b_0. Similar equations are used for temperature. Using the station latitude and longitude coordinates in the MLR provides information on the local-scale influences on the climate variables that are not related to elevation, for example, the distance to a topographic barrier. To account for physiographic and seasonal climate variations, MLR equations are developed for each month using mean values from a set of selected stations in and around each subregion. The Chesapeake Bay watershed and southwestern Virginia have been divided into six physiographic subregions for analysis (Figure 2-2). The monthly MLRs are computed to determine the regression surface that describes the spatial relations between the monthly dependent variables and the independent variables (x, y, and z). Note that for each month, the best MLR relation will not always include all the independent variables (i.e., in some months, latitude, longitude, or elevation might be unimportant to the regression).

To estimate daily precipitation for each land-segment, the following procedure was used: (1) mean daily precipitation (p) and corresponding mean latitude, longitude, and elevation (x, y, z) values from a selected station set (determined using an Exhaustive Search analysis) were used with the *slopes* (b_1, b_2, b_3) of the monthly MLR to compute a unique b_0 for that day; (2) the MLR equation was then solved using the x, y, z values of points on a 5-km grid; and (3) these gridded estimates were integrated over the land-segment area (land-segments are described in Section 3). The process used for the precipitation model is graphically represented in Figure 2-3.

2.2.3 Generation of Hourly Rainfall Records

The daily rainfall records were used to derive the daily volume of precipitation. The volume was then disaggregated to hourly values for the land-segment (usually a county) using a *nearest neighbor* approach applied to about 200 hourly precipitation observed stations across the Phase 5.3 domain. Although there were about 200 hourly stations in the two decades of the data set, usually only about 10 hourly stations would be working on any one day. For that reason, the search pattern had a wide cast to capture hourly stations to disaggregate the daily rainfall data.

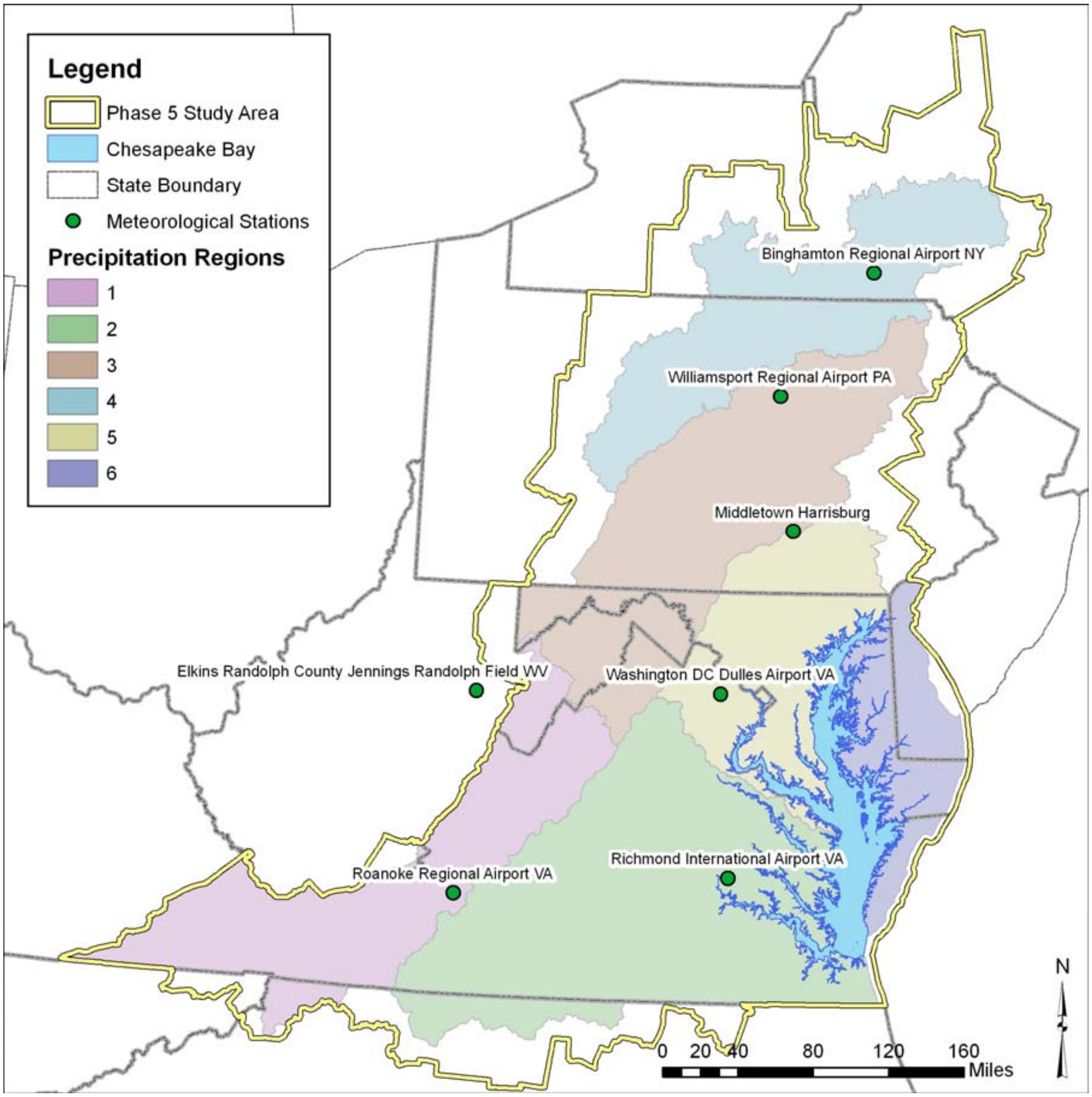


Figure 2-2. The six precipitation regions used to develop the monthly MLRs used in the precipitation model. The seven primary meteorological stations are also shown.

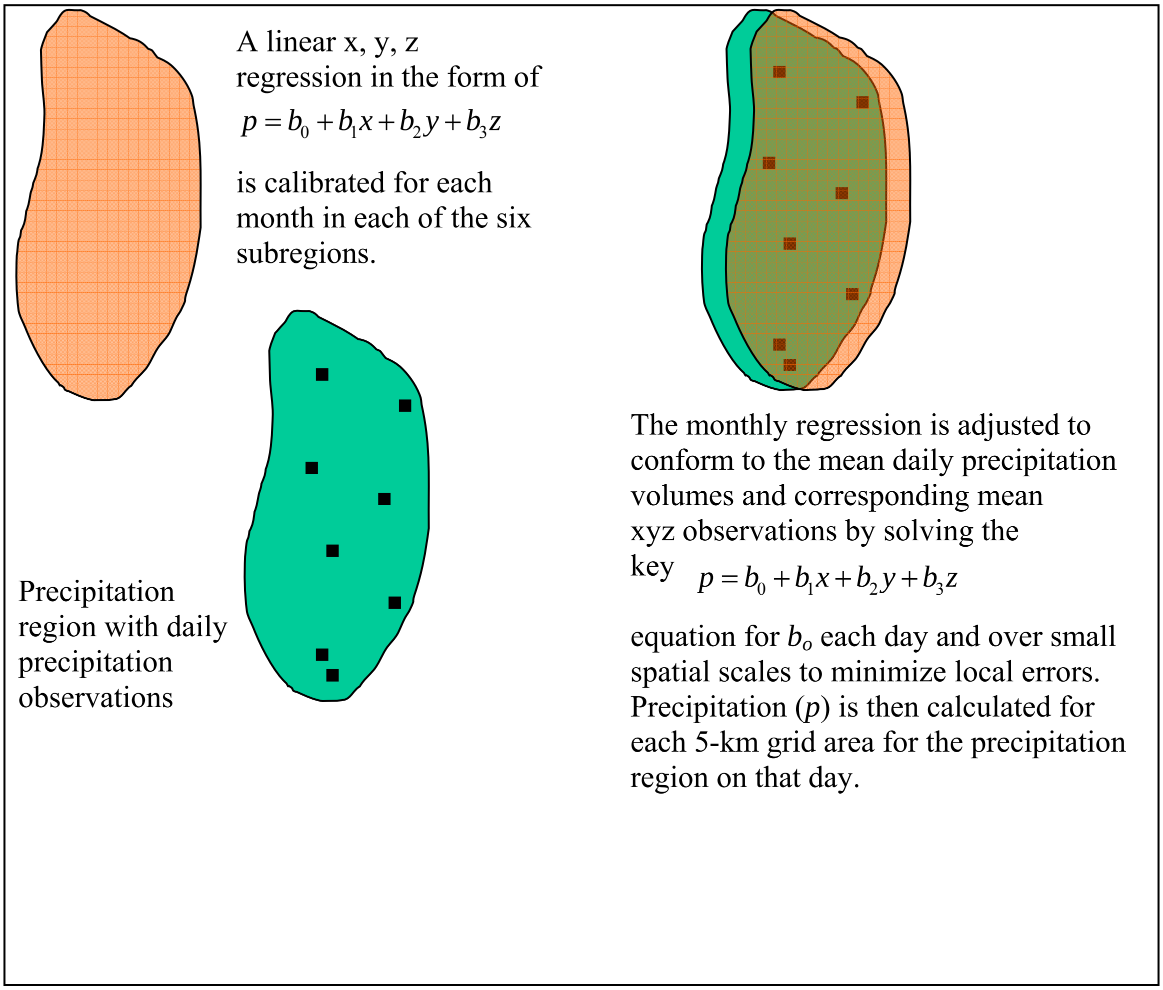


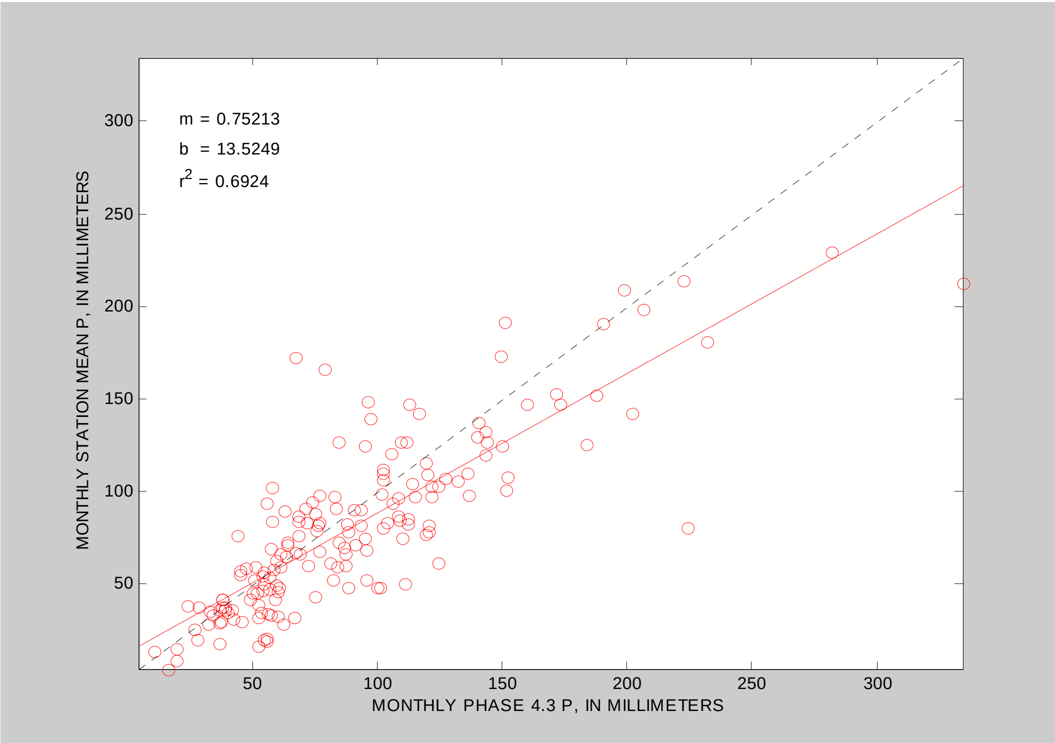
Figure 2-3. Graphical representation of the precipitation model.

In the final precipitation data for the hourly disaggregation of the daily precipitation stations, 57 percent of the stations were disaggregated using an hourly station 100 km from a daily station with the precipitation volume within 100 percent of calculated daily volume. Relaxing the distance constraint allowed an additional 26 percent of the daily stations to be disaggregated to hourly estimates. Relaxing both the distance and volume constraints allowed an additional 17 percent of the daily estimated precipitation estimates to be disaggregated. Finally, very few hourly stations (0.3 percent) were unresolved even with distance and volume constraints relaxed, and so disaggregation used daily values divided by 24.

2.2.4 Comparison of Simulated and Observed Rainfall and Potential Evapotranspiration

A compared the average monthly precipitation for all stations in a land-segment with estimated Phase 5.3 and Phase 4.3 monthly precipitation in that land-segment (Figure 2-4). Regression analysis indicated an improvement in estimation as reflected in r^2 values that increased from approximately 0.7 to values of about 0.96 from Phase 4.3 to Phase 5.3.

Hourly precipitation, temperature, and daily and potential evapotranspiration (PET) time series were converted to standard HSPF WDM files, and then annual summaries were prepared (Figures 2-5 and 2-6).



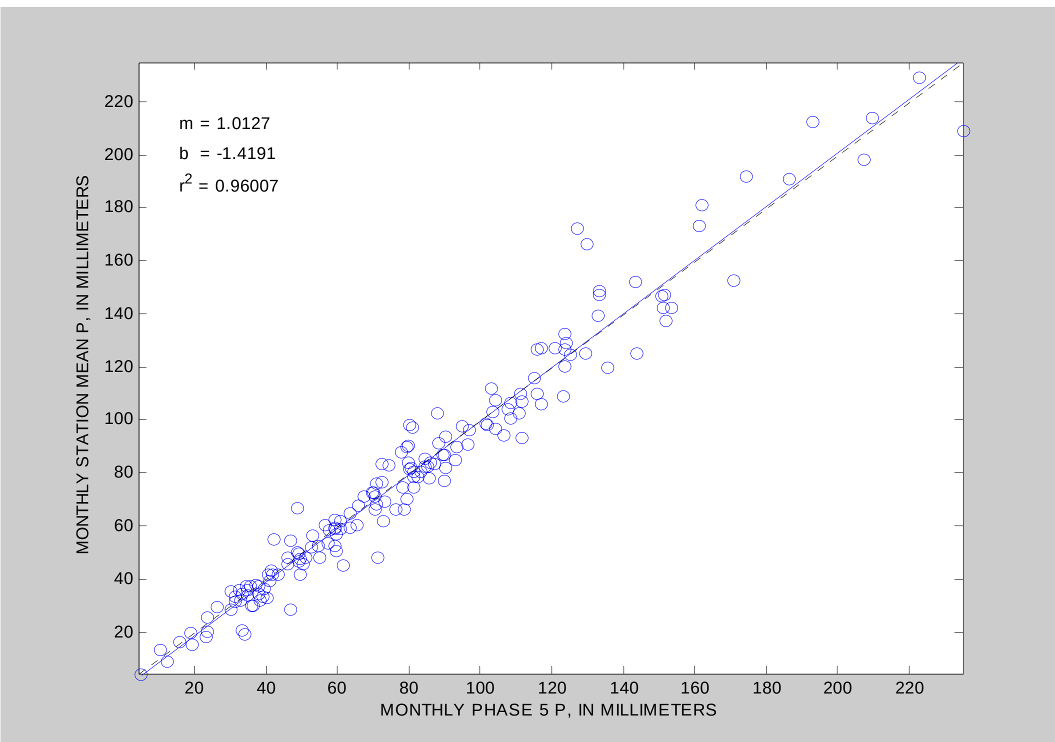


Figure 2-4. Monthly station precipitation plotted versus Phase 4.3 (top) and Phase 5.3 (bottom) estimates for a land-segment.

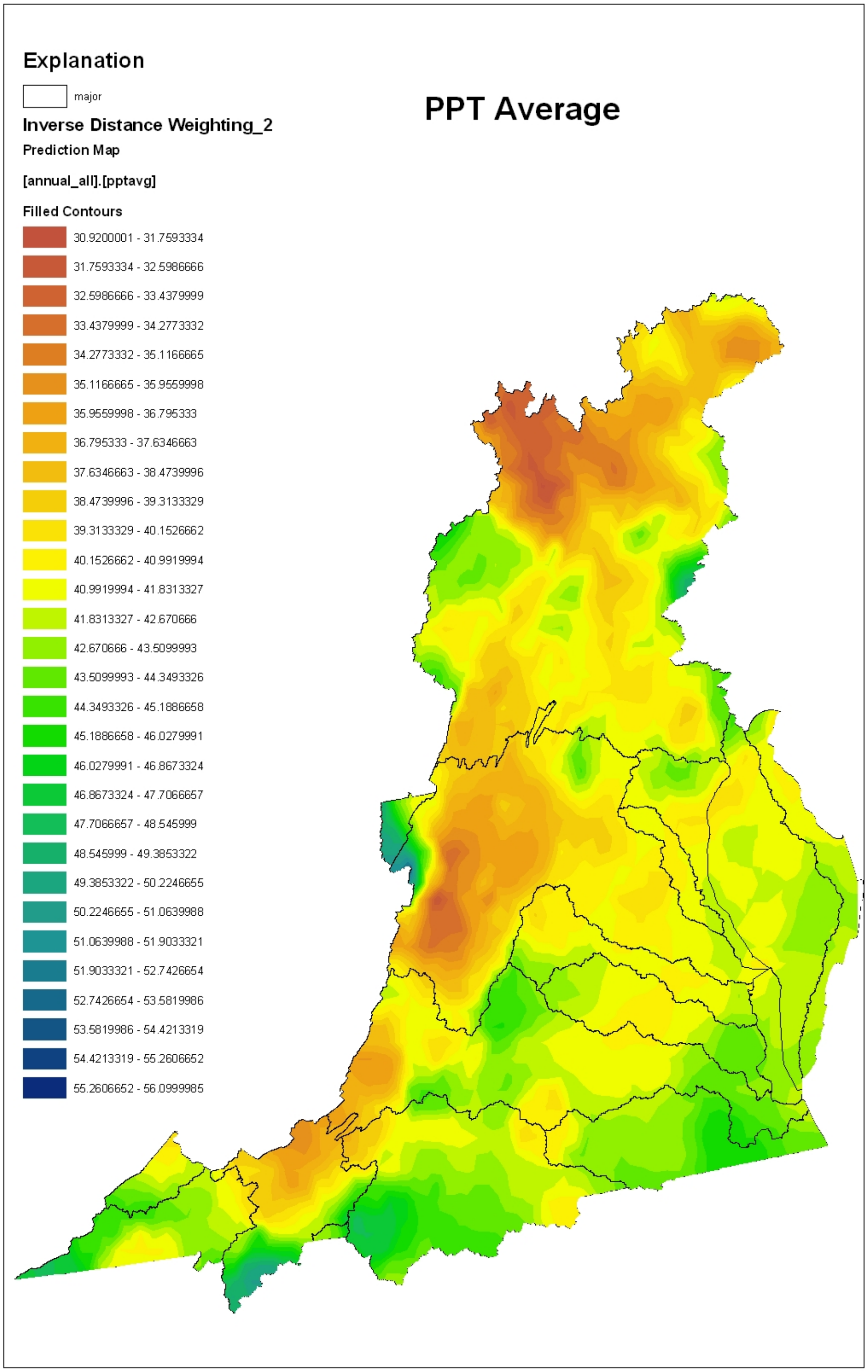


Figure 2-5. Modeled average annual precipitation, 1984–1999. Values are in inches.

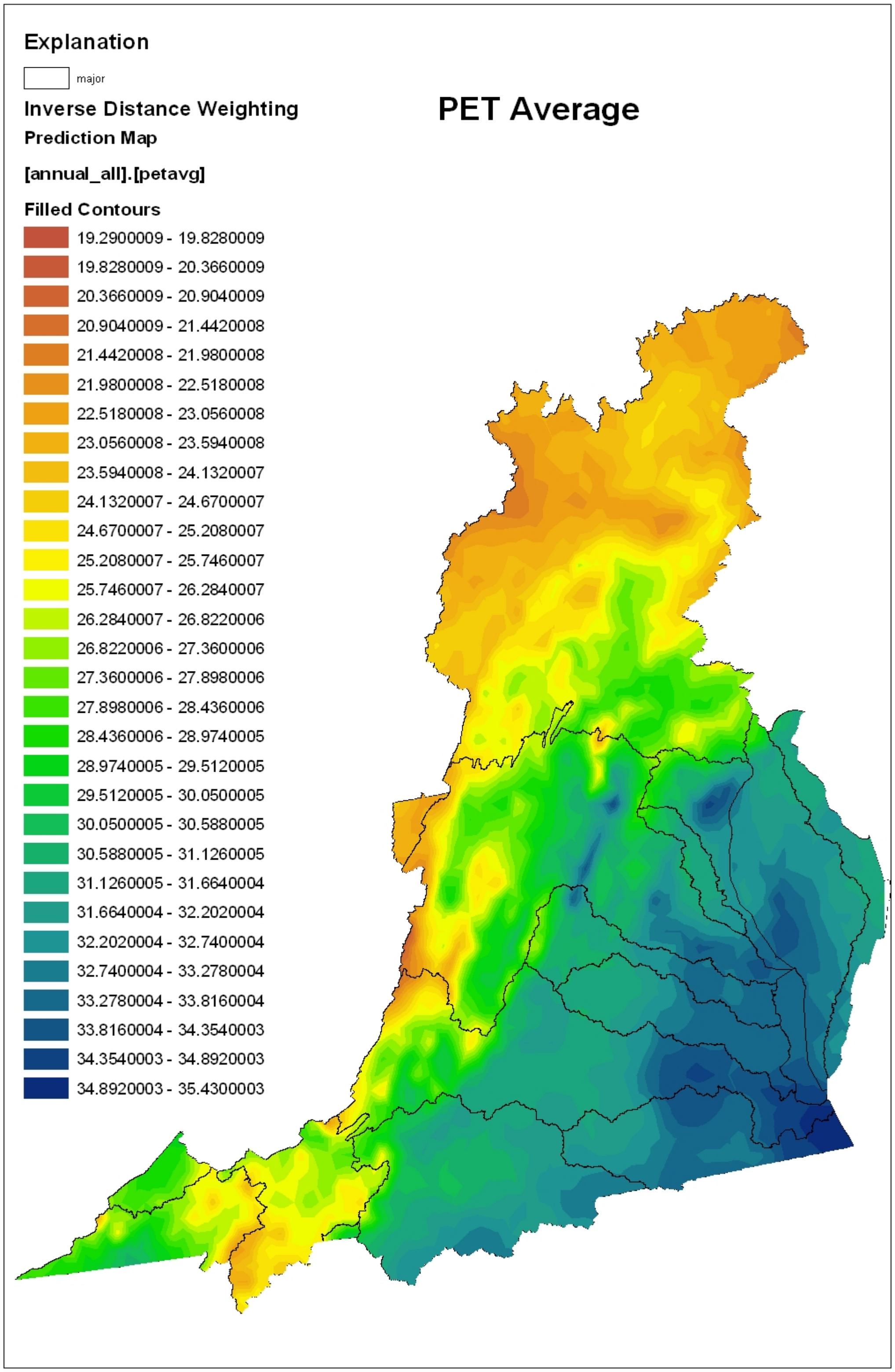


Figure 2-6. Modeled average annual PET, 1984–1999. Values are in inches.

2.3 Regional Meteorological Data

The hourly meteorological data in the Phase 5.3 Watershed Model include air temperature, wind speed, and solar radiation. Air temperature is modeled from observations from numerous stations (Figure 2-1) using a model similar to the precipitation model. Wind speed and solar radiation were compiled from observed meteorological data of daily average wind speed and daily cloud cover from sunrise to sunset taken at the seven primary meteorological stations available (Table 2-1). The National Oceanic and Atmospheric Administration's (NOAA's) Climatic Data Center provided the data (NOAA 2007).

The entire watershed is divided among the seven primary meteorological stations available for the entire 1985–2005 calibration period. The seven regions contained model segments that had the same input of meteorological information from a primary meteorological station that had relatively complete records over the entire simulation period. With the only exception of air temperature as noted above, the observed meteorological data from each station are directly applied to the entire Phase 5.3 region. Data gaps in the primary stations are filled by alternate stations or by an adjacent primary station if the data in the alternate station are also missing. The seven primary meteorological stations are Binghamton, New York; Williamsport, Pennsylvania; Harrisburg, Pennsylvania; Elkton, West Virginia; Dulles Airport, Virginia; Richmond, Virginia; and Roanoke, Virginia, as illustrated in Figure 2-1 and listed in Table 2-1. Table 2-1 also lists the alternate stations used to fill missing data in the primary stations.

Table 2-1. Stations used to develop 1984–2002 regional meteorological data

Region	Station	Location
1	04725	Binghamton, NY
2	14778	Williamsport, PA
3	14711	Middletown/Harrisburg, PA*
4	13729	Elkins, WV
5	93738	Dulles Airport, VA
6	13741	Roanoke, VA
7	13740	Richmond, VA
Alternative Stations		
1b**	14768	Rochester, NY
2b**	14777	Wilkes-Barre/Scranton, PA
7b**	13733	Lynchburg AP, VA

* Note: The Harrisburg, PA, station was used until 10/1/91. After 10/01/91 the Middletown, PA, station was used because the Harrisburg station data was unavailable.

** Note: The stations with the region number possessing the suffix 'b' were used as alternative stations to fill in any missing data for the corresponding primary stations.

Phase 5.3 uses 1984–2005 meteorological data input—an expansion of the Phase 4.3 meteorological database, which covered the period 1984–1997. The 1984 initial year is used as a *spinup* year needed to calculate appropriate initial conditions for 1985, the first year of reported model output. In the Phase 4.3 meteorological data development (1984–1997), slightly different methods were used in 1984–1991 and 1991–1997 because of upgrades in computer hardware and software (Wang et al. 1997). Various programs were used to develop the 1984–1991 Watershed Data Management (WDM) files (a file structure used in HSPF), whereas in the 1991–1997 WDM development, the program METCMP (USGS 1996; Flynn et al. 1995) was used. In all cases, the programs were designed for the same purpose and generated the same type of output.

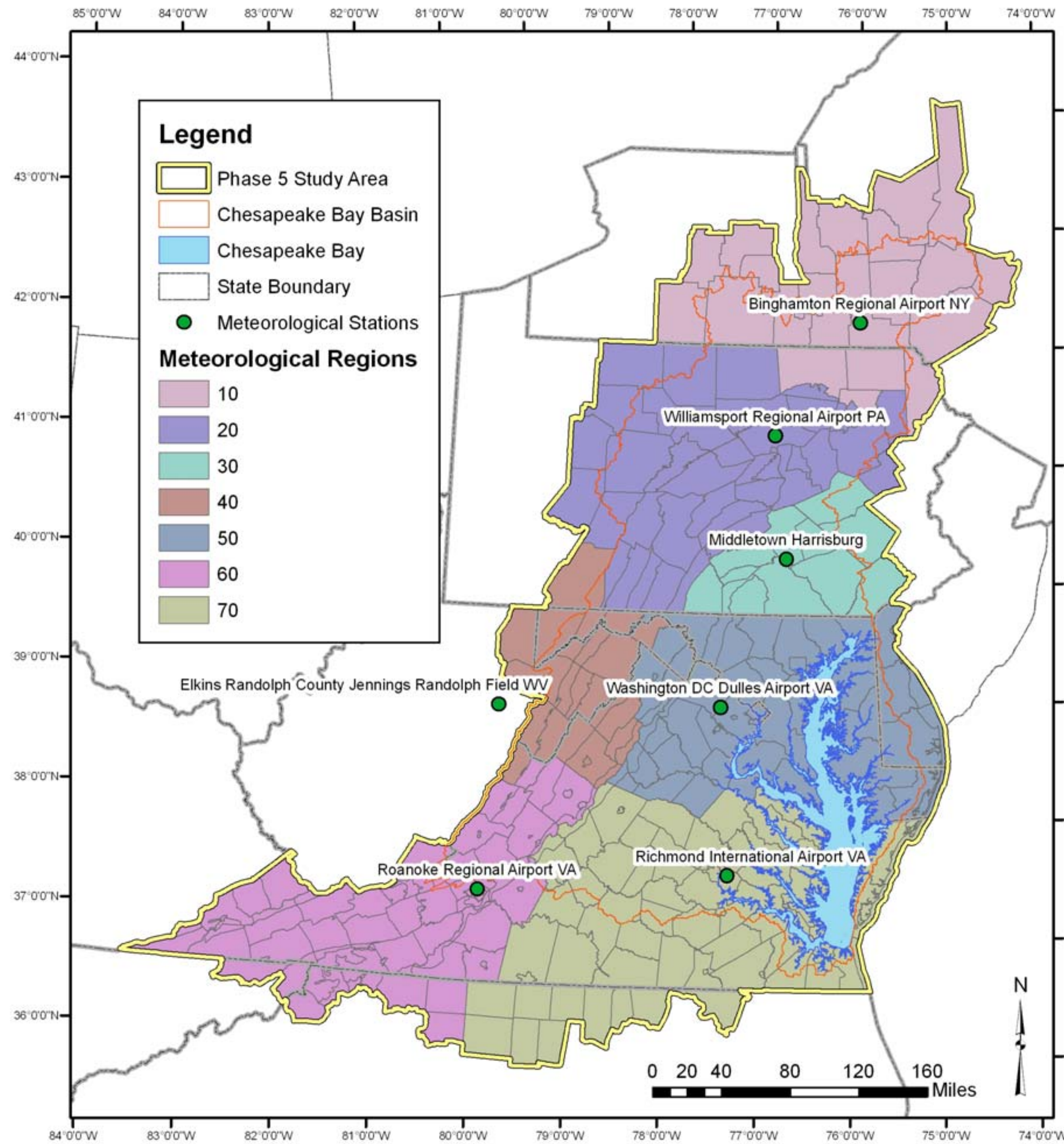


Figure 2-7. Map of regional meteorological stations and associated land-segments.

To assess comparability between the 1984–1991 and the 1991–1997 data, the overlapping 1991 year of data generated by the two different methods was evaluated. No significant differences were discerned in the 1991 data generated from the two methodologies. The two methodologies are consistent—most with less than 0.01 percent difference, although up to 1–2 percent difference in the monthly values summed from the daily data were observed. Those differences were due to the different methods in calculation, particularly for solar radiation.

The Phase 5.3 extension of 1998–2005 meteorological data development used the same method as for the 1991–1997 meteorological data developed in Phase 4.3, using USGS METCMP software (Wang et al. 1997).

2.3.1 Cloud Cover, Solar Radiation, Wind Speed, and Dewpoint Temperature

Cloud cover, solar radiation, dew point temperature, and wind speed are used in the snow pack simulation, particularly for snow sublimation and melting. Cloud cover is used to calculate solar radiation, which is then used to calculate light available for snow pack dynamics as well as for algal growth. Daily mean cloud cover data from sunrise to sunset are obtained from the NOAA Climatic Data Center. The daily mean cloud cover from sunrise to sunset, time, and latitude of the meteorological station are used to calculate hourly solar radiation. Daily mean dew point temperature data are collected directly from the NOAA Climatic Data Center.

METCMP disaggregates hourly wind speed from daily mean wind speed. The distribution in the 24 hours is based on the assumption of constant diurnal variation. The variation of the diurnal curve is assumed to be the highest at midday and lowest at midnight with a maximum ratio of about 1.7.

Solar radiation, wind speed, and dew point temperature are estimated on a county or land-segment level to be consistent with the Phase 5.3 land use calculations. Estimated Phase 5.3 solar radiation, wind speed, and dew point temperature data for all hours between 1984 and 2005 are available on the CBP Community Model Web site: http://ches.communitymodeling.org/models/CBPhase5/index.php

2.3.2 Potential Evapotranspiration

About half of the input precipitation in the mid-Atlantic region is lost to evapotranspiration. A first step in a hydrology calibration is to achieve an overall water balance as measured against long-term flow. That is done by adjusting PET.

Previous versions of the Watershed Model used the Penman method to calculate daily PET using daily mean maximum and minimum air temperatures, daily mean dew point temperature, daily mean wind speed, hourly solar radiation, and the station's latitude. Monthly correction factors were estimated by examining observed pan evaporation records. A drawback of that method is that the Penman method requires information such as wind speed and dewpoint temperatures, which were available from only the seven primary meteorological stations. Data from the seven primary meteorological stations had to be interpolated over the entire watershed, and the sparse evaporative pan data used for PET corrections, which was at different locations than the primary stations, also had to be spatially interpolated.

In Phase 5.3, a different approach was used because of the greater number of calibration stations available for flow. In Phase 4.3, only 20 calibration stations were used for flow, but the Phase 5.3 application increased that by more than an order of magnitude. For the Phase 5.3 effort, 237 calibration stations for flow in the Chesapeake watershed and 265 calibration stations in the entire Phase 5.3 domain were used. The increased number of calibration stations provided the opportunity to use the monitored flow as the integrated net result of precipitation and evapotranspiration, and thus provide a way to adjust by a simple factor the PET estimated by the Hamon method (Hamon et al. 1961) which uses only temperature as a data input in the following way:

Hamon (1963) Method (PET = *0 when* T < *0*)
$PET = 0.1651 \times Ld \times RHOSAT \times KPEC$
where
PET is the daily PET (mm)
Ld is the daytime length or time from sunrise to sunset in multiples of 12 hours
RHOSAT is the saturated vapor density (g/m^3) at the daily mean air temperature (*T*)

and where
$RHOSAT = 216.7 \times ESAT / (T + 273.3)$
$ESAT = 6.108 \times EXP(17.26939 \times T / (T + 237.3))$
T is the daily mean air temperature ($^\circ$C)
ESAT is the saturated vapor pressure (mb) at the given *T*
KPEC is the calibration coefficient

The Hamon method was used to calculate PET from interpolated temperature inputs. Then the annual water balance was examined by looking at the long-term average net difference between the simulated and monitored average flows. Using that, a factor was applied to the Hamon-calculated PET for all the model segments upstream of the monitoring station used to compare the simulated and observed flows and PET to get an estimate of the actual evapotranspiration (AET). For the model segments that drained directly to the tidal Chesapeake Bay and were unmonitored for flow, adjacent model segments were used to get PET correction factors.

An advantage of the Hamon method was that the daily temperature input to the Phase 5.3 segments were modeled on a 5 km grid which gave good spatial estimates of daily temperature for each model segment. Another advantage was the ease of changing evapotranspiration through the temperature alone, an advantage when using global climate model estimates as values like wind speed and dewpoint temperatures are either unavailable or highly uncertain. A comparison of six PET methods were examined in one study, and the Hamon method was recommended as suitable for the Chesapeake region (Lu et al. 2005).

2.4 Extreme Events

Two extreme high-flow events occurred during the 1985 to 2005 simulation period. Hurricane Juan occurred in November 1986 and the other, the *Big Melt,* on the Susquehanna, in January 1996. Both events generated 100-year flows capable of producing substantial water quality loads to the Chesapeake Bay. Juan caused 100-year flows in the Potomac and James rivers, and the January 1996 event caused 100-year flows in the Susquehanna River.

2.4.1 Hurricane Juan—November 1985

Hurricane Juan formed off Louisiana on October 28, 1985 (Figure 2-8). Once over land, Juan rapidly weakened and became extratropical storm over Tennessee on November 1. Remnants of the hurricane combined with a low-pressure system moving in from the west and further combined with a stalled system over the Appalachian Mountains. The resultant moisture-laden weather system caused severe flooding in large areas of West Virginia and Virginia, and significant flooding in parts of Maryland and Pennsylvania (NOAA 1985). New maximum discharges were recorded at 63 streamflow-gaging stations, all exceeding 100-year recurrence intervals. Although the storm was a 100-year storm for the Potomac and James rivers, it had little effect in other Chesapeake western tributaries, including the Patuxent, Rappahannock, and York rivers. Flooding in West Virginia was the worst in the state's history. Some of the largest impacts occurred in the South Branch Potomac River.

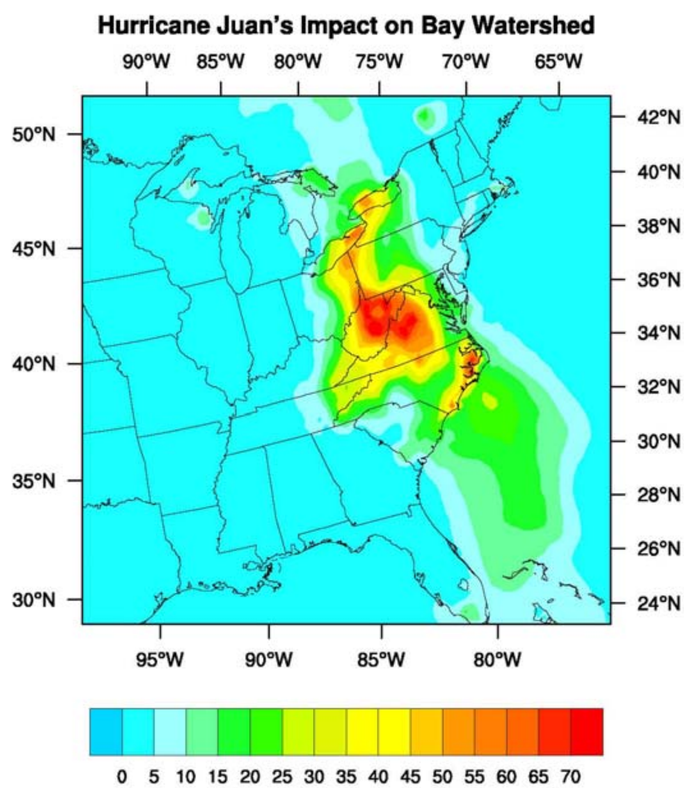


Figure 2-8. Remnants of Hurricane Juan, November 4, 1985, shown as total precipitation (mm) from North American Regional Reanalysis (Mesinger et al. 2006).

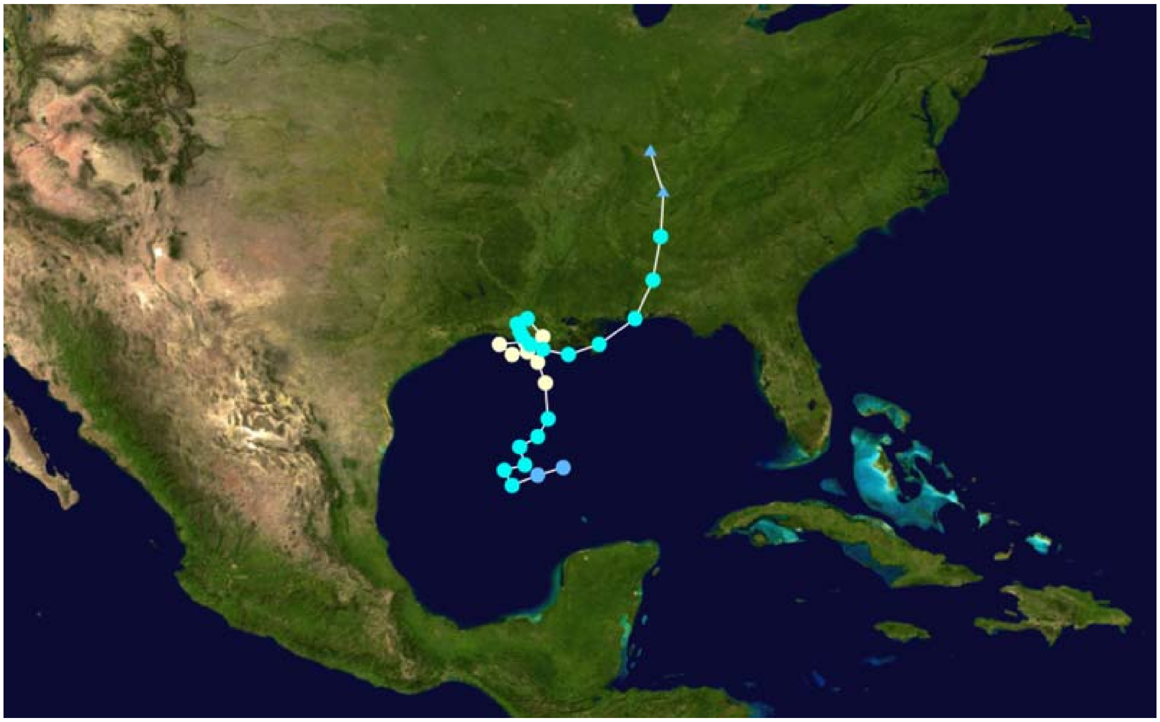


Figure 2-9. Hurricane Juan's track.

The previous Phase 4.3 version of the Watershed Model had only about half the simulated flow that should have been calculated for this storm, so the precipitation records were examined. Precipitation stations were found that either went offline or gave strange results, i.e., zero inches or hundreds of inches in a day. That problem was resolved by using the average of surrounding stations with complete records of the storm to fill in the missing data. The fix was applied to about a week or so of the precipitation record, and it gave what was needed to capture the 100-year storms in the Potomac and James rivers.

2.4.2 The Susquehanna Big Melt—January 1996

Sediment loads delivered to the Chesapeake in a few days by extreme storms can be comparable to annual average sediment loads. An example is the June 1972 event of Hurricane Agnes (CRC 1976). Thought to be a key event in the long-term degradation of the Chesapeake SAV resource, "…all [SAV] decreased significantly through 1973…eelgrass decreased the most (89 percent)…For all species combined, the decrease was 67 percent."

A flood of similar proportions occurred in January 1996, which led to flooding on the same scale as Hurricane Agnes because of a period of warmer weather and extensive rain on snowpack, as well as the formation and subsequent breaching of an ice dam. Precipitation over the entire Susquehanna Basin was above average for January, with the upper portion of the basin receiving more than 75 percent above normal. Snowpack over the upper portion of the basin through January 12 averaged 8 to 10 inches. Mild temperatures, combined with a precipitation event of 0.75 to 1.50 inches, caused the

January 1996 flood event (SRBC 2006). The event had flows and sediment loads comparable to Hurricane Agnes. The June 1972 Agnes event delivered an estimated 30 million MT (metric tons), and the January 1996 event delivered 10 million MT of silts and clays, each over a period of days compared to an annual-average, fine-grain sediment load of about 1 million MT for the Susquehanna.

2.5 Community Model Data Sharing of Phase 5.3 Meteorological Data

For model practitioners interested in using the Phase 5.3 data, the meteorological and precipitation data for all hours between 1984 and 2005 are available on the CBP Community Model Web site http://ches.communitymodeling.org/. Phase 5.3 precipitation is estimated to approximately a county or land-segment level to be consistent with the Phase 5.3 land use calculations as described in Section 3.

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