

David A. Robinson*
Rutgers University, Piscataway, New Jersey

1. INTRODUCTION

After ravaging portions of the Bahamas and dropping extremely heavy rain on already saturated ground in eastern North Carolina, Hurricane Floyd unleashed torrential rains on central and northern New Jersey on September 16, 1999. This led to record flooding within several NJ river systems, including the Raritan basin, where rivers crested at as much as 4.3 meters (14 feet) above flood stage, 1.4 m above the previous record crest in 1971. Thousands of individuals were evacuated from homes that had water up to the second floor, business districts were severely damaged, and a water plant serving over a 500,000 people was inundated and put out of service for a week.

This paper will focus on the distribution and amount of rainfall observed across the Garden State from Floyd. Maps and a table of Floyd rainfall, using observations from close to 200 stations will be shown, with particular attention paid to the Raritan basin in the central portion of the state. Floyd rainfall will be compared with totals from Tropical Storm Doria in 1971. This comparison is of interest to hydrologists, local authorities, business owners, and residents, as attempts are made to determine whether the September 1999 flood exceeded the 1971 event due to: 1) Floyd having more rainfall, 2) Floyd rains falling over a shorter period, 3) considerable suburban development in the Raritan basin over the past several decades influencing the timing and quantity of runoff, or 4) a combination of the above.

This investigation is part of "The Great Raritan Flood Project", an interdisciplinary effort being conducted by students, faculty and staff in the Rutgers University Department of Geography. Other Project contributors are exploring the hydrologic data in greater detail, investigating property losses and populations that suffered the greatest losses, and evaluating the warning, response and recovery aspects of the devastating flooding.

2. FLOYD ON THE MOVE

Floyd was an extremely powerful hurricane with sustained winds of 250 km/hr (155 mph) as it moved through the subtropical Atlantic. It began to weaken as it approached the Southeastern US coast, but still had winds of over 160 km/hr (100 mph). After brushing the Southeast coast and dumping heavy rains on an already saturated eastern North Carolina, Floyd

continued to parallel the eastern US coastline as it moved north. Late on September 15, well in advance of the core of the storm, rains associated with Floyd began to fall in New Jersey. Isolated areas of central NJ picked up as much as an inch of rain earlier on the 15th from an approaching frontal system. These two systems were about to combine to unleash torrential rains in the Middle Atlantic.

By the morning of the 16th, with Floyd still a hurricane and near the mouth of the Chesapeake Bay, heavy rains began to fall in New Jersey. At this time, the frontal system stalled on a line from the northern Delmarva through southeastern Pennsylvania, into central NJ and across northeastern NJ counties into southeastern New York. This front served to enhance the rainfall in the western and northern counties of NJ, particularly for 25 km (15 miles) on either side of a northeast trending line from the intersection of Mercer, Hunterdon and Somerset counties in west central NJ, across western and northern Somerset County, along the borders of Morris County with Union, Essex and Passaic counties, and into northwestern Bergen County (cf. figure 1 for county locations). As the warm 20-25°C saturated air (surface air temperature) driven in from the ocean by Floyd ran into an atmospheric wall of 15°C air along and to the northwest of the front heavy rainfall was enhanced. This worst case scenario for heavy regional rain remained nearly stationary for upwards of 12 hours, producing prodigious rainfall totals, some exceeding projections of daily rainfall expected in New Jersey once every 100 years.

Floyd remained a hurricane until late afternoon on the 16th, and was downgraded to a tropical storm just before reaching the off shore waters near Cape May. The eye of Tropical Storm Floyd passed within about 10 miles of the south Jersey coast and by early evening made landfall in western Long Island. By that time the heaviest of the rains were over in New Jersey.

3. PRECIPITATION OBSERVATIONS

Observations from 205 automated and manually read precipitation gauges situated at 191 stations throughout NJ (some sites had multiple gauges) have been assembled to evaluate the distribution of precipitation associated with Floyd. Most observations were made by volunteer observers who belong to one or more of several networks across the state, including the National Weather Service's Cooperative Network, the Office of the State Climatologist's NJ Home Network, and the NOAA Geophysical Fluid Dynamics Laboratory Network (west-central NJ). Data from National Weather Service automated gauges at airports and along some streams and rivers are also used in the evaluation.

*Corresponding author address: David A. Robinson, New Jersey State Climatologist, Rutgers University, Department of Geography, Piscataway, NJ 08854; e-mail: drobins@rci.rutgers.edu

Most of the rainfall reports from the mid September event are of a high quality, however following an assessment conducted in cooperation with hydrologists Walter Nickelsberg of the National Weather Service and Robert Schopp of the U.S. Geological Survey, some suspect observations have been set aside (the author is solely responsible for the final selection of data used in this paper). This evaluation included comparing collocated observations, those at nearby sites, and station observations with radar estimates of storm totals. For instance, nearby station reports and a radar estimate suggest that a 130 mm (5.10") observation at the Long Valley (Morris County) Cooperative Observing Station (manual observation) is about 75 mm too low. An automated gauge in Somerville (Somerset County) recorded 321 mm (12.64"), while 15 other observations (manual and electronic) within about 10 km (6 miles) of the station observed between 183 and 245 mm. The larger figure and the Long Valley observation have been excluded from this study. A final example considers the Little Falls observing site in Passaic County. Two electronic gauges are collocated with a manual gauge (NWS Cooperative station). The two electronic instruments recorded 292 mm (11.50") and 302 mm (11.89") during the event, while the manual observation was 359 mm (14.13"). A relatively nearby NWS Spotter (manual observation) reported 367 mm (14.45"), suggesting that the 359 mm reading may be legitimate. Therefore, while additional research of the three Little Falls observations is necessary, none of these observations were eliminated from this study. It also bears mention that totals for collocated or closely located instruments often showed close agreement. These examples illustrate the benefits gained from having a dense network of surface observations and the availability of radar estimates in order to gain the most accurate depiction of the magnitude and spatial distribution of storm values. They also demonstrate the danger in relying on one or only several observations. In total, 197 observations from 183 stations are considered of a sufficient quality for the precipitation analysis in the following section.

4. STORM PRECIPITATION

At least one station in 12 of New Jersey's 21 counties reported over 203 mm (8") of rain from Floyd, with at least two sites in seven of these counties accumulating over 254 mm (10") (figure 1, table 1). The extreme southeastern portion of NJ received from 51-102 mm (2-4") of rain from Floyd. Moving northwestward, totals climbed slowly, reaching over 150 mm by the NJ Turnpike, which runs from the southwestern to northeastern corner of the state. Further northwest, along the line of heaviest rain, totals were in the 200-250 mm range with some higher values, five stations exceeding 279 mm (11"). The heaviest totals were measured along the Sourland and Watchung mountains, where the influx of moisture from the southeast first ran into terrain that is at least 100 m above the coastal plain. This may have enhanced the rainfall somewhat, though the previously mentioned

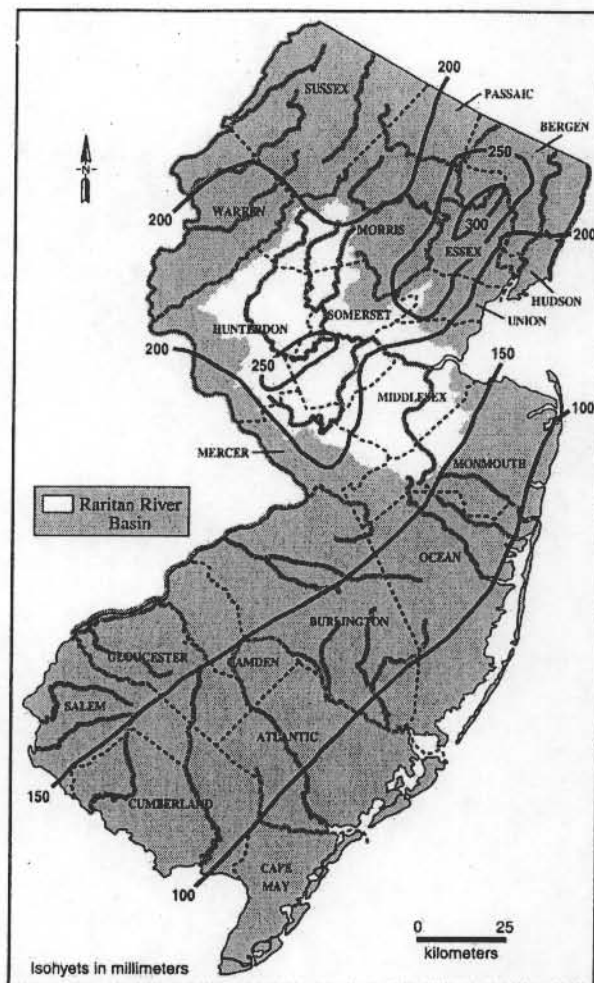


Figure 1. Distribution of precipitation across New Jersey associated with Hurricane Floyd: September 15-16, 1999. Based on an evaluation of 197 observations.

frontal mechanism was clearly most important. Heavy rains also fell in northwestern NJ, running in the 180-230 mm range in Warren County and tapering to 130-180 mm in most of Sussex County. National Weather Service radar-derived estimates of rainfall are spatially quite similar to the gauge measurements. However they appear to be 25 mm, perhaps locally more than 50 mm, too high in the zone of heaviest rain. Further study is needed to understand these differences.

Within the Raritan basin, 200-250 mm, with locally as much as 280 mm, fell in the western two thirds (headwaters) of the basin (figure 2). The eastern third saw 150-200 mm. Prior to Floyd, the flood of record in the Raritan basin resulted from rains associated with Tropical Storm Doria on August 27-28, 1971. An

Table 1. Stations where more than 250 mm of rain fell (Pcp) from Floyd (9/15-16, 1999: the vast majority falling on 9/16)

Station	County	Pcp (mm)
Franklin Lakes	Bergen	271
West Paterson	Bergen	279
Woodcliff Lake	Bergen	259
Caldwell	Essex	259
Canoe Brook	Essex	255
Cedar Grove	Essex	302
Essex Fells	Essex	271
Maplewood	Essex	363
Verona	Essex	276
East Amwell	Hunterdon	254
Wertsville	Hunterdon	254
Chatham Township	Morris	264
Gillette	Morris	255
Lincoln Park	Morris	255
Millington	Morris	267
Pequanock	Morris	271
Garrett Mountain	Passaic	275
Hawthorne	Passaic	266
Little Falls	Passaic	359
Pompton Lakes	Passaic	367
Wayne	Passaic	273
Wayne	Passaic	307
Neshanic	Somerset	255
Neshanic Station	Somerset	260
Cranford	Union	275
Plainfield	Union	256

evaluation of rainfall from this event shows that statewide, more rain fell during Doria than Floyd, however an area of rainfall approaching or exceeding 250 mm was not observed in 1971. Of the 67 Doria station observations, only two exceeded that amount. Still, 15 counties had at least one station with more than 203 mm (8").

Doria rains amounted to 200-254 mm in the eastern third (downstream portion) of the Raritan basin, and 180-250 fell in the western two thirds (figure 2). With fewer station observations available in 1971 than in 1999, particularly in the headwater regions of the basin, and radars from the former era unable to estimate precipitation totals, uncertainties arise as to how much rain fell in Doria. However it appears that rainfall in the headwater regions was 25-50 mm greater during Floyd than Doria. The bulk of the rainfall from both systems fell within a 24 hour interval, though it appears that Floyd's heaviest rains fell in a more concentrated 12 hour interval.

5. DISCUSSION

After experiencing the second driest early-middle growing season of the century (April-July statewide precipitation was 229 mm (9.02"), some 181 mm (7.14") below normal), New Jersey had received close to average rainfall from mid August to mid September. The state remained in a Drought Emergency as Floyd arrived (in fact the author attended a drought meeting at the Department of Environmental Protection the morning of the storm). This was lifted shortly after the event, as reservoir levels in central and northern NJ rose from 11% below the seasonal average to 11%



Figure 2. Precipitation observations within the Raritan basin associated with Hurricane Floyd: September 15-16, 1999 (black boxes) and Tropical Storm Doria (8/27-28, 1971) (white boxes).

above average in a week (average mid-September capacity: 71%). Higher river levels prior to Floyd would have exacerbated flooding somewhat, and it is certain that flooding would have been worse in the Passaic River basin of northern NJ had a series of reservoirs not retained a considerable amount of the runoff from upstream portions of the basin.

The Raritan River crested at 12.8 m (42.1') in Bound Brook, some 4.3 m (14.1') above flood stage and 1.4 m (4.6') above the previous record crest during Doria in August 1971. A land use assessment is needed within the Raritan basin to determine the impact development has had on the delivery of precipitation to the streams and rivers of the basin over the past 30 years. It is possible that the higher flood levels associated with Floyd compared to Doria in 1971 are in part the result of the partial conversion of farmland to residential and commercial developments.

6. CONCLUSIONS

Flooding associated with Hurricane Floyd will go down as one of the worst natural events of the 20th century in central and northeastern NJ. In New Jersey, 6 deaths, numerous dangerous rescues, approximately 25,000 evacuees, and damage of close to \$1 billion resulted from Floyd (Storm Data, NOAA: September 1999). The situation would likely have been worse, particularly in the Passaic basin, had an extended period of drought not preceded the event. Rainfall of over 203 mm fell in 12 counties, and at least two sites in seven of these counties accumulated over 254 mm, as copious moisture from Floyd collided with a stationary

frontal system draped across central and northern portions of the state. This amounted to over 20% of the mean annual precipitation in some areas and contributed greatly to statewide 1999 precipitation exceeding normal by 76 mm (3.00"), despite 7 months having below average precipitation (5 of these months with less than 75% of normal precipitation). Perhaps the only bright side of Floyd was the impact on reservoir levels, with a rebound from levels 11% below to 11% above the seasonal average. Further investigation is needed to determine the impact that development in the Raritan basin (and basins with severe flooding elsewhere in the state) may have had in making this flood worse than the previous flood of record in 1971. However, observations suggest that more rain fell in the headwaters of the basin during Floyd and in a shorter interval, thus a combination of natural and anthropogenic forcings likely led to greater flooding.

7. ACKNOWLEDGMENTS

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