New Jersey Geological Survey

Open-File Report 08-1

Ground-Water Recharge in the New Jersey Highlands Region

New Jersey Department of Environmental Protection

Land Use Management

STATE OF NEW JERSEY
Jon S. Corzine, *Governor*

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Karl Muessig, *State Geologist*

NEW JERSEY DEPARTMENT OF ENVIRONMENTAL PROTECTION

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Ground-Water Recharge in the New Jersey Highlands Region

by

Jeffrey L. Hoffman and Mark A. French

New Jersey Department of Environmental Protection
Land Use Management
Geological Survey
PO Box 427
Trenton, NJ 08625

2008

Conversion Factors

Multiply inch-pound units	by	to obtain metric (SI) units	Multiply inch-pound units	by	to obtain metric (SI) units
Volume			**Flow Rate**		
cubic inches (in^3)	16.39	cubic centimeters (cm^3)	million gallons/ day (mgd)	0.04381	cubic meters/second (m^3/s)
cubic feet (ft3)	0.02832	cubic meters (m^3)	cubic feet per second (cfs)	2,447	cubic meters/day (m3/d)
gallons (gal)	3.785	liters (L)	million gallons/ year (mgy)	3,785	cubic meters/year (m^3/y)
gallons (gal)	$3.785X10^{-3}$	cubic meters (m^3)	gallons/minute (gpm)	0.06309	liters/second (L/s)

Note: In this report 1 billion = 1,000 million; 1 trillion = 1,000 billion

The rain is plenteous but, by God's decree,
Only a third is meant for you and me;
Two-thirds are taken by the growing things
Or vanish Heavenward on vapour's wings:
Nor does it mathematically fall
With social equity on one and all.
The population's habit is to grow
In every region where the water's low:
Nature is blamed for failings that are Man's,
And well-run rivers have to change their plans.

— Sir Alan Herbert, *Water*

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ABSTRACT

The Highlands of New Jersey currently supplies a third of the State's drinking water. For over a century runoff from this area has been the primary source of water for the major population centers of northeastern New Jersey. The Highlands Water Protection and Planning Act of 2004 defines the 'Highlands Region' and calls for significant restrictions on new development in order to protect its water resources.

One factor that controls water resources is the amount of recharge that occurs in the Highlands Region. This recharge helps to define the carrying capacity, that is, how many inhabitants the region can support on a sustainable basis.

The New Jersey Geological Survey's methodology of estimating ground-water is based on an average annual soil-moisture budget for the period 1957-1986. Applying this methodology to the Highlands Region yields an average annual ground-water recharge of 14.6 inches per year. Applying this methodology to the drought of record in New Jersey, the period 1961-1966, gives an estimated drought ground-water recharge of 9.8 inches per year.

Four major watersheds drain the Highlands Region - Delaware, Passaic, Raritan and Wallkill. Average annual ground-water recharge estimates for these four watersheds are 14.1, 14.3, 16.3 and 13.8 inches per year, respectively. Drought annual ground-water recharge estimates for these four watersheds are 9.2, 10.2, 10.4 and 9.4 inches per year, respectively.

INTRODUCTION

Since the 19th century, the New Jersey Highlands have been recognized as an important source of drinking water. In 1894, the New Jersey Geological Survey noted:

> Our Highlands water-sheds, to which we call attention more fully hereafter, must be the first source from which this demand [*for additional water*] is to be met. They lie convenient to the metropolitan district, at a sufficient elevation for the delivery of their waters by gravity, are not populous, have just the right amount of forest, geological and topographical conditions favorable to purity and if they could be preserved in their present favorable condition would form in all respects an ideal gathering-ground. They have already begun to be utilized, and every succeeding decade must see a more rapid advance in their development. They are also threatened at points with pollution.
>
> Their protection and conservation for the future needs of the State seem to be merited by their unusual excellence. (Vermeule, 1894)

The recognition of the Highlands to yield high-quality water, and a call for its protection, was repeated in 1907:

> The Highland watersheds are the best in the State in respect to ease of collection, in scantiness of population, with consequent absence of contamination; in elevation, giving opportunity for gravity delivery, and in softness as shown by chemical analysis. These watersheds should be preserved from pollution at all hazards, for upon them the most populous portions of the State must depend for water supplies. There has been too much laxness in the past regarding this important matter. (New Jersey Potable Water Commission, 1907)

In 1999, the Highlands Region supplied 34% of the potable water used in New Jersey (Hoffman and Domber, 2004). Water from the Highlands Region wholly or partially supplied the drinking water in 292 municipalities in 16 counties. These municipalities are home to 64% of the State's population.

The special qualities and importance of the region were formally recognized with the passage the Highlands Water Protection and Planning Act of 2004:

> The Legislature further finds and declares that the New Jersey Highlands is an essential source of drinking water, providing clean and plentiful drinking water for one-half of the State's population, including communities beyond the New Jersey Highlands, from only 13 percent of the State's land area; … (P.L. 2004, Chapter 120, approved August 10, 2004).

This Act defined a 'Highlands Region' (fig. 1). In this region the Act allows for restrictions on land-use changes which could reduce the supply of clean water. The amount of ground-water water that can be used in the Highlands Region without affecting downstream supplies depends on the volume of ground-water recharge. Defining this volume is necessary in order to provide for new development in the Highlands Region that meets the restrictions of the Highlands Act.

Ground-water recharge is defined here as that volume of water which infiltrates into the ground below

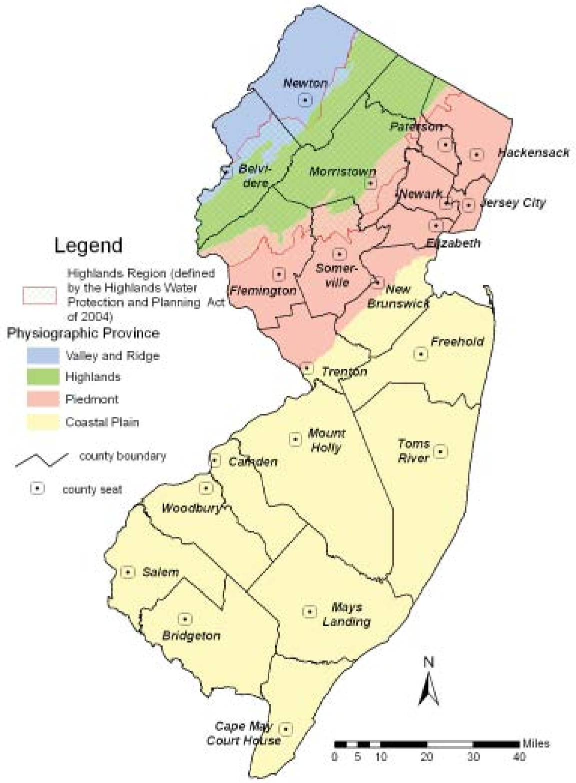


Figure 1. The Highlands Region with New Jersey's physiographic provinces.

the root zone of surface vegetation. Some of this water then encounters less-permeable layers and is diverted horizontally to discharge at nearby springs and streams. The remaining water continues downward and recharges the underlying water-table aquifer. In the Highlands Region areas of poor ground-water recharge generally cannot support a significant volume of pumpage from the water-table aquifer. This report uses the ground-water recharge estimation technique developed by the New Jersey Geological Survey (Charles and others, 1993).

During dry periods flow in a stream is sustained by water discharging from the ground to the surface. This dry-weather flow is called baseflow. Baseflow is sustained by ground-water recharge and those land-use practices which reduce this recharge will reduce the baseflow. It is thus important to understand what the current ground-water recharge is and how proposed land-use changes will affect it in order to protect the water resources of the Highlands Regions.

LOCATION

The Highlands Water Protection and Planning Act of 2004 defines the Highlands Region in northern New Jersey (fig. 1). This Region consists of the Highlands physiographic province along with portions of the neighboring Valley and Ridge and Piedmont provinces (fig. 1). The Highlands province in northern New Jersey is generally marked by a series of rounded ridges and narrow valleys that trend in a northeast-southwest direction (Lewis and Kummel, 1940). The ridges tend to be about 400 to 600 feet higher than the neighboring valley floors.

The Highlands Region is drained by four major watersheds (fig. 2). Streams in the Wallkill River's watershed flow generally northward, into New York, and eventually drain to the Hudson River. Streams in the Delaware River's watershed flow generally southwest into the Delaware River, which flows south into the Delaware Bay. Streams in the Passaic River's watershed eventually flow into the Newark Bay to the east. The Raritan River's watershed drains generally southeastward into the Raritan Bay.

Ground-water recharge can be estimated in different ways. This report presents estimates using two different approaches. The first is a soil-moisture budget approach,

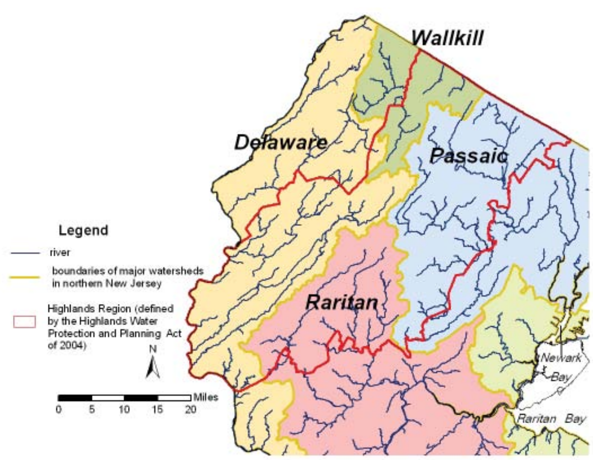


Figure 2. the Highlands Region with major watersheds and rivers in northern New Jersey.

developed by Charles and others (1993), and referred to as the NJGS methodology. This estimates ground-water recharge based on water entering the aquifers. The other is an analysis of baseflow using the methodology of Posten (1984). The Posten method estimated ground-water recharge by analyzing what exits the aquifers as stream baseflow.

GROUND-WATER RECHARGE ESTIMATION

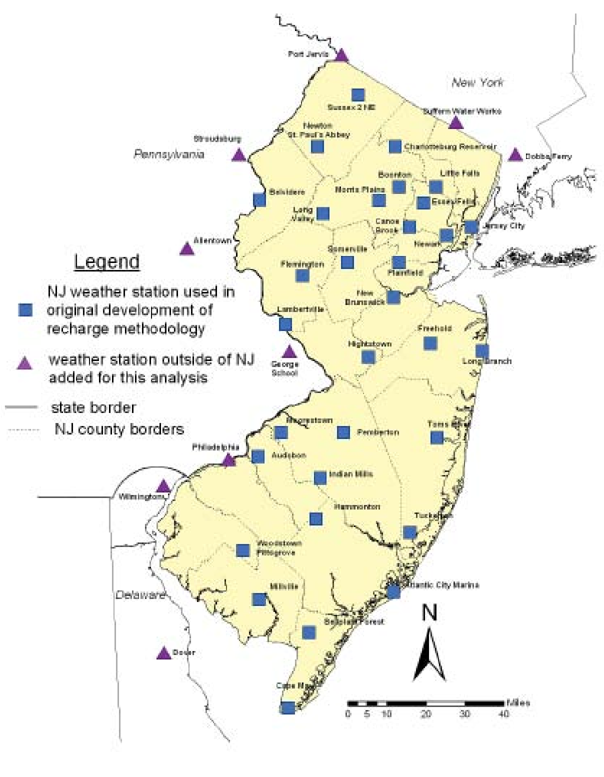


Figure 3. Weather stations used in the NJGS ground-water recharge methodology.

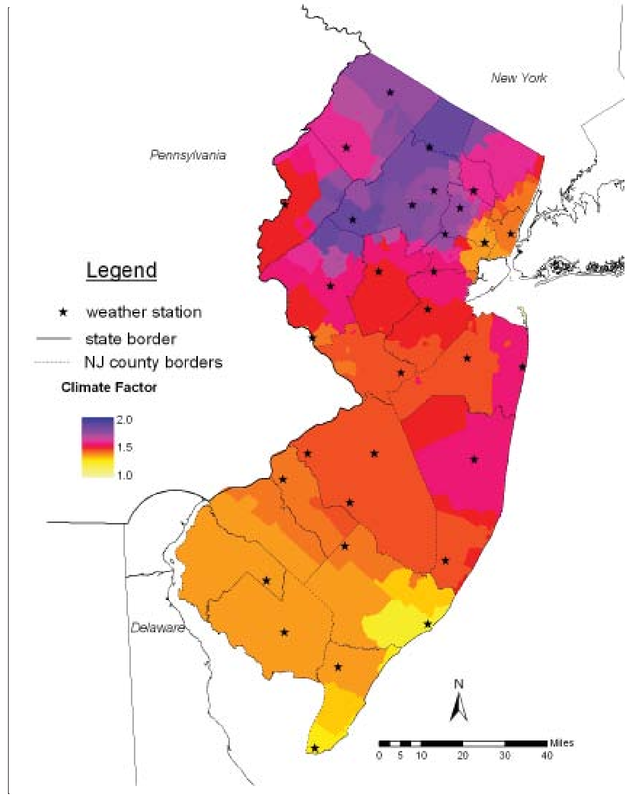


Figure 4. Initial municipality-based average conditions climate factors for the NJGS ground-water recharge methodology.

NJGS ground-water recharge methodology

The New Jersey Geological Survey's methodology for estimating ground-water recharge is based on a monthly soil moisture water budget, summed to an annual basis, that depends on site-specific knowledge of meteorological conditions, soil type, and land use characteristics (Charles and others, 1993). It has been used extensively throughout New Jersey for water-supply studies (Hoffman and French, 1999, 2000; French and Hoffman, 2000). It has also been used in water-quality dilution analyses (Hoffman and Canace, 2004). Spatial Geographical Information System (GIS) coverages of ground-water recharge estimates developed by this methodology are available for 19 of New Jersey's 21 counties (French, 2002).

The NJGS methodology incorporates meteorological data by means of a "climate factor." This is the ratio of annual-average precipitation to annual-average evapotranspiration at a weather station (Charles and others, 1993). The original methodology calculated climate factors based on data for the years 1957 to 1986 from 32 weather stations in New Jersey (fig. 3). A Thiessen-polygon approach then provided estimates of average climate factors for every municipality in New Jersey (fig. 4). This approach led to abrupt changes in ground-water recharge estimates at municipal boundaries even when other factors were identical across the municipal boundary. Also, this approach provides estimates of recharge in a year of average precipitation.

French and Hoffman (2002) expanded this approach to provide climate factors for watersheds of various sizes. However, this still resulted in discontinuities of ground-water recharge estimates across watershed boundaries in addition to applying only to estimates of ground-water recharge in a year of average precipitation.

This report expands the approach of Charles and others (1993) by providing a smoother definition of average climate factors. It also provides an estimate of drought climate factors. These improvements are discussed below.

The process for improving the climate factors started by adding data from nine weather stations outside of, but close to, New Jersey (fig. 3). This improved approach used GIS software to create a smoothly-varying function

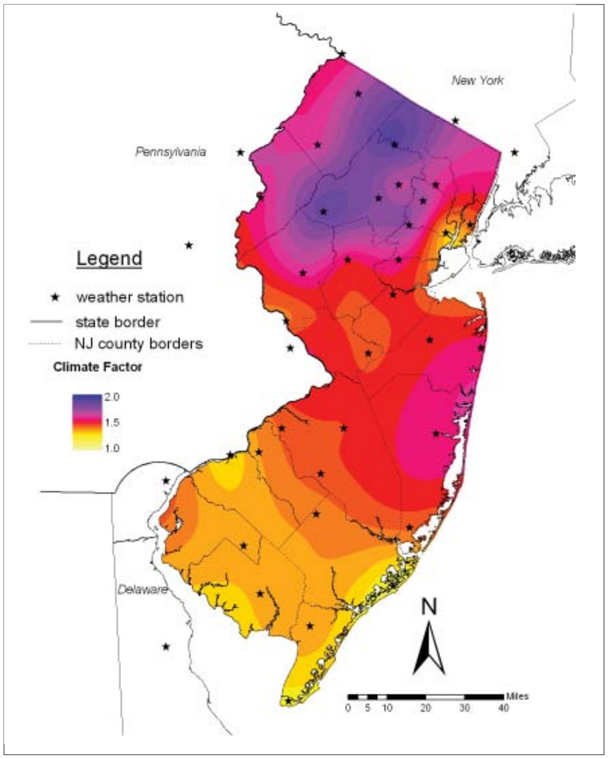


Figure 5. Revised climate factors for the NJGS ground-water methodolgy under normal conditions.

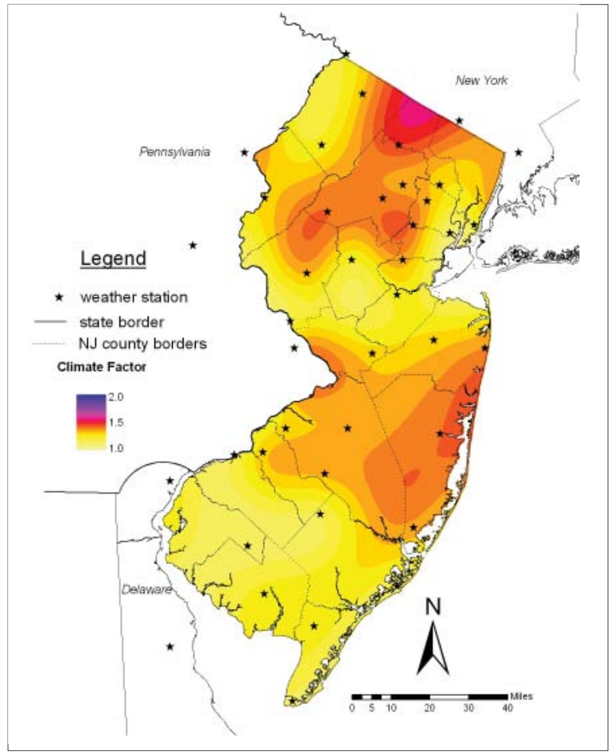


Figure 6. Revised climate factors for the NJGS ground-water methodolgy under drought conditions.

that matched the average climate factors at all 41 weather stations. This function was then rasterized into 100-foot by 100-foot grids across New Jersey using the GIS spatial analyst[1]. Using the zonal statistics tool in spatial analyst, this smoothly-varying rasterized average climate factor function was then overlaid on a state-wide polygonal coverage of soil type and 2002 land use to determine an appropriate average climate factor for each polygon. This was applied to meteorological data for the entire period of record to result in a smoothly-varying climate factor distribution under average conditions (fig. 5).

Climate factors were recalculated using only meteorological data for the period 1961 to 1966, the drought of record for New Jersey (Bauersfeld and others, 1991). This produced drought climate factors at the 41 weather stations. The drought climate factors were rasterized with the same procedure as produced average climate factors (fig. 6).

This approach first led to improved estimates of annual precipitation. Figure 7 shows the estimate of annual precipitation under normal precipitation conditions in New Jersey using the 41 weather stations. Figure 8 shows an estimate of annual precipitation under drought conditions.

The NJGS ground-water recharge methodology (Charles and others, 1993) then provided an estimate of ground-water recharge in each polygon using the soil, land use, and average climate factor for that polygon. This approach resulted in a smoothly varying estimate of ground-water recharge across the State that did not have artificial jumps at municipal or watershed boundaries.

Wetlands, hydric soils and surface waters may be recharge areas, discharge areas, or neither. The site-specific investigations needed to determine recharge or discharge at these areas mean that the NJGS recharge methodology does not apply to them (Charles and others, 1993). These areas are set aside and not considered in the estimation of average ground-water recharge.

Areas mapped as totally (100%) impervious, in addition to areas mapped as having urban soils, are assumed to produce no ground-water recharge. These areas are retained in the calculations of average recharge and assumed to contribute no recharge.

Average and drought ground-water recharge in the Highlands Region are shown in figures 9 and 10, respectively. These come from GIS coverages of recharge in the Highlands Region created by clipping the two state-wide GIS recharge coverages with a GIS coverage of the Highlands Region. The area-weighted average ground-

[1] Online help pages, ESRI, Inc., accessed January 2008 at http://webhelp.esri.com/arcgisdesktop/9.2/index.cfm?TopicName=An_overview_of_Spatial_Analyst

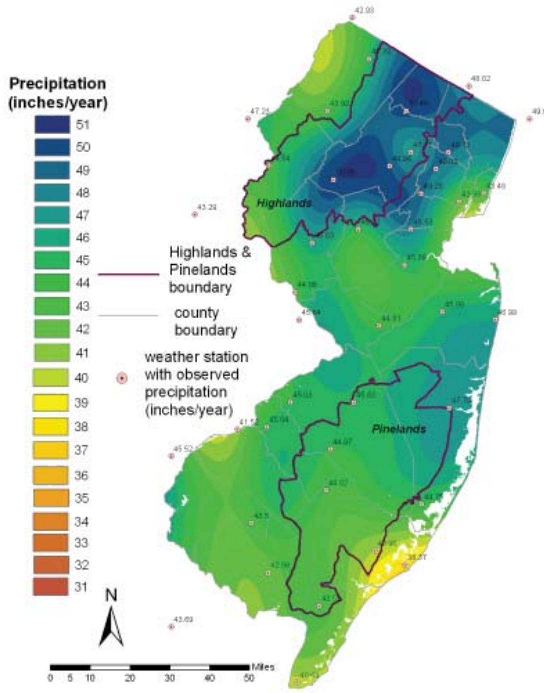


Figure 7. Average annual precipitation under normal conditions.

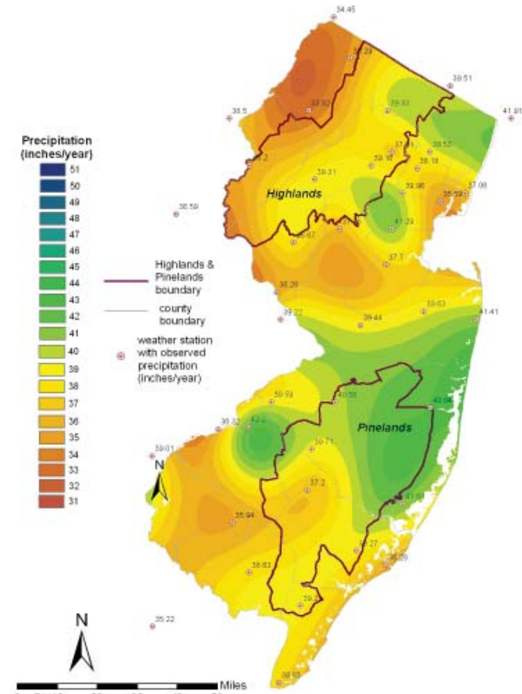


Figure 8. Average annual precipitation under drought conditions.

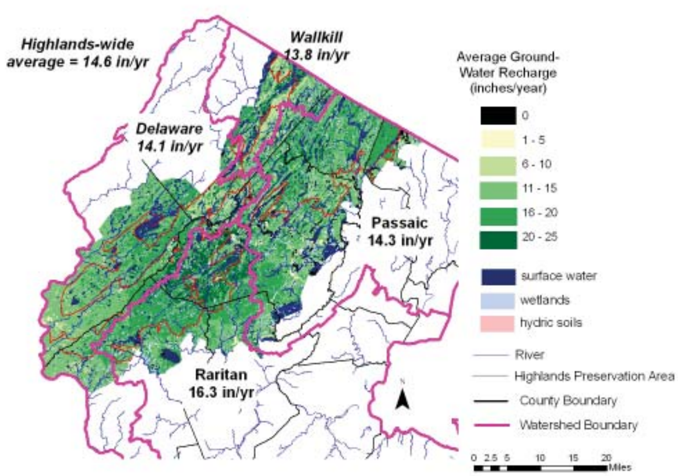


Figure 9. Highlands Region ground-water recharge under average precipitation conditions, with estimates for each major watershed.

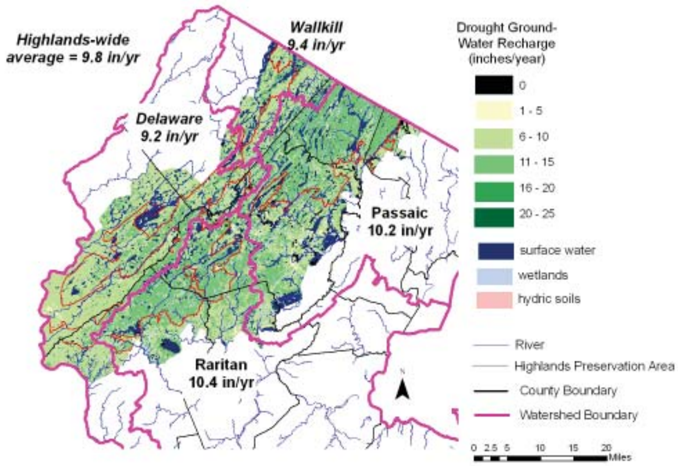


Figure 10. Highlands Region ground-water recharge under drought precipitation conditions, with estimates for each major watershed.

water recharge estimate for the Highlands Region is 14.6 inches/year. The area-weighted drought ground-water recharge estimate for the entire Highlands Region is 9.8 inches/year (table 1).

Four major watersheds drain the Highlands Region - the Delaware, Passaic, Raritan and Wallkill (fig. 2). GIS coverages of each major watershed were intersected with the average and drought ground-water recharge coverages. These watershed-specific coverages then were analyzed to yield area-weighted recharge estimates (table 1).

In the Delaware watershed, the average-annual ground-water recharge estimate is 14.1 inches/year, while the drought value is 9.2 inches/year. In the Passaic watershed, the average and drought values are 14.3 and 10.2 inches/year, respectively. In the Raritan watershed, the average and drought values are 16.3 and 10.4 inches/year, respectively. In the Wallkill, watershed the average and drought values are 13.8 and 9.4 inches/year, respectively.

The underlying analysis produces estimates of ground-water recharge on a parcel-by-parcel basis. Each parcel has a different combination of soils and land use from all adjourning parcels. The results are stored in a GIS polygonal coverage that can be further analyzed by breaking ground-water recharge into categories. Figure 11 shows the acres of the Highlands Region in each inch-category for average-annual and drought-annual ground-water recharge. These graphs also show a cumulative percentage curve. The average annual recharge curve shows that the 14 inch-per-year category has the most area, almost 100,000 acres. For the estimate of drought recharge, the 9 inch-per-year category is the greatest, with about 135,000 acres. The greatest average annual recharge rates are 22 inches per year whereas the greatest drought ground-water recharge rates are 16 inches per year.

Table 1. Estimates of ground-water recharge under average and drought conditions in the Highlands Region

Watershed	Ground-Water Recharge (inches/year)		Area (acres)
	average precipitation	drought precipitation	
Delaware watershed	14.1	9.2	244,626
Passaic watershed	14.3	10.2	237,126
Raritan watershed	16.3	10.4	159,925
Wallkill watershed	13.8	9.4	57,957
Highlands-wide	14.6	9.8	699,634

Table 2. Posten baseflow estimates at selected Highlands Region streamgages

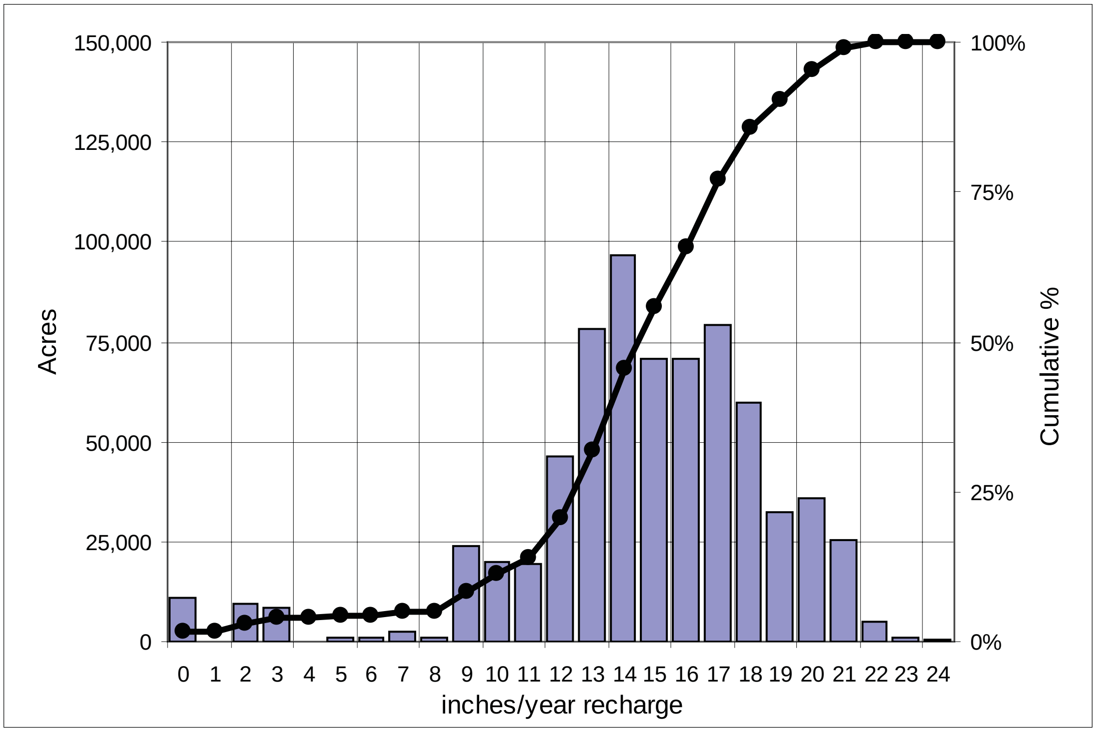
Major Water-shed	Stream Gage number	Stream Gage name	Watershed Area (sq mi)	Period of Record	Baseflow (in/yr)[1] average[2]	Baseflow (in/yr)[1] drought[3]
Delaware	01446000	Beaver Brook near Belvidere	36.7	1923-1961	11.1	--
	01455160	Brass Castle Creek near Washington	2.3	1978-1983	10.9	--
	01457000	Musconetcong River near Bloomsbury	141.0	1922-1989	15.7	9.9
	01456000	Musconetcong River near Hackettstown	68.9	1922-1973	14.8	9.1
	01445500	Pequest River at Pequest NJ	106.0	1922-1989	12.8	7.8
Passaic	01386500	Blue Mine Brook (Wanaque)	1.0	1934-1958	11.3	--
	01387500	Ramapo River near Mahwah	120.0	1923-1989	12.9	10.7
	01388000	Ramapo River at Pompton Lakes	160.0	1922-1989	11.9	6.3
	01384500	Ringwood Creek near Wanaque	19.1	1935-1978, 1986-1989	12.8	9.5
	01380500	Rockaway River above Boonton Reservoir	116.0	1938-1989	15.1	9.8
	01386000	West Brook (Wanaque River Basin)	11.8	1935-1978	12.8	10.2
	01381500	Whippany River at Morristown	29.4	1922-1989	13.4	9.6
Raritan	01399500	Lamington River near Pottersville	32.8	1922-1989	14.7	9.0
	01398500	North Branch Raritan River near Far Hills	26.2	1922-1975, 1978-1989	13.9	8.8
	01396500	South Branch Raritan River near High Bridge	65.3	1919-1989	15.0	10.3

1. Baseflow computed using the Posten (1984) methodology
2. All stream flow data used.
3. Only streamflow during the drought of record, 1961-1966, used to estimate baseflow.

Posten ground-water recharge methodology

Posten (1984) developed a methodology to estimate ground-water recharge. His method assumes that baseflow in a stream is an indicator of average recharge in the watershed. It yields an average recharge value for the entire watershed above the gage at which streamflow is measured. The methodology is also affected by any withdrawals and discharges in the watershed that alter streamflow.

Table 2 shows results for an application of the Posten methodology for streamgages in the Highlands Region. The methodology was applied twice, first for baseflow estimated using all available streamflow data, and second for streamflow during the drought years 1961-1966. Using all available data, the area-weight value for the Highlands Region is 13.7 inches per year. This compares very favorably to the 14.6 inches per year from the NJGS methodology. Using only streamflows during the drought of record, the Posten methodology yields an area-weighted drought average of 9.0 inches per year for the Highlands Region. This also compares very favorably to the NJGS estimation of a drought ground-water recharge of 9.8 inches per year.



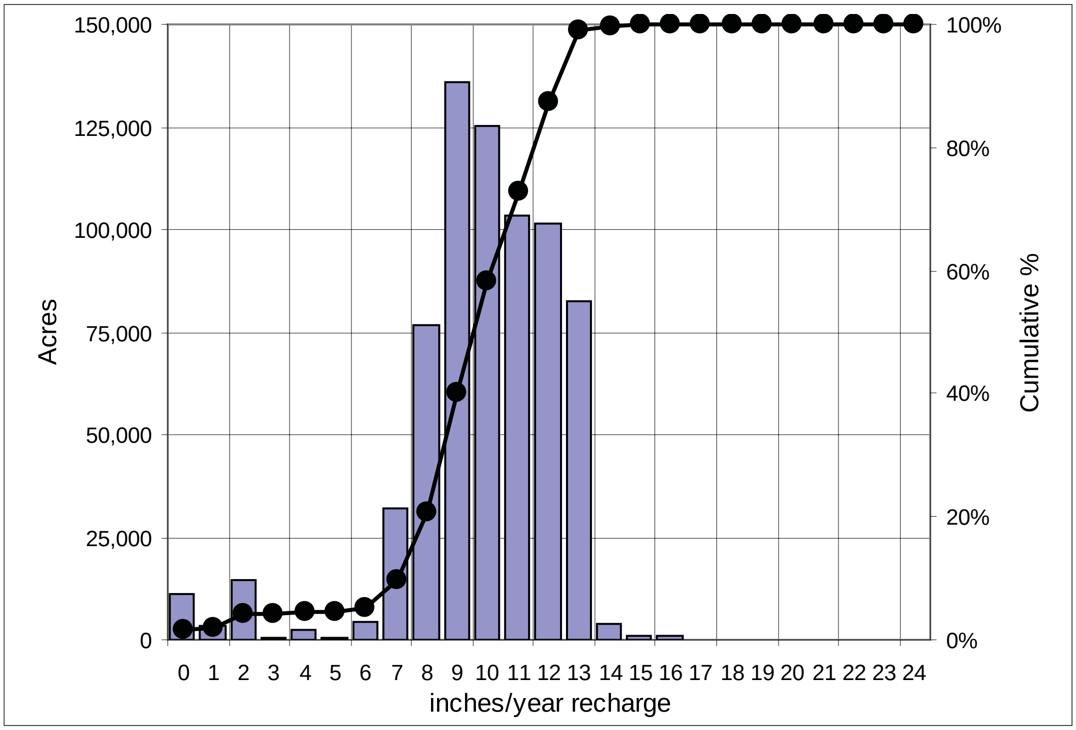


Figure 11. Statistical distribution of ground-water recharge under average (top) and drought (bottom) precipitation conditions in the Highlands Region.

CONCLUSION

The Highlands Water Protection and Planning Act of 2004 defines the Highlands Region, 1,093 square miles in northwestern New Jersey, as “an essential source of drinking water” for the State. The water resources of the Highlands Region in New Jersey are sustained by precipitation infiltrates into the ground becoming recharge. This recharge sustains streamflow between precipitation events and replenishes aquifers with water for human consumption.

The New Jersey Geological Survey’s ground-water recharge methodology uses monthly water budgets to estimate the volume of water which infiltrates below the root zone. The methodology uses a parcel-specific approach. Each parcel has a climate factor (that incorporated estimates of precipitation and evaporation), land use, and soil type. The original methodology estimated climate factors appropriate for average precipitation conditions based on data from 32 weather stations in New Jersey for the period 1957-1986. An update to this approach adds data from nine additional weather stations outside, but near, New Jersey. The update also added drought climate factors based on weather data for the period 1961-1966, the drought of record in New Jersey.

This approach does not consider recharge on hydric soils, wetlands, or surface water since these areas may be recharge or discharge areas. Site-specific studies are needed to determine if these are recharge areas. Additionally, areas which are mapped as being totally covered by impervious material are considered to supply no ground-water recharge.

Using this approach to ground-water recharge, the area-weighted average annual ground-water recharge in the Highlands is 14.6 inches per year (in/yr). Under drought conditions, this amount drops to 9.8 in/yr.

The Highlands is drained by four major watersheds, the Delaware, Passaic, Raritan and Wallkill. Under average precipitation conditions the area-weighted annual ground-water recharge in these watersheds is 14.1, 14.3, 16.3 and 13.8 in/yr, respectively. Under drought precipitation conditions, the area-weighted annual ground-water recharge in these watersheds is 9.2, 10.2, 10.4 and 9.4 in/yr, respectively.

These estimates compare favorable with the Posten estimates of baseflow. The Posten approach uses streamflow recession curves to estimate net baseflow in the watershed above a streamgage. It thus represents the net of ground-water recharge, minus any extractions, in the watershed.

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