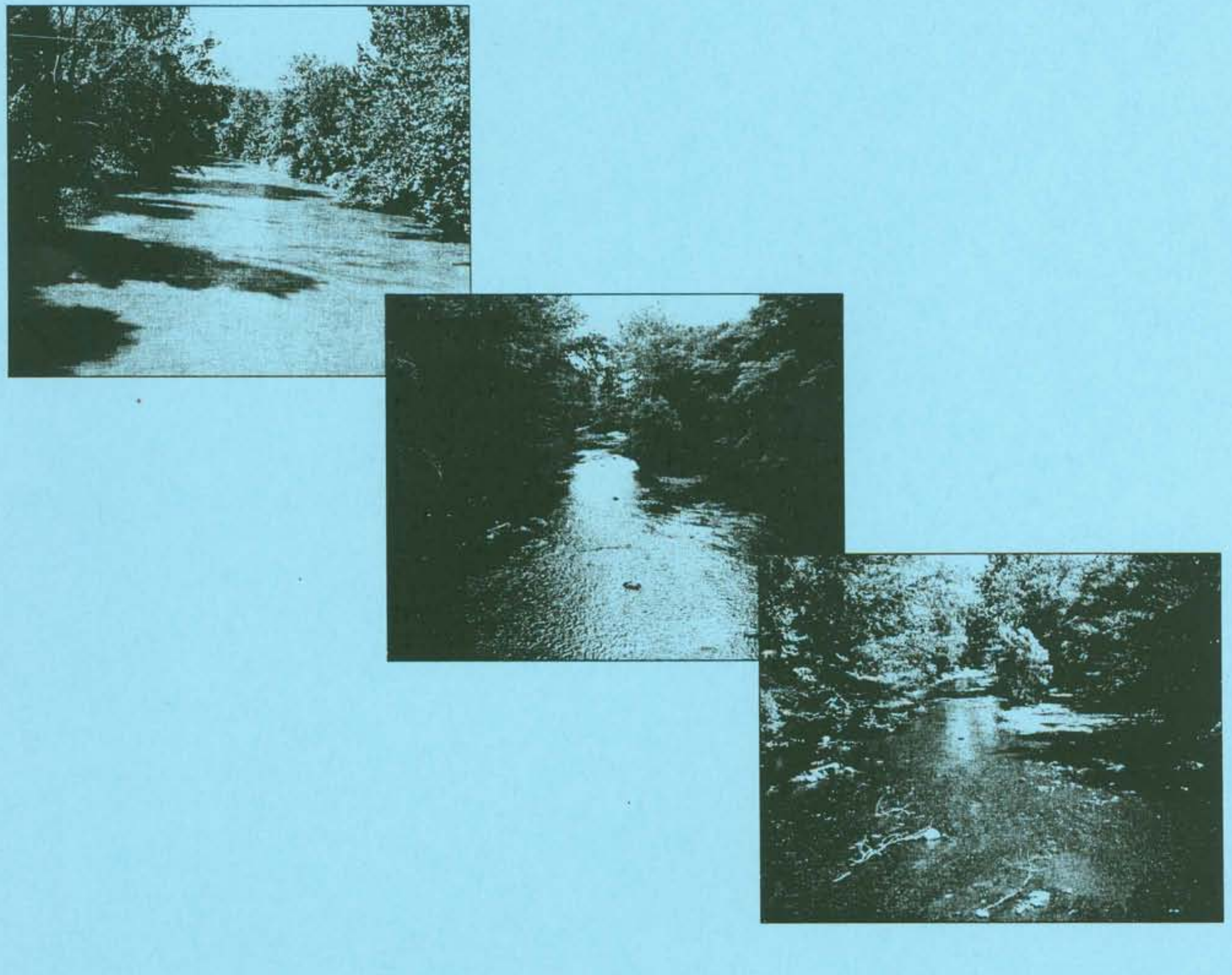
New Jersey Geological Survey
Open-File Report OFR 04-2

DEVELOPMENT OF STREAMFLOW AND GROUND-WATER DROUGHT INDICATORS FOR NEW JERSEY



New Jersey Department of Environmental Protection
Land Use Management

NEW JERSEY DEPARTMENT OF ENVIRONMENTAL PROTECTION

The mission of the New Jersey Department of Environmental Protection is to assist the residents of New Jersey in preserving, sustaining, protecting and enhancing the environment to ensure the integration of high environmental quality, public health and economic vitality.

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Cover illustration: South Branch Raritan River, Clinton Township, Hunterdon County viewed from the overpass on Grey Rock Road. Left to right: flood conditions after Hurricane Floyd, September 1999; normal conditions, June 1999; drought conditions, August 1999. Photos courtesy of Dan Van Abs, New Jersey Water Supply Authority.

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Development of Streamflow and Ground-Water Drought Indicators for New Jersey

by

Jeffrey L. Hoffman and Steven E. Domber

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

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Conversion Factors

Volume			Flow Rate		
Multiply inch-pound units	by	to obtain metric (SI) units	Multiply inch-pound units	by	to obtain metric (SI) units
cubic inches (in^3)	16.39	cubic centimeters (cm^3)	million gallons/day (mgd)	0.04381	cubic meters/second (m^3/s)
cubic feet (ft^3)	0.02832	cubic meters (m^3)	cubic feet per second	2,447.	cubic meters/day
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)	.06309	liters/second (L/s)

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

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"Man can do little to modify the natural climatic phenomena that combine to cause droughts. He can, however, do much to lessen their impact on his activities through foresightedness in maintaining hold-over storage; in digging deeper wells or in lowering intakes to ground-water supplies; in adopting all practices known to conserve water; in limiting or adjusting economic development to assured sources of water supply; and in adopting a mode or scale of living in conformity with the dictates of nature."

Hoyt, W.G., 1942, Droughts, *in* Meinzer, O.E., editor, Hydrology: New York, McGraw-Hill Book Co., Inc., p. 579-591.

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ABSTRACT

Droughts occur when less precipitation than normal falls for an extended period of time. Water-supply droughts are defined as times when the volume of water normally needed is greater than the volume available. These may occur in New Jersey several times a decade. They may be moderate or severe in intensity, short or long in duration, and local or Statewide in extent. Identifying which parts of the State are experiencing drought, and the severity of the drought, is vital for effective response. Identifying which areas are heading towards an emergency situation may allow for preemptive actions (such as voluntary water-use reductions or increased water transfers from less-stressed areas) that could extend the available water supply. Identifying the end of drought allows for the cessation of drought-remediation efforts without endangering the public water supply or the integrity of the water sources.

There are a large number of data available concerning the factors that affect the water supply of New Jersey. In order to effectively communicate to the public and decision makers information on these factors it is necessary to have indicators that accurately summarize hydrologic conditions, make intuitive sense, can be quickly updated with real-time data, and are amenable to quick and easy distribution. This report documents the development of streamflow and ground-water indicators that meet these needs.

A drought indicator summarizes one factor that affects water supply in one of the six drought regions in New Jersey. Indicators are available for precipitation, streamflow, levels of unconfined ground-water, and water stored in reservoirs both in New Jersey and in the upper Delaware River basin in New York. Each indicator is assigned to one of four conditions: normal or above normal, moderately dry, severely dry, or extremely dry.

Development of the streamflow drought indicator was done in two phases. 1) A statistical tool was developed based on 3-month cumulative streamflow deviations from mean. A frequency analysis of the 3-month deviations associated with each calendar month showed that the 10% exceedence frequency curve (only 10% of observed deviations in that month were less than this number) was the most successful tool in tracking drought emergencies in New Jersey. The 30% exceedence frequency curve was useful in tracking drought warnings. 2) The application phase resulted in a method to apply the statistical tool to 90-day cumulative streamflow deviations from mean daily streamflow. If the 90-day cumulative streamflow deviation is in the lowest 10% of calculated 3-month deviations then the indicator is classified as extremely dry, above 10% but less than or equal to 30% is severely dry, above 30% but less than or equal to 50% is moderately dry, and greater than 50% is classified as near or above normal. The 90-day deviations are based on real-time daily streamflow data from three gages in each drought region. Figure 1 delineates the drought regions.

Mean monthly ground-water levels are the basis of the ground-water drought indicator. Observed daily levels are compared to monthly exceedence frequency curves developed from a statistical analysis of mean monthly values. If the observed ground-water level on a given day is in the lowest 10% of observed values for that month, then the ground-water drought indicator for that well is set to extremely dry; above 10% but less than or equal to 30% is severely dry, above 30% but less than or equal to 50% is moderately dry, and greater than 50% is classified as near or above normal. The ground-water indicator in each region is based on professional evaluation of the status of the wells in that region. There are an insufficient number of wells in the drought monitoring network to allow for a more rigorous approach. All wells were selected to minimize, as much as possible, impacts on water levels by any nearby pumping.

The streamflow and ground-water drought indicators depend on a frequency analysis of historical values. The New Jersey Department of Environmental Protection (DEP) intends to update the probability distributions and exceedence frequency curves for both the streamflow and ground-water drought indicators after each drought.

These indicators, together with indicators evaluating reservoir storage and precipitation, will help water-supply professionals in DEP evaluate the adequacy of the State's water supply to meet demands during dry periods. The indicators are evaluated weekly during dry periods and less frequently during wet ones. The indicators assist but do not replace professional judgement. Once the indicators have been analyzed, DEP staff recommend an appropriate drought status in each region. The DEP Commissioner has the authority to declare or lift a drought watch or drought warning. Only the Governor of New Jersey has the authority to declare or lift a drought emergency.

The drought indicators described above were developed following the 1998-1999 drought and were implemented in January 2001. In late 2001 dry conditions resulted in lowered streamflows and ground-water levels. The drought indicators proved to be useful in tracking the conditions and assisting DEP decision makers in deciding when to recommend a change in drought status in each drought region.

The current drought indicators and declared drought status (normal, watch, warning, or emergency), along with other drought-related information, are made public over the DEP's drought information web site: http://www.njdrought.org.

INTRODUCTION

A drought occurs when precipitation has been less than normal for an extended period of time. A water-supply drought occurs when the available or developed supply of water is less than, or is predicted to be less than, the demand. Water-supply droughts can be forestalled by limiting water demand, storing water during wetter times for later use, developing new sources of water, reducing passing flow requirements, and/or transferring water from wetter areas to drier ones. To be most effective, the responses require an accurate analysis of where the water shortages are occurring. Also, an accurate prediction of the start of drought allows for more efficient preparation and public-education effort. An accurate definition for the end of drought allows for the cessation of drought-remediation efforts without endangering the public water supply or the integrity of the water sources.

The goal of this research was to develop region-specific drought indicators for New Jersey. The New Jersey Department of Environmental Protection (DEP) divides the State into six drought regions based on water supply considerations: northeast, northwest, central, coastal north, coastal south, and southwest (Hoffman, 2001; fig. 1). The drought indicators allow tracking the severity of a water shortage over time as well as determining which drought region is most impacted.

DEP staff evaluate the water-supply conditions in each region on a regular basis. Based on professional evaluation of the indicators (of streamflow, ground water, precipitation, and reservoir levels) the water-supply situation in each region is classified as normal, drought watch, drought warning, or drought emergency. The DEP Commissioner has the authority to declare or lift a drought watch or drought warning. Only New Jersey's Governor has the authority to declare or lift a drought emergency. These indicators assist but do not replace professional judgement; they are not triggers that automatically signal a change in water-supply status.

Wilhite and Glantz (1985) identify four types of droughts: meteorological (based on precipitation), hydrological (lowered water levels), agricultural (soil-moisture deficits), and socioeconomic (impacts to economic health due to a water shortage). In New Jersey the declaration of a drought emergency by the Governor is, using this nomenclature, notice that a socioeconomic drought is underway.

This report details the process that led to the development of drought indicators for streamflow and ground-water levels. The drought indicators are designed to characterize gradations in degrees of dryness. For this reason wet conditions are not analyzed more closely.

Acknowledgements

Many DEP staff members and outside water-supply professionals contributed to development of the drought indicators. Jan Gheen of the DEP's Bureau of Water Allocation, Bob Schopp of the U.S. Geological Survey, and Dave Robinson, the New Jersey State Climatologist, submitted very helpful reviews throughout the process. The DEP's drought task force sat through many presentations and had significant input, especially Tom Baxter, Shing-Fu Hsueh and Ray Cantor. Bob Canace, Karl Muessig, Dick Dalton, and John Dooley of the N.J. Geological Survey also had many helpful comments.

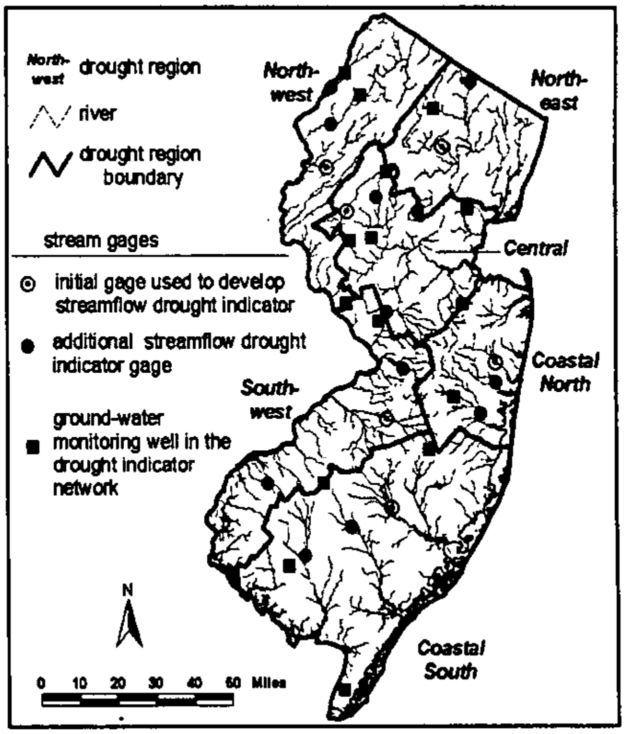


Figure 1. Drought regions in New Jersey with streamflow gages and ground-water monitoring wells in the drought-indicator network.

DROUGHTS IN NEW JERSEY

Water-supply conditions are divided into 4 stages in New Jersey: normal, watch, warning, and emergency. This is based on an evaluation of water sources in New Jersey and the Delaware River Basin, and the threat to water-supplies when demand exceeds supply in dry periods.

A near or above normal condition means that the situation is wet, or that water levels are not far enough below normal to be a significant concern.

A drought watch condition implies that although water supplies are not dangerously stressed, they are low enough to be of a concern. This condition was added in 2000 after an analysis of the State's response to the drought of 1999. This is intended primarily as an alert to water-supply professionals and purveyors to monitor the situation closely and to begin the initial stages of drought response.

In New Jersey a drought warning indicates that water supplies are low and that the public is encouraged to conserve water. The declaration of a drought warning is made by the Commissioner of the Department of Environmental Protection. During a drought warning water-supply professionals and purveyors actively monitor the situation and implement appropriate drought-response activities. In some cases, there actions may delay or forestall declaration of a drought emergency. After public hearings the DEP may exercise its non-emergency powers such as requiring water purveyors to transfer water from one region to another to meet needs.

Drought emergencies are declared by the Governor of New Jersey. They indicate that the water supply is threatened and steps must be taken to reduce demand. A declaration of drought emergency allows the State to order mandatory water restrictions. Table 1 summarizes declarations of drought warning and emergencies in New Jersey since the mid-1960.

The Delaware River Basin Commission has the authority to declare drought warnings and emergencies in the Delaware River watershed. These declarations are based mainly on the status of water levels in reservoirs in New York and Pennsylvania, flow volumes in the Delaware River, and the location of the salt-water front in the lower Delaware River (Paulachok and others, 2000). Table 2 summarizes drought warnings and emergencies declared by the Delaware River Basin Commission in the past 20 years.

Recognition of droughts depends on what parameter is analyzed. Bauersfeld and Schopp (1991) recognize five droughts in New Jersey between 1900 and 1990. This is based on their analysis of annual streamflow volumes at six gages. The five times are:

May 1929 - October 1932
February 1949-October 1950
May 1953 - July 1955
June 1961 - August 1966
June 1980 - April 1981

In contrast, the Office of the New Jersey State Climatologist (2002), based on an analysis of 5-year accumulated precipitation totals, defines six drought periods in New Jersey between 1900 and 1990. Their analysis considers the first three years to be the "most severe portion of a drought" and the remaining two years a recovery period. The six periods defined this way are:

1908 - 1912
1916 - 1920
1923 - 1927
1929 - 1933
1964 - 1968
1980 - 1984

Table 1. Recent drought emergencies and warnings called by the New Jersey State Government

Warnings	Emergencies	Comment
mid-1960's	mid-1960's	Drought of record for NJ
8/80 - 9/12/80	9/12/80 - 4/27/82	Started in northeastern NJ and expanded to central and northern Delaware basin
	4/17/85 - 3/24/86	Northeastern NJ
8/2/95-9/12/95	9/13/95 - 11/3/95	Northeastern NJ
12/14/98 - 2/2/99		Northeastern NJ
8/2/99 - 8/4/99	8/5/99 - 9/14/99 8/5/99 - 9/27/99	Southern NJ Northern NJ
9/15/99-7/17/00 9/28/99-7/17/00		Southern NJ Northern NJ
11/21/01 - 3/21/02	3/4/02 - 1/8/03	See table 12 for more detail

Table 2. Recent drought warnings and emergencies called by the Delaware River Basin Commission

Warnings	Emergencies
10/17/80 - 1/15/81	1/16/81 - 4/27/82
11/31/82 - 3/27/83	
11/09/83 - 12/20/83	
1/23/85 - 5/12/85	5/13/85 - 12/18/85
1/16/89 - 5/12/89	
9/13/91 - 6/17/92	
9/21/93 - 12/06/93	
9/15/95 - 11/12/95	
10/27/97 - 1/13/98	
12/14/98 - 2/02/99	
8/18/99 - 9/30/99	
11/6/01 - 12/17/01	12/18/01 - 11/25/02

DEVELOPMENT OF A STREAMFLOW DROUGHT INDICATOR

The goal of a streamflow drought indicator is to integrate numerous data into one summary statistic that has a close correlation with known periods of drought. The indicator must depend only on readily-available data that can be incorporated on a near-real-time basis. The indicator must also intuitively be consistent with water-supply concerns. These goals are accomplished by analyzing and quantifying how far below normal streamflow has been in the recent past.

The streamflow drought indicator is not a direct function of instantaneous flow or total flow on a given day at the stream gage. This is because streamflow can rise quickly to above mean flows following a rain event, even in a drought. And streamflow occasionally may be classified as below normal during overall wet times. For these reasons the degree by which streamflow differs from mean flow on a given day is not suitable for use as a drought indicator.

However, the cumulative volume by which streamflow has differed from normal flow over a period of time integrates these short-term variations. If over a long period of time streamflow has been lower than normal, then a water shortage may exist. Defining an appropriate time period, and how to classify the degree to which streamflow has been lower than normal, was the purpose of this research.

The process described below was first applied to monthly streamflow measured at six gages, one per drought region (table 3). After the approach was chosen and applied, it was expanded to an additional two gages per drought region (table 4). All gages were chosen to be as unaffected as possible by upstream reservoirs and major surface-water diversions. However, it was not possible to select three gages per drought region that were totally unaffected by surface-water or ground-water withdrawals. It is hoped that by analyzing deviations from mean flows the impacts of any withdrawals will be lessened.

The process of developing an appropriate summary statistic for use as a streamflow drought indicator is illustrated below using data from the gage on the

Rockaway River above the reservoir at Boonton (gage #01380500, table 3). This is in the northeast drought region. Figure 2 shows total annual yearly flow for this gage for 1938-2000. Over this period of time mean annual flow at the gage was 54,203 million gallons per year. The bars of this graph are drawn extending upwards from this line (for years with greater than mean flow) or downwards (for years with less than mean flow).

The drought indicator development process was done in two phases, a development phase and an application phase. Each phase consisted of many steps.

Development Phase

The development phase involved deriving the statistics that are the baseline to which deviation from mean daily streamflows are compared. The steps involved in this phase were: 1) calculate total monthly stream flow; 2) calculate mean monthly streamflow volumes; 3) for each month calculate the deviation between observed and mean monthly-flow volumes; 4) for each month calculate the cumulative flow deviation over five antecedent periods (1, 3, 6, 9 and 12 months); 5) for each calendar month and antecedent period estimate the exceedence frequencies of the cumulative flow deviation; and 6) compare selected exceedence frequency values from the probability distribution to periods of known droughts to determine which antecedent period and exceedence frequency provides the most useful match to drought periods. Each of these steps is described in more detail below.

The first step of the development phase was to calculate total monthly flow volume for each month in the

Table 3. Stream gages used in initial development of drought indicators

Stream Gage		Drought Region
Number	Name	
01396500	South Branch Raritan River near High Bridge	Central
01408000	Manasquan River at Squankum	Coastal North
01409400	Mullica River near Batso	Coastal South
01380500	Rockaway River above the reservoir at Boonton	Northeast
01445500	Pequest River at Pequest	Northwest
01467000	North Branch Rancocas Creek at Pemberton	Southwest

Table 4. Stream gages added to drought indicators after development

Stream Gage		Drought Region
Number	Name	
01401000	Stony Brook at Princeton	Central
01399500	Lamington River at Pottersville	Central
01408120	North Branch Metedeconk River near Lakewood	Coastal North
01408500	Toms River near Toms River	Coastal North
01411000	Great Egg Harbor River at Folsom	Coastal South
01411500	Maurice River at Norma	Coastal South
01379000	Passaic River near Millington	Northeast
01384500	Ringwood Creek near Wanaque	Northeast
01440000	Flat Brook near Flatbrookville	Northwest
01443500	Paulins Kill at Blairstown	Northwest
01477120	Raccoon Creek near Swedesboro	Southwest
01464500	Crosswicks Creek at Extonville	Southwest

data record. The total monthly streamflow is defined as:

$$MQ_{m,y} = \sum_{i=1}^{Dm} DQ_{i,m,y} \qquad (1)$$

where:

$DQ_{d,m,y}$ = total daily streamflow on day (d) of month (m) in year (y).

$MQ_{m,y}$ = total streamflow volume in month (m) of year (y)

D_m = number of days in month (m)

The variable i is a summation variable. The subscript m always varies from 1 to 12 and corresponds to calendar months. The subscript y is bounded by the stream gage's data record. For the Rockaway River above the reservoir at Boonton stream gage the subscript y varied between 1938 and 2000 in this step. Total monthly streamflow volumes are shown in figure 3. This graph highlights the high variability of total flows from one month to the next.

The second step of the development phase was to calculate mean monthly streamflow volumes for each calendar month. It is calculated as:

$$\overline{MQ}_m = \frac{\sum_{i=ylo}^{yhi} MQ_{m,i}}{y_{hi} - y_{lo} + 1} \qquad (2)$$

where:

$\overline{MQ}_m$ = the mean stream flow in calendar month m

y_{lo} = the first year in the data record

y_{hi} = the last year in the data record.

The variable (i) is a summation variable. The mean monthly streamflow volumes are shown in table 5 and figure 4.

The third step of the development phase was to compute monthly streamflow deviations from normal. This is defined as observed monthly flow minus mean monthly flow:

$$\Delta MQ_{m,y} = MQ_{m,y} - \overline{MQ}_m \qquad (3)$$

where:

$\Delta MQ_{m,y}$ = the deviation from mean of total monthly streamflow in month (m) of year (y)

The other variables are as previously defined.

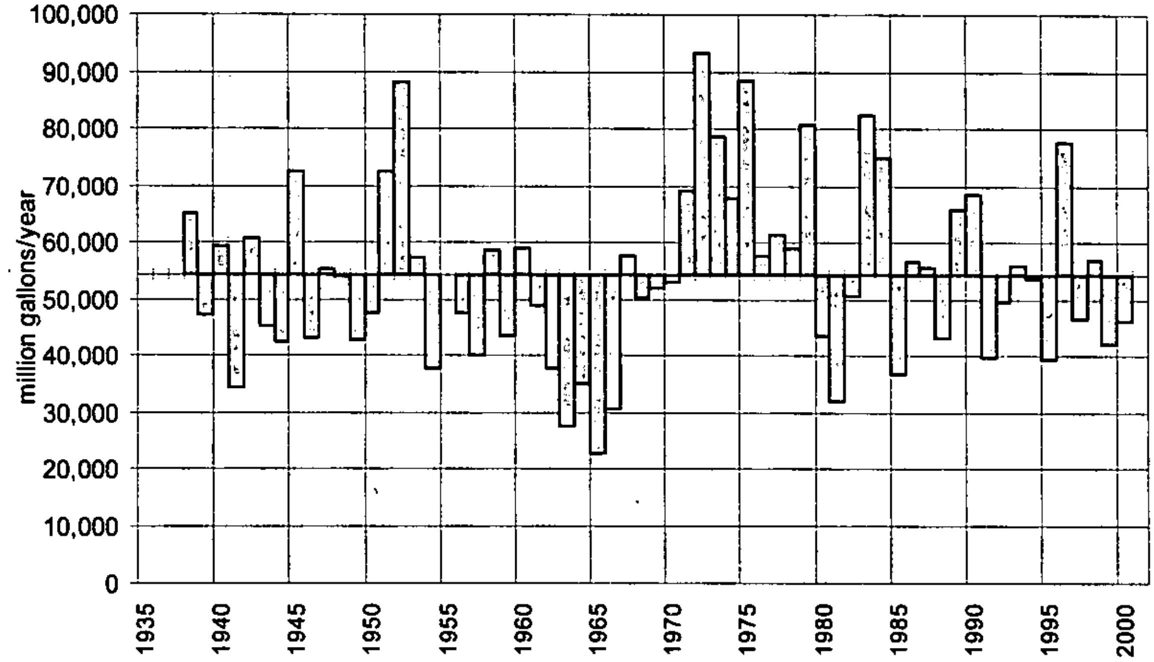


Figure 2. Total yearly streamflow, Rockaway River above the reservoir at Boonton, 1938-2000. (Bars are drawn upwards or downwards from the mean annual flow over this period -- 54,203 million gallons per year. Bars extending upwards indicate more stream flow than normal that year, bars extending down indicate less streamflow than normal that year. The length of each bar indicates how much wetter or drier than normal each year was.)

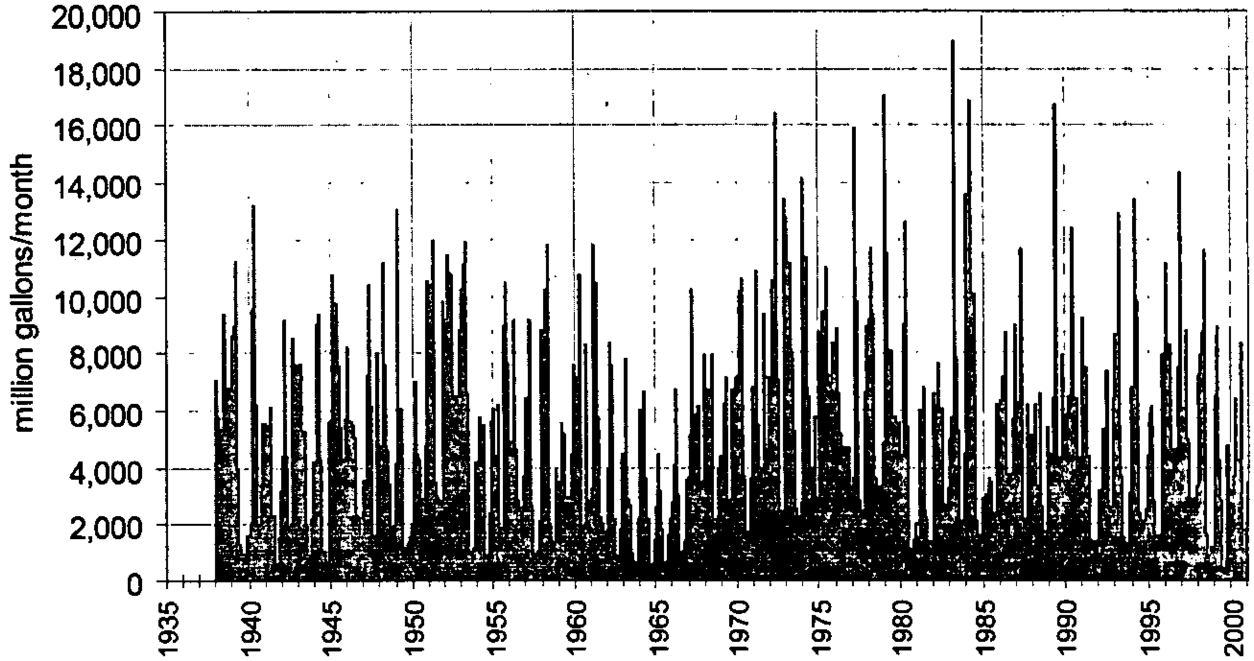


Figure 3. Total monthly streamflows, Rockaway River above the reservoir at Boonton, 1938-2000.

Table 5. Mean monthly streamflows, Rockaway River above the reservoir at Boonton, 1938-2000

month	Mean monthly flow, (million gallons)
Jan	5,319
Feb	5,040
Mar	7,865
Apr	7,567
May	5,554
Jun	3,517
Jul	2,535
Aug	2,380
Sep	2,345
Oct	2,483
Nov	4,165
Dec	5,433

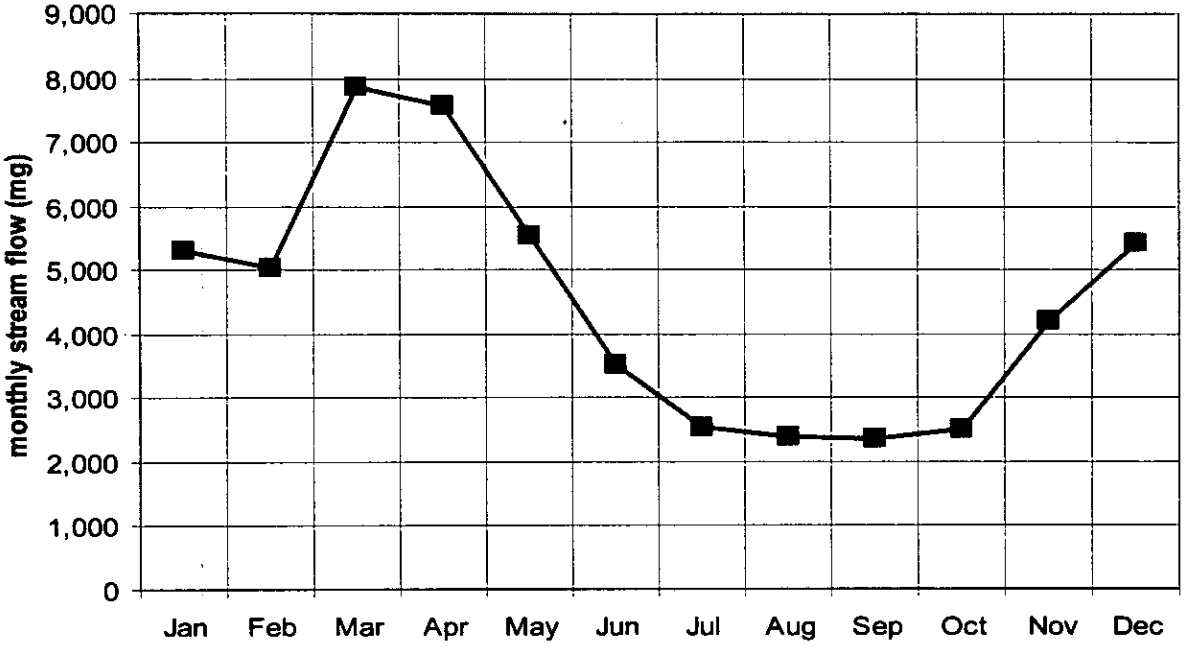


Figure 4. Mean monthly streamflows, Rockaway River above the reservoir at Boonton, 1938-2000.

These monthly deviations for 1938-2000 for the Rockaway gage are shown in figure 5. A positive number indicates that the streamflow that month was greater than mean, a negative number less than mean.

There is a lot of scatter in these data. During periods of drought some months showed a total streamflow volume above mean. And there are months of less than mean monthly streamflow volumes during times of sufficient water supply. This statistic by itself is not a useful predictor of water-supply droughts in New Jersey.

The fourth step of the development phase was to look at cumulative streamflow deviations from normal over longer periods. This is done to better detect the longer-term dry periods which cause water-supply shortages. This statistic is calculated by adding a month's observed streamflow deviation to the observed deviations in previous months.

The n-month cumulative streamflow deviation in month m of year y ($\Delta MQ\_cum_{m,y,n}$) is the sum of the cumulative streamflow deviation for that month and the (n-1) previous months:

$$\Delta MQ\_cum_{m,y,n} = \sum_{i=0}^{n-1} \Delta MQ_{(m-i),y} \qquad (4)$$

where i is a summation variable and the other variables are as previously defined. For some values of m and i the results are negative. This indicates calculation for months early in a given year includes monthly deviations from the end of the previous year.

The n-month cumulative streamflow deviation was calculated for antecedent time periods of 1, 3, 6, 9 and 12 months. This statistic was determined for every month in the data record 1938-2000, except for those months in 1938 which did not have a sufficient number of antecedent months. Note that the 1-month cumulative streamflow deviation is the same as the monthly streamflow deviation:

$$\Delta MQ\_cum_{m,y,1} = \Delta MQ_{m,y} \qquad (5)$$

Figure 6 shows the cumulative monthly streamflow deviations for the Rockaway River gage above the reservoir at Boonton based on data from 1938 to 2000 for 1-, 3-, 6-, 9-, and 12-month periods. Visual analysis of this curve shows longer time periods have a smoother appearance; short-term fluctuations are not as noticeable. On the other hand, the longer the time period, the longer it takes for this statistic to exhibit a change in streamflow patterns. The 12-month cumulative streamflow deviation curve may be influenced by a wet period for months after that period has ended and a dry period started. The longer the time period, the greater that chance that the signal from a short-term but intense drought may be hidden by antecedent or subsequent wet conditions.

The fifth step of the development phase involved calculating the frequency distribution of monthly cumulative streamflow deviations for each of the five antecedent periods. The cumulative monthly streamflow deviations for each of the twelve calendar months and each of the five antecedent summation periods (1, 3, 6, 9, and 12 months)

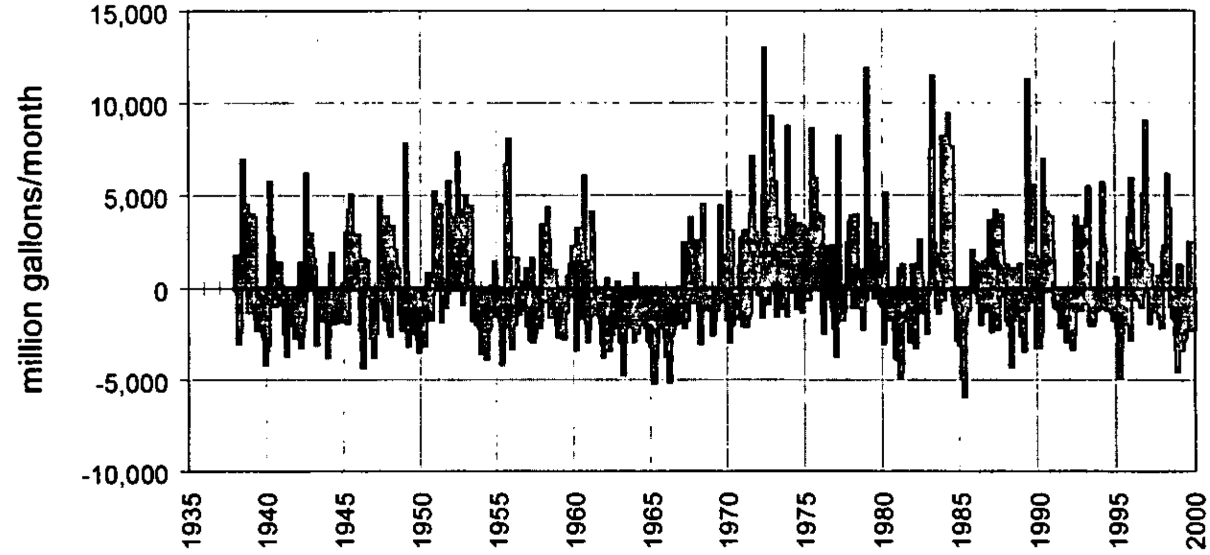


Figure 5. Monthly streamflow deviations, Rockaway River above the reservoir at Boonton, 1938-2000.

was ordered from the greatest to the least. This resulted in 60 orderings. Each ordering had as many entries as there are years in the data record. Each of the 60 orderings was then broken into ten deciles (Gibbs and Maher, 1967). A decile contains 10% of the reported values. The lowest decile of each ordering contained the lowest 10% of calculated cumulative streamflow deviations for that month and summation period observed in the data record.

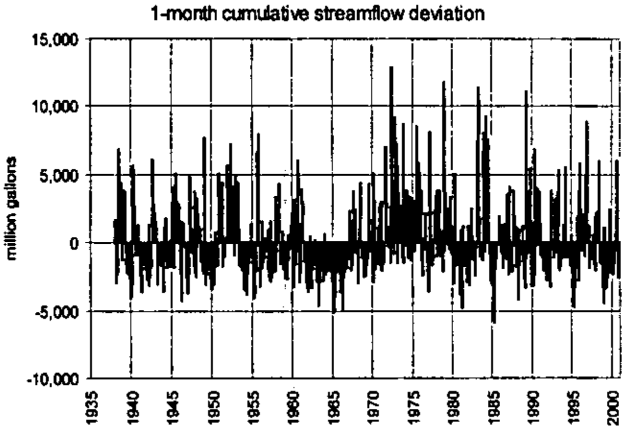
Three 'exceedence frequency' statistics for the monthly flow (MQef) were then calculated for each of the 60 orderings of monthly cumulative streamflow deviations. The 10% monthly flow exceedence frequency value ($\text{MQef}_{m,n,10\%}$) is defined as that streamflow volume which, for the ordering of values for month m and a summation period of n months, separates the lowest 10 % of the values from the greatest 90%. It is equivalent to that value which divides the first (lowest) decile from the next higher one. The 30% monthly flow exceedence frequency value ($\text{MQef}_{m,n,30\%}$) separates the three lowest deciles from the remainder. The 50% monthly flow exceedence frequency ($\text{MQef}_{m,n,50\%}$) is the median value of the ordering.

The 10% and 30% exceedence frequencies were chosen in order to be consistent with unpublished work done on reservoir safe yields in northeastern New Jersey by the DEP (Asghar Hassan, DEP, Water Supply Administration, 2000, oral communication). The 50% expected frequency was chosen as a reference point of what value can be expected, based on the historical record, to divide observed values in half.

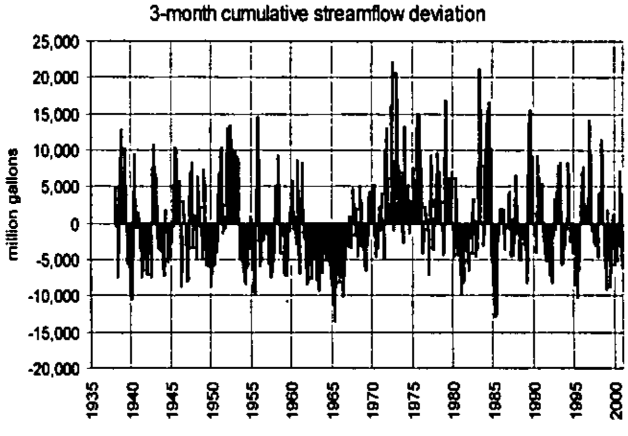
Figure 7 shows calculated monthly 50%, 30% and 10% monthly flow exceedence frequencies for the 1-, 3-,6-, 9-, and 12-month cumulative streamflow deviation curves for the Rockaway River stream gage above the reservoir at Boonton based on data from 1938 to 2000. For example, the January 1-month cumulative streamflow deviation 10% exceedence frequency value is -3,072 million gallons; only 10% of the Januaries had a 1-month streamflow deficit drier than this whereas 90% were wetter.

Similarly, the January 1-month cumulative streamflow deviation has a 50% exceedence frequency of -609 million gallons. This means that of all the 1-month streamflow deviations observed in January over the period of record, 50% were greater and 50% were lower. This is the median value of this frequency distribution. It is interesting to note that the median is not zero. This is because streamflows do not show a normal distribution; higher streamflows skew the distribution to the right. The mean of all 1-month cumulative streamflow deviations would be zero, the median is not.

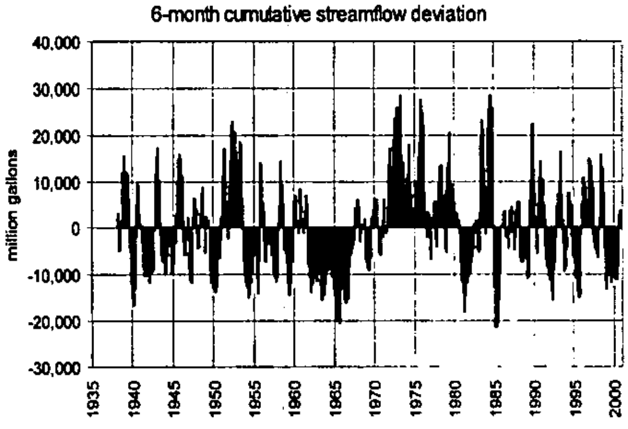
The sixth and final step of the development phase was to compare the observed monthly cumulative deviations to the exceedence frequency curves for the five antecedent summation periods to determine what forms a useful drought indicator. This is equivalent to superimposing figure 7 on figure 6. Since figure 7 shows values by calendar month, each curve has to be repeated once per year over the period of record. Figure 8 shows this superposition for the period 1960-2000. Only cumula-



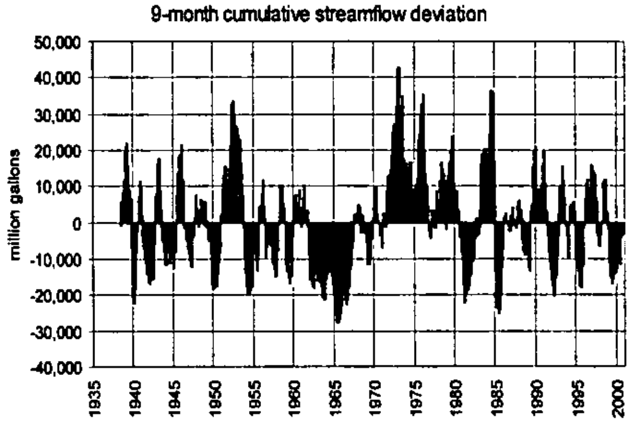
1-month cumulative streamflow deviation



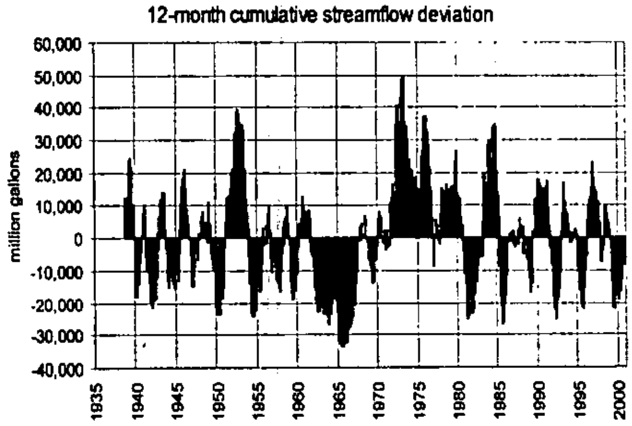
3-month cumulative streamflow deviation



6-month cumulative streamflow deviation



9-month cumulative streamflow deviation



12-month cumulative streamflow deviation

Figure 6. Cumulative monthly streamflow deviations above the Boonton Reservoir, 1938-2000, for 1, 3, 6, 9, and 12 month periods.

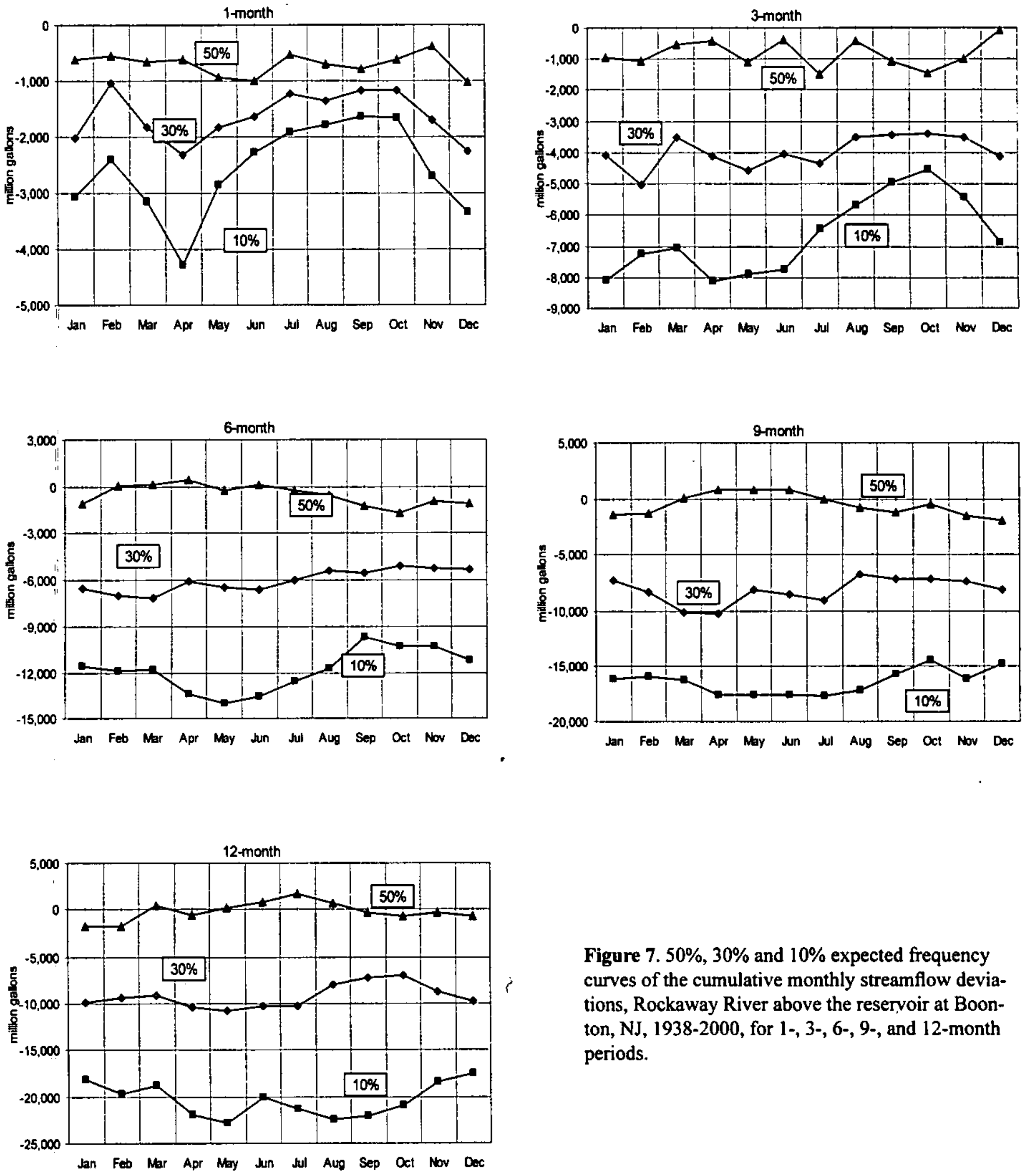


Figure 7. 50%, 30% and 10% expected frequency curves of the cumulative monthly streamflow deviations, Rockaway River above the reservoir at Boonton, NJ, 1938-2000, for 1-, 3-, 6-, 9-, and 12-month periods.

tive streamflow deviations less than zero are shown as these represent the drier periods that are of interest for this drought analysis. The 50% expected frequency curve is not shown in order to lessen graphical clutter.

Figure 8 was the basis for determining the most useful statistic for tracking periods of water-supply shortages using this cumulative-streamflow-deviation approach. The analysis consisted of visually comparing when the cumulative streamflow deviation fell below the 10% and 30% exceedence frequency curves, and comparing this to times of water shortages (tables 1 and 2) for the six stream gages in table 3. This analysis resulted in a determination that the 1-month cumulative streamflow deviation curve reacted too quickly. The 6-, 9-, and 12-month cumulative streamflow deviation curves did match longer-term dry periods better but they reacted too slowly to the start and stop of these periods. The 3-month cumulative-streamflow-deviation curves showed the best match to the start of times of declared water shortages. A 3-month period was also determined by Harnack and Small (2002) to be the most useful time period for tracking precipitation deficits at the New Brunswick precipitation gage.

When the monthly 3-month cumulative streamflow deviation curve was in the lowest 10% of values observed in that month ($\Delta MQ\_cum_{m,y,3} < MQef_{m,3,10\%}$) it was a reasonable indicator of extremely dry conditions at that gage. When the deviation curve was in the 10% to 30% range ($MQef_{m,3,10\%} < \Delta MQ\_cum_{m,y,3} < MQef_{m,3,30\%}$) it was a reasonable indicator of severely dry conditions at that gage. And when deviation curve was in the 30% to 50% range ($MQef_{m,3,30\%} < \Delta MQ\_cum_{m,y,3} < MQef_{m,3,50\%}$) it was a reasonable indicator of moderately dry conditions.

This approach provided the baseline to which observed data are compared. However, since it is based on cumulative monthly streamflows it can be updated only when all data for that month are available. This is not acceptable during the onset of a drought when the DEP must decide, on a weekly or daily basis, whether or not conditions have worsened enough to warrant changing the drought condition. In order to make this a useful tool it must be applied to daily streamflows rather than to total monthly flows.

Application Phase

The application phase consisted of developing a methodology to apply the monthly exceedence frequency curves on a daily basis for each gage. The steps in this second phase were: 1) calculate mean daily streamflows; 2) calculate daily deviation between observed and mean daily streamflow; 3) calculate a running 90-day cumulative-streamflow deviation; 4) determine the exceedence frequency for the observed 90-day cumulative flow deviation for that day; and 5) average the exceedence frequencies from all stream gages in a drought region. Each step is described in more detail below, using the Rockaway River gage above the reservoir at Boonton as an example. All data from the period 1938-2000 were used in this phase. In order to simplify the graphics, however, only data from 1998-2000 are shown in the figures.

The first step of the application phase was to determine the mean daily streamflows. This was done by dividing mean monthly streamflows (table 5) by the number of days in each month:

$$\overline{DQ}_m = \overline{MQ}_m / D_m \qquad (6)$$

where:

$\overline{DQ}_m$ = the mean daily streamflow in calendar month (m)

$\overline{MQ}_m$ = the mean total monthly streamflow volume in calendar month (m)

D_m = the number of days in calendar month (m).

(February was assumed to always have 28 days in this step.) The result is expressed in millions of gallons per day (mgd). Figure 9 shows $\overline{DQ}_m$ values (based on the period 1938 to 2000) with observed daily streamflow values for 1998-2000.

The second step of the application phase was to calculate daily streamflow deviation. This is the difference between observed daily streamflow and expected mean daily streamflow:

$$\Delta DQ_{d,m,y} = DQ_{d,m,y} - \overline{DQ}_m \qquad (7)$$

where:

$\Delta DQ_{d,m,y}$ = difference between observed and mean aily streamflow for day (d) of month (m) of year (y)

$DQ_{d,m,y}$ = observed daily streamflow for day (d) of month (m) of year (y)

$\overline{DQ}_m$ = the mean daily streamflow in calendar month (m)

The daily deviations are the difference between the two lines in figure 9 are shown in figure 10. Values less than zero in figure 10 indicate streamflow that day was less than the long-term mean-daily flow for that month. The high peak in September 1999 is runoff from Tropical Storm Floyd.

The third step of the application phase was to calculate the 90-day cumulative streamflow deviation. Nine-

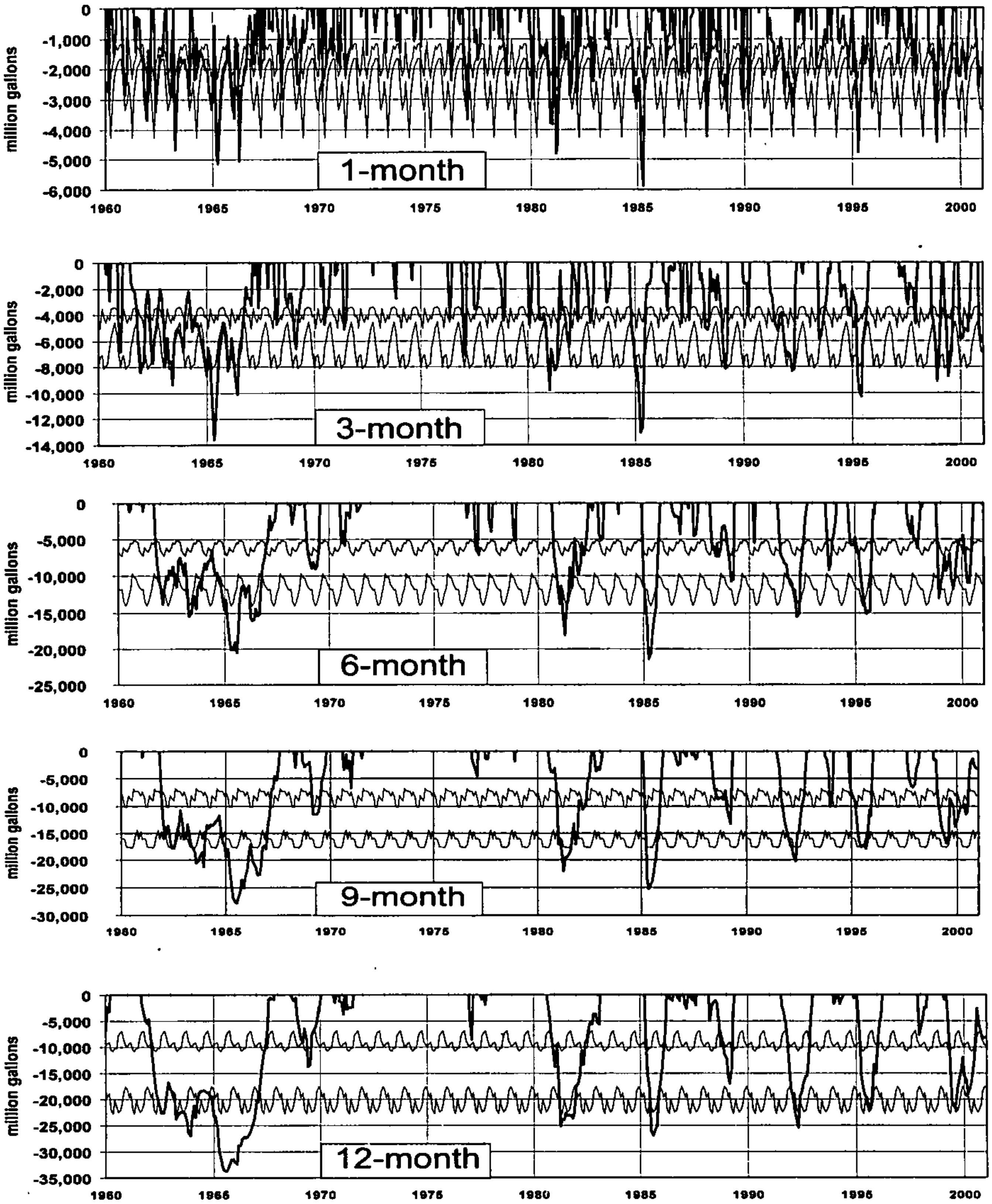


Figure 8. Cumulative monthly streamflow deviations less than 0 million gallons, Rockaway River above the reservoir at Boonton, 1938-2000, for 1-, 3-, 6-, 9- and 12-month periods with 10% and 30% expected frequency curves.

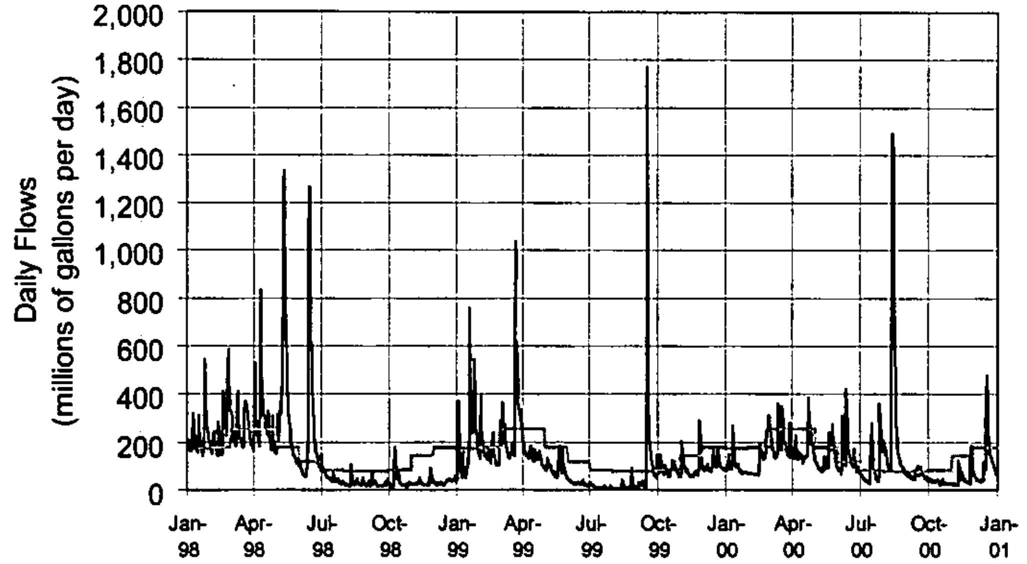


Figure 9. Observed daily streamflow (black line) and long-term mean daily streamflow (gray line) at the Rockaway River above the reservoir at Boonton, 1998-2000.

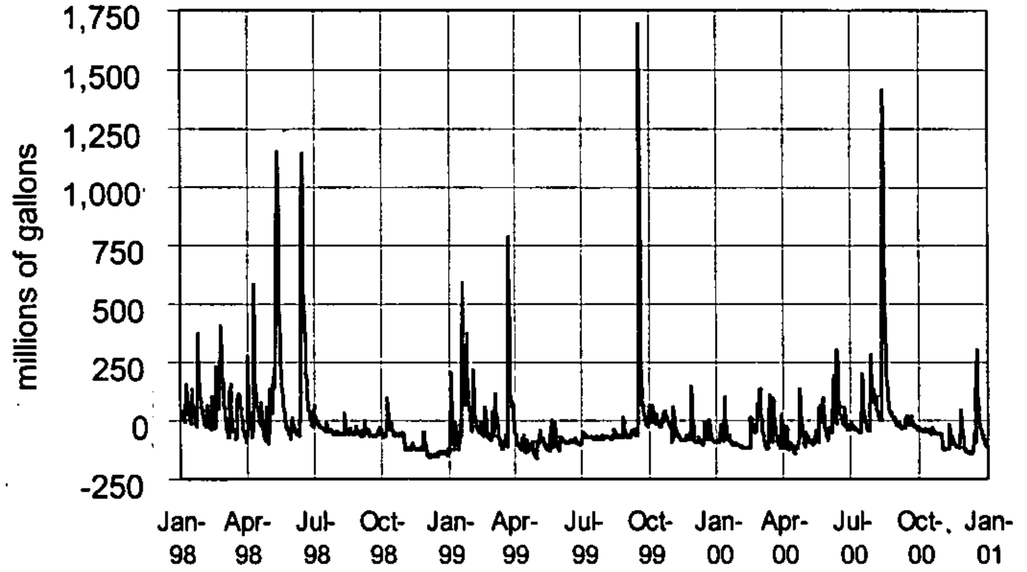


Figure 10. Observed daily streamflow deviations, Rockaway River gage above the reservoir at Boonton, 1998-2000.

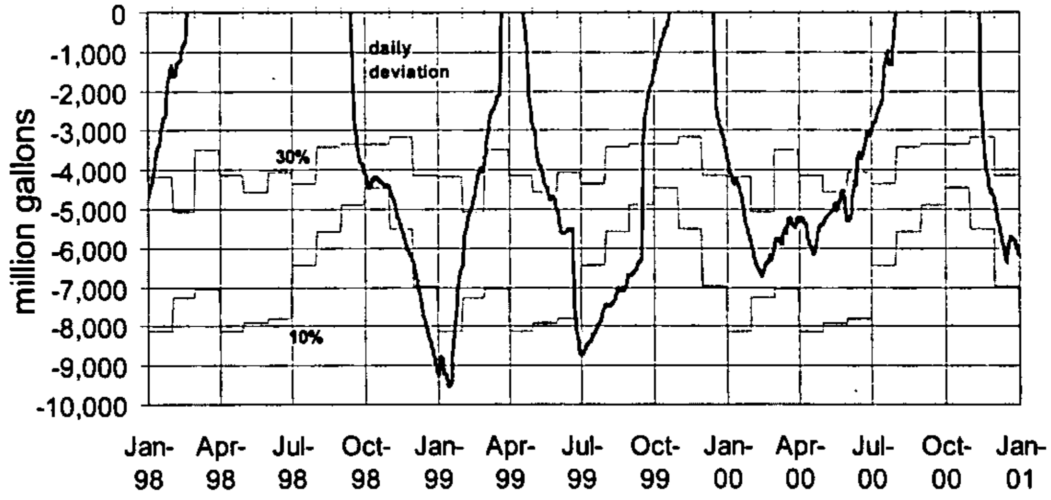


Figure 11. 90-day cumulative daily streamflow deviations, Rockaway River above the reservoir at Boonton, 1998-2000, with 10% and 30% monthly exceedence frequency curves.

ty days is roughly equivalent to 3 months, the time lag that was determined to provide the best match between monthly cumulative streamflow deviation and periods of known water-supply shortages. The 90-day cumulative streamflow deviation is the streamflow deviation at a given day added to the deviations for the previous 89 days:

$$\Delta DQ\_cum_{d,m,y,90} = \sum_{i=0}^{89} \Delta DQ_{d-i,m,y} \qquad (8)$$

where $\Delta DQ\_cum_{d,m,y,90}$ is the 90-day cumulative streamflow deviation for day d of month m of year y, and i is a summation variable. For many values of d and i the result is a negative number. This indicates that values from a previous month are included in the sum.

This step results in the statistic that supports the analysis of streamflow conditions. Figure 11 shows the 90-day cumulative streamflow deviations (the black line) that were less than 0 for 1998-2000. (Only negative deviations are shown as this indicates a drier-than-normal period that is of interest in a drought analysis.) Also in figure 11 are the 10% and 30% expected-frequency curves for the 3-month cumulative streamflow analysis ($MQef_{m,3,10\%}$ and $MQef_{m,3,30\%}$). Any day when the 90-day cumulative streamflow deviation is less than the 10% frequency curve, streamflow at this gage is judged to be in an extremely dry condition. When the deviation is between the 10% and 30% frequency curves streamflow is judged to be in a severely dry condition. This relationship is qualified in table 6.

The third step resulted in a flow volume (in millions of gallons) that can be compared to the expected-frequency curves (which also have units of millions of gallons) developed for that gage (fig. 11). This visual comparison is sufficient to characterize the results from one streamflow gage. But this isn't sufficient to allow combining results from different gages in a drought region. Streams with larger mean flow volumes will develop greater deviations. In order to integrate the results from different gages a metric that is independent of volume is required. This is done in the fourth and fifth steps of the application phase.

The fourth step of the application phase consisted of estimating more precisely the expected frequency of the 90-day cumulative streamflow deviation. Numerically, this step consists of comparing the 90-day cumulative streamflow deviation ($\Delta DQ\_cum_{d,m,y,90}$) to the ordering of the 3-month cumulative streamflow deviation ($\Delta MQ\_cum_{m,y,3}$) from steps 4 and 5 of the development phase. For example, on June 14, 1999 the 90-day cumulative daily streamflow deviation at the Rockaway River

Table 6. Relation between streamflow condition, 90-day cumulative streamflow deviation and monthly exceedence frequency

Streamflow condition	90-day cumulative streamflow deviation status
near or above normal	$\Delta DQ\_cum_{d,m,y,90} > MQef_{m,3,50\%}$
moderately dry	$MQef_{m,3,50\%} \geq \Delta DQ\_cum_{d,m,y,90} > MQef_{m,3,30\%}$
severely dry	$MQef_{m,3,30\%} \geq \Delta DQ\_cum_{d,m,y,90} > MQef_{m,3,10\%}$
extremely dry	$\Delta DQ\_cum_{d,m,y,90} \leq MQef_{m,3,10\%}$

gage was -5,373 million gallons (fig. 11). This puts the daily deviation between the 10% and 30% exceedence frequency curves. A frequency analysis of the June 3-month cumulative streamflow deviations for this gage shows that a value of -5,373 million gallons is estimated to have an exceedence frequency of 18.2% in June. This was done for every day in the data record. Figure 12 shows 90-day cumulative streamflow deviation at the Rockaway River gage, plotted as a percent exceedence, relative to the observed 3-month cumulative streamflow deviations for each month.

This step has it's complications. Because daily cumulative deviations are being compared to monthly deviations (which tends to smooth out daily fluctuations), it is possible for daily values to be greater or lower than historical monthly values. In this case the frequencies are set to either 100% or 0%, respectively. An additional complication is that while the 90-day cumulative deviation tends to change smoothly from one day to the next the monthly cumulative deviation jumps between months (fig. 11). Thus while the 90-day cumulative deviation volume may change little from the last day of one month to the first day of the next, the percent exceedences assigned to each day may be quite different.

The fifth step of the application phase was to develop a region-wide number. This is done by averaging the expected frequency of the 90-day cumulative streamflow deviations for all three gages in a drought region. If this average is less than 10%, the region as a whole is considered to be extremely dry. If it is between 10% and 30%, it is severely dry, and between 30% and 50% is moderately dry. Over 50% is near or above normal. For example, on June 15, 1999 the Rockaway River gage's expected frequency of the 90-day cumulative streamflow deviation was 18.2%, for the Passaic River near Millington it was 21.6% and Ringwood Creek near Wanaque was 22.8% (table 7). The average of these values is 20.9%. Thus on this date the DEP considered streamflow in the northeast drought region as a whole to have been in a severely dry condition.

Application and limitations

This process was developed throughout 2000 and implemented in January 2001. It is applied to each stream gage and drought region when the drought indicators are updated. This is generally done weekly during dry times and biweekly during normal and wet periods.

The DEP intends to update the underlying monthly statistics (steps 1 through 4 of the development phase) after each drought. As currently implemented, the entire period of record of a gage is used to develop the monthly statistics. There is some discussion of whether or not this is appropriate. Perhaps only the most recent 30 years of streamflow should be used, in recognition of the fact that changing land use practices in the watershed above each gage may affect runoff. But the drought of record in New

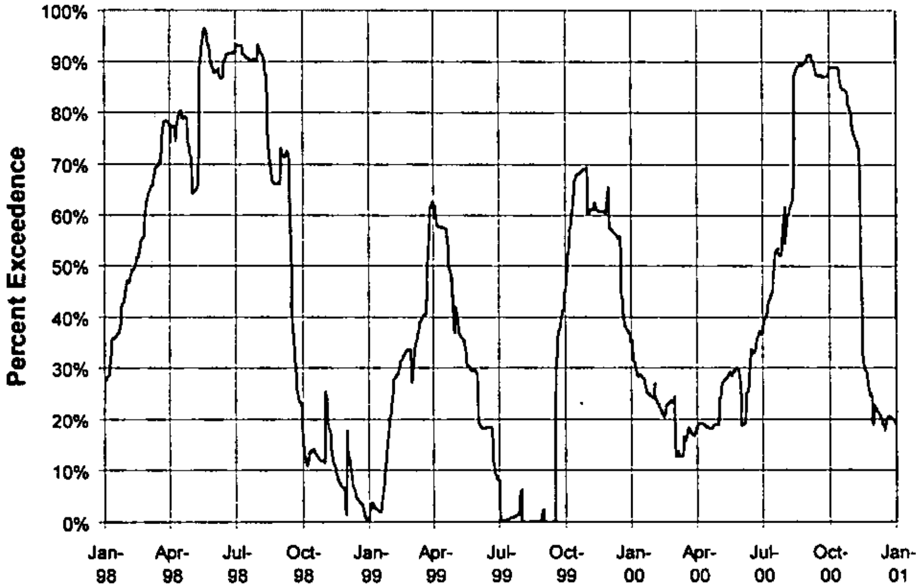


Figure 12. Ninety -day cumulative streamflow deviation at Rockaway River above the reservoir at Boonton, 1998-2000, as percent exceedence of historical 3-month cumulative streamflow deviations. (Values greater than 50% indicate wetter than normal conditions, less than 50% are drier than normal.)

Table 7. Northeast drought region streamflow gage data June 15, 1999

Stream gage	Daily flow (mg[1])	90-day cumulative flow deviation (mg[1])	Estimated exceedence frequency
Rockaway River above reservoir at Boonton	31.34	-5,373	18.2%
Passaic River near Millington	11.63	-2,016	21.6%
Ringwood Creek near Wanaque	5.49	-617	22.8%
average:	--	--	20.9%

[1] mg = million gallons

Jersey occurred in the mid-1960s. Any statistical analysis which does not include this period may not be suitable for this application. An additional concern is the impact of any long-term climatic cycles. But defining these cycles, identifying them in the data record, and then incorporating this knowledge into a predictive tool, is problematic. This question of the most appropriate period to use in calculating the reference monthly statistics has not been resolved.

The approach detailed above creates an expected mean daily flow by dividing mean monthly streamflows (table 5) by the number of days in each month. This results in the same value for each day of a month, for a total of 12 different values. A different but more accurate way to do this is to actually calculate the mean daily flow for each day based on the data record. Thus there is one value for January 1, another for January 2, and so on, for a total of 366 values. (These mean daily flows are available on the U.S. Geological Survey's internet web page.) Daily streamflow deviations were calculated using this alternate way to estimate mean daily flows and the analysis procedure redone for one gage (Rockaway River above the reservoir at Boonton). The net result was that there were no substantive differences in the 90-day cumulative deviations calculated. Thus for the purposes of this analysis the method used to calculating monthly mean daily streamflows is appropriate.

This approached detailed above is not the only possible approach to developing a streamflow drought indicator. However, it does yield an indicator that has proven to be useful to the DEP. It produces a summary of streamflow conditions in a drought region that is easy to understand. It can be updated quickly using daily streamflows supplied by the U.S. Geological Survey on a real-time basis. It yields a percentage that can be used to combine information from streams of greatly differing flow volumes. And it can be used to compare the drought situation in different drought regions or to track the progression of drought over time in one region.

DEVELOPMENT OF A GROUND-WATER DROUGHT INDICATOR

Ground-water levels in the water-table aquifer are important for two reasons. As these levels fall during a drought shallow wells go dry or experience difficulties in supplying water. Additionally, the water-table aquifer is the principal source of base flow to streams which sustains streamflow between storm events. As ground-water levels in the water table drop this base flow diminishes. This can create difficulties for water purveyors that depend on downstream water-supply intakes. An analysis of ground-water levels can help anticipate times of low stream base flows.

Ground-water levels in confined aquifers in New Jersey do not show a direct impact of droughts. Thus an analysis of confined water levels is not useful in analyzing drought severity. However, increased withdrawals from a confined aquifer during a drought to compensate for lesser volumes of water available from other supplies can cause greater than normal drawdowns. Thus a drought can indirectly affect confined ground-water levels.

Ground-water levels do not lend themselves to the cumulative exceedence analysis done for streamflow. Instead, the analysis is done by comparing observed water levels on a given day to a probability distribution of reported water levels for that calendar month.

The development and application of a drought indicator is done in three steps: 1) Compute mean monthly water levels for the period of record; 2) set up expected frequency distributions for calendar-month water levels; and 3) compare observed water level to the frequency distribution for that month to determine drought status. This process is illustrated below using data from the Lebanon observation well in Burlington County (table 8).

The first step is to compute monthly mean water levels. The Lebanon well has been monitored since Septem-

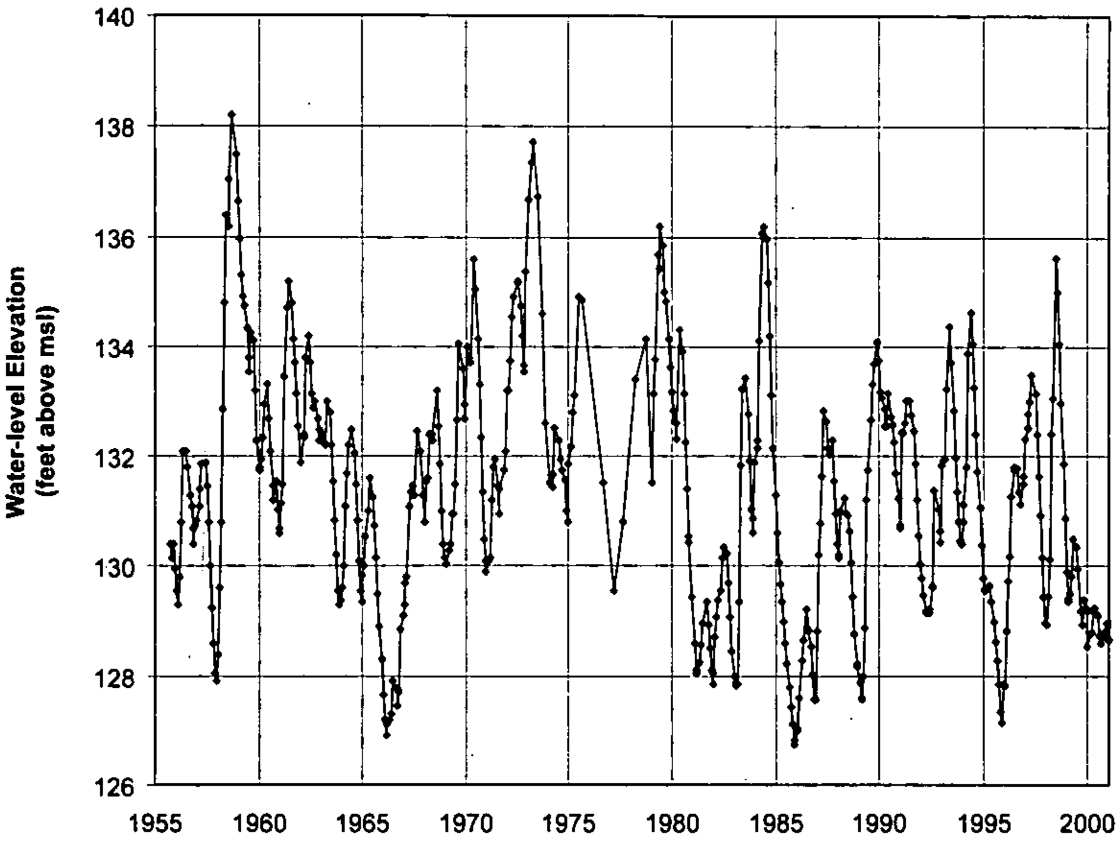


Figure 13. Lebanon observation well mean monthly ground-water levels, 1955-2000 (msl = mean sea level).

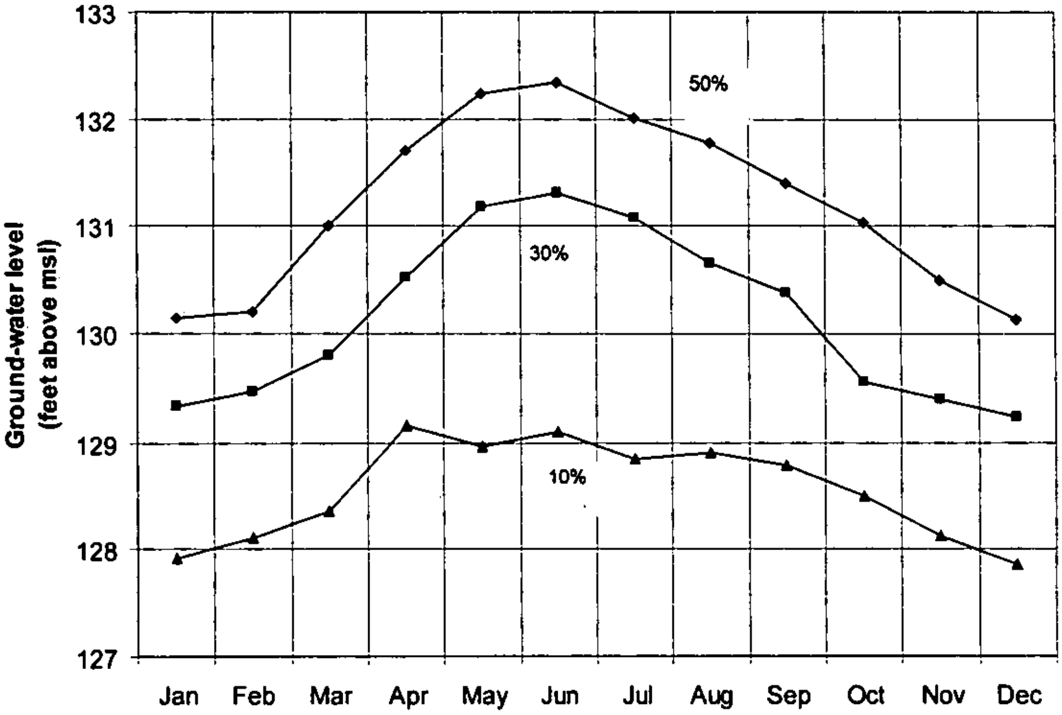


Figure 14. Lebanon observation well 10%, 30% and 50% exceedence frequency curves.

Table 8. Long-term water-table water-level observation wells in the drought indicators network, 2002

Well name	USGS ID	County	Aquifer	Well depth	Drought Region	Data from
Lebanon SF 23-D	05-0689	Burlington	Kirkwood-Cohansey	33	Coastal South	9/1955
Winslow 5	07-0503	Camden	Kirkwood-Cohansey	76	Southwest	12/1972
Pump Pond N.	09-0333	Cape May	Holly Beach	43	Coastal South	7/1992
Vocational School 2	11-0042	Cumberland	Kirkwood-Cohansey	47	Coastal South	3/1972
Corsalo Rd.	19-0251	Hunterdon	Passaic Formation	299	Central	6/1989
Readington School 11	19-0270	Hunterdon	Passaic	101	Central	4/1990
Environmental Center 1	19-0276	Hunterdon	Stockton Formation	175	Central	3/1991
Cranston Farms 15	21-0364	Mercer	Stockton	200	Southwest	3/1990
Morrell 1	23-0104	Middlesex	Englishtown	11	Central	10/1923
Green Pond 5	27-0028	Morris	Stratified Drift	120	Northeast	11/1981
Black River 10	27-1190	Morris	Precambrian	200	Central	4/1991
LNAS-EC	29-1060	Ocean	Kirkwood-Cohansey	38	Coastal North	5/1992
Taylor	37-0202	Sussex	Bossardville Limestone	95	Northwest	10/1988
Swartswood Park 5	37-0205	Sussex	Allentown Dolomite	148	Northwest	4/1991
Union Co. Park	39-0119	Union	Passaic Formation	290	Central	6/1943

ber 1955. For months with more than one measurement, a mean was computed to produce one value per month. Months that lacked a water-level measurement were dropped from the analysis. Figure 13 shows monthly water levels in this well for the period 1955 - 2000.

The second step is to calculate, based on the mean monthly water levels, the probability distribution and exceedence frequencies of ground-water levels in each month. The 10%, 30% and 50% exceedence frequencies were chosen to be consistent with what was developed for the streamflow drought indicators. Figure 14 shows the exceedence frequency for the Lebanon observation well. For example, the frequency analysis of mean June water levels shows that only 10% were lower than 129.1 feet above mean sea level, only 30% were lower than 131.2 feet, and the median reported value was 132.4 feet.

The statistics calculated in this step are very dependent on the length of the data record. Some of the wells, for example, Pump Pond and Environmental Center (table 8) have less than 10 years of data. Thus the exceedence frequency curves for these are probably not very accurate. However, they are the best that can be done with available data. As more data become available, the DEP intends to revise these statistics.

The third and last step is to compare observed water levels to the exceedence frequency curves. This is done based on the latest available water levels. Figure 15 shows observed ground-water levels and the frequency curves for the period 1990-2000. Water levels in this well fell into the severely dry range in early 1995 and into the extremely dry range in mid-1995. Ground-water levels did not recover until early 1996. Levels again fell into the severely dry range in early 1999 and remained in either this range or the extremely dry range throughout 1999 and 2000.

In late 2001 there were seven wells in the drought well network (Jones and others, 2002). By 2002 this number had increased to 15 (table 8, fig. 1). The DEP and USGS plan to add wells to this network as time and money allow. The distribution and limited number of drought wells throughout New Jersey do not support a strict quantitative approach to setting a region's ground-water drought status based on these data. Instead, the status of all wells in a region, as well as of any wells located outside but close to the region and judged to be in a similar geologic setting, are used in a qualitative manner to set a region's ground-water status.

This process was implemented on a formal basis in January 2001. It is generally done for each well in the drought network weekly during dry times and biweekly during normal and wet periods.

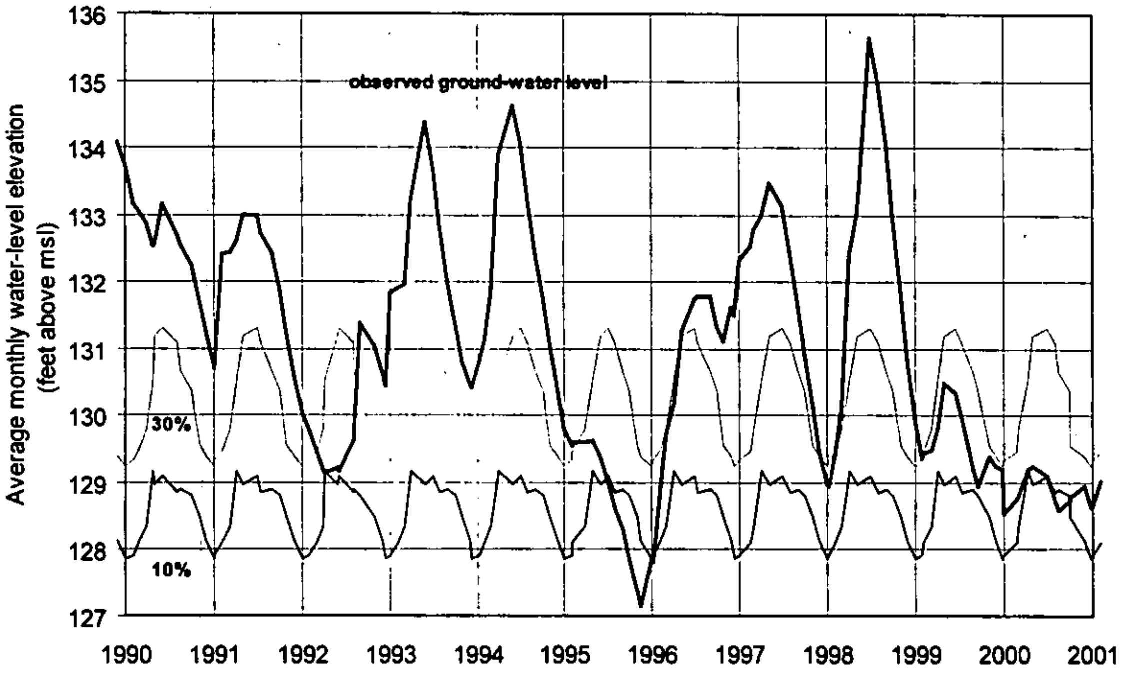


Figure 15. Lebanon observation well mean monthly ground-water levels with 10% and 30% exceedence frequency curves, 1990-2000 (msl = mean sea level).

CURRENT IMPLEMENTATION AND FUTURE PLANS

Currently (2003) the drought indicators are updated biweekly during normal periods and weekly during dry periods. The results are made available on the DEP's drought web site:

http://www.njdrought.org

The United States Geological Survey provides streamflow and ground-water data on a real-time basis over the Internet. Data from numerous sites are reported to a central station and then made available on the Internet within a few hours of being measured. Data for New Jersey are available at:

http://waterdata.usgs.gov/nj/nwis/rt

The DEP downloads data from this web site to evaluate current status and update the drought indicators.

The streamflow drought indicator for each region is based on an analysis of streamflow deficits at three gages in that region. These gages were picked to avoid flow modifications by reservoirs and major intakes. There are currently no plans to increase the number of gages per region. This is partially due to the time commitment required to update the indicators on a weekly basis during a dry period, the difficulty in finding gages without significant upstream water diversions, and the judgement that adding more gages in each region would not increase the usefulness of this indicator.

The ground-water indicator in each region is based on the status of the wells in that region and wells in neighboring regions in similar hydrogeologic settings. There are an insufficient number of wells in the drought monitoring network to allow for a more rigorous approach. The eventual goal is to have at least one well per county in New Jersey (Jones and others, 2002).

The DEP also uses reservoir and precipitation regional drought indicators to help determine an appropriate drought stage in each region.

Reservoir drought indicators are based on rule curves developed as part of a safe-yield analysis of each reservoir. One drought indicator is used to indicate the status of reservoirs in New Jersey. Another indicator is used for reservoirs in the upper Delaware River Basin in New York.

The New Jersey reservoir drought indicators are based on combined storage in all reservoirs in a region. It is thus possible for an individual reservoir to contain more water or less water than the regional drought indicator. Reservoir levels in the Northwest and Coastal South regions are based on one small reservoir in each region. These small reservoirs are important to the communities they serve but are not important to the overall water supply of the drought region.

The Delaware River reservoir drought indicator is based on water storage in three large reservoirs in the upper Delaware River watershed in New York. The storage volumes are reported by the Delaware River Basin Commission on its web site:

http://www.state.nj.us/drbc/drbc.html

The precipitation drought indicator is currently based on a visual examination of county 90-day precipitation deficits provided by the Middle Atlantic River Forecast Center at:

http://www.erh.noaa.gov/er/marfc/Maps/precip.html

The DEP has developed a precipitation drought indicator. The ultimate goal is to develop a cumulative precipitation deficit indicator comparable to that for streamflow. Currently, real time precipitation data are not readily available on a statewide basis. The DEP is working with the Office of the New Jersey State Climatologist to remedy this deficit by installing a network of precipitation gages that will supply real-time data available on the Internet. These data will be available on the New Jersey Weather and Climate Network:

http://climate.rutgers.edu/njwxnet/

Not all sources of water are of equal importance to the water supply of each drought region. Table 9 is an evaluation of the relative importance of ground water, reservoir and river withdrawals to each drought regions. For example, reservoirs are a major source of water in the Northeast drought region but are not a significant source in the Coastal South region. The rankings are relative to each drought region.

Applying the drought indicators, 2001-2002

Precipitation during 2001 was below normal (fig 16). This resulted in low streamflows and low ground-water levels. The regional drought indicators helped to bring this issue to the attention of the water-supply decision makers who make the actual declarations of drought watch, warning and drought. The indicators especially helped focus attention on streamflows and ground-water levels (table 10) in southern New Jersey. This led to a declaration of drought on November 21, 2001 (table 11). An analysis of precipitation (fig. 16) was also critical in

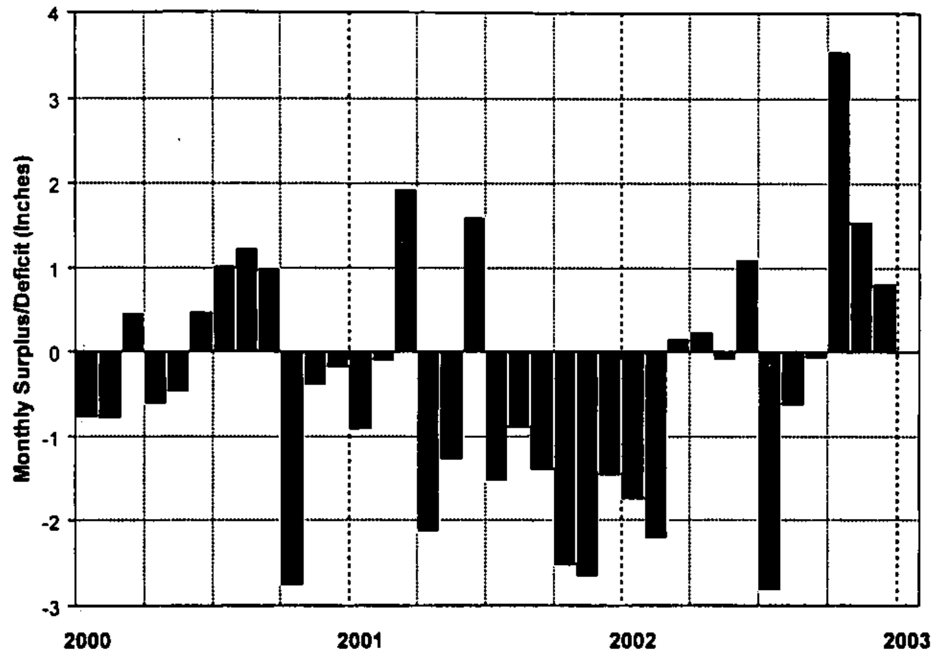


Figure 16. Statewide monthly precipitation surplus/deficit, 2000-2002. The bars are drawn upwards, representing a wetter-than-average month, or downwards, representing a drier-than-average month. A value of zero would indicate that precipitation in that month was exactly average. Average precipitation in each month is shown in the figure. Based on webpage data from the Office of the New Jersey State Climatologist: http://climate.rutgers.edu/stateclim/

Table 9. Relative importance of different sources to potable water supply in each drought region

Drought Region	Water Source			
	Reservoir Withdrawals		River withdrawals	Ground-water withdrawals
	New Jersey reservoirs	Delaware River Basin reservoirs outside NJ		
northwest	minor	minor	major	major
central	moderate	moderate	major	minor
northeast	major	minor	major	minor
southwest	none	major	major	major
coastal north	moderate	none	moderate	major
coastal south	minor	none	minor	major

- Rankings between regions are relative. A minor source of water to one drought region may represent a larger quantity of water than a major source of water in another.
- Rankings are relative to the whole region. A specific water source may be significant for one community but not for the region as a whole.
- Some reservoir releases are to surface water for downstream intakes.
- Drought regions are shown in figure 1.
- Based on information from Paul Schorr (DEP, Water Supply Administration, oral communication, 2000) and Jan Gheen (DEP, Water Supply Administration, oral communication, 2002).
- Delaware River Basin reservoir status affects required passing flows in the Delaware River and the volume NJ is allowed to withdraw from the river via the Delaware and Raritan Canal.
- This table supercedes a similar table in Hoffman, 2001.

Table 10.

Summary of 90-day streamflow and unconfined ground-water drought indicators by region, 2001-2002

Date	Streamflow by Drought Region						Unconfined ground-water by Drought Region					
	Northwest	Central	Southwest	Northeast	Coastal North	Coastal South	Northwest	Central	Southwest	Northeast	Coastal North	Coastal South
1/1/01	░	□	▒	▒	▒	□	□	□	□	□	□	▒
3/1/01	□	▒	□	▒	□	▒	□	□	□	□	□	▒
5/18/01	□	□	□	▒	□	□	□	□	□	□	□	▒
5/30/01	□	□	□	▒	□	□	□	□	□	□	□	□
6/13/01	□	□	□	□	□	□	□	□	□	□	□	□
6/27/01	□	□	□	□	□	□	□	□	□	□	□	□
7/11/01S	□	□	□	□	□	□	□	□	□	□	□	□
7/27/01	□	□	▒	□	□	▒	□	□	□	░	□	□
8/10/01	□	□	▒	□	□	▒	□	□	□	▒	□	□
8/24/01	░	□	▒	□	□	▒	□	□	□	▒	□	▒
9/20/01	▒	□	▒	▒	▒	▒	□	□	□	▒	□	□
10/4/01	■	□	■	▒	▒	■	░	░	□	▒	▒	□
10/18/01	■	▒	■	▒	▒	■	░	░	░	░	▒	□
10/31/01	■	■	■	■	■	■	░	░	■	■	■	▒
11/6/01	▒	▒	■	░	■	■	■	▒	■	■	■	▒
11/14/01	▒	▒	■	■	■	■	■	■	■	■	■	▒
11/21/01	■	▒	■	■	■	■	■	■	■	■	■	■
11/28/01	■	■	■	■	■	■	■	■	■	■	■	■
12/5/01	▒	▒	■	■	■	■	■	■	■	■	■	■
12/12/01	▒	▒	■	■	■	■	■	■	■	■	■	■
12/19/01	■	▒	■	■	■	■	■	■	■	■	■	■
12/26/01	■	■	■	■	■	■	■	■	■	■	■	■
1/2/02	■	■	■	■	■	■	■	■	■	■	■	■
1/9/02	■	■	■	■	■	■	■	■	■	■	■	■
1/16/02	■	■	■	■	■	■	■	■	■	■	■	■
1/23/02	■	■	■	■	■	■	■	■	■	■	■	■
1/30/02	■	■	■	■	■	■	■	■	■	■	■	■
2/6/02	■	■	■	■	■	■	■	■	■	■	■	■
2/13/02	■	■	■	■	■	■	■	■	■	■	■	■
2/20/02	■	■	■	■	■	■	■	■	■	■	■	■
2/27/02	■	■	■	■	■	■	■	■	■	■	■	■
3/6/02	■	■	■	■	■	■	■	■	■	■	■	■
3/13/02	■	■	■	■	■	■	■	■	■	■	■	■
3/20/02	■	■	■	■	■	■	■	■	■	■	□	■
3/27/02	■	■	■	■	■	■	□	▒	■	▒	▒	■
4/3/02	■	■	■	■	■	■	■	■	■	■	▒	■
4/10/02	■	■	■	■	■	■	■	■	■	■	▒	■
4/17/02	■	■	■	■	■	■	▒	■	■	■	▒	■
4/24/02	■	■	■	■	■	■	■	▒	■	▒	▒	■
5/1/02	■	■	■	■	■	■	□	░	▒	□	░	■
5/8/02	■	■	■	■	■	■	□	□	▒	□	□	■
5/15/02	■	■	■	■	■	■	□	□	▒	□	□	■
5/22/02	■	▒	■	■	■	■	□	□	▒	□	□	■
5/29/02	■	▒	■	■	■	■	□	□	▒	□	□	■
6/5/02	■	▒	■	■	■	■	□	□	▒	□	□	■
6/12/02	▒	░	■	▒	■	■	□	□	▒	□	□	■
6/19/02	▒	░	■	▒	■	■	□	□	▒	□	□	■
6/26/02	▒	░	■	□	■	■	□	□	▒	□	□	■
7/3/02	░	░	■	□	■	■	□	□	▒	□	□	■
7/10/02	░	░	■	□	■	■	□	□	▒	□	□	■
7/17/02	░	░	■	□	■	■	░	□	▒	░	▒	■
7/24/02	□	□	■	□	■	▒	░	░	▒	▒	▒	■
7/31/02	□	□	■	□	■	▒	░	▒	■	▒	▒	■
8/7/02	□	░	■	□	■	▒	░	░	■	▒	▒	■
8/14/02	░	░	■	□	■	▒	▒	▒	■	■	▒	■
8/21/02	░	▒	■	▒	■	▒	▒	▒	■	■	■	■
8/28/02	░	▒	■	▒	■	▒	▒	■	■	■	■	■
9/4/02	░	░	■	▒	■	▒	░	▒	▒	■	▒	■
9/11/02	▒	▒	■	▒	■	▒	▒	▒	▒	■	▒	■
9/18/02	▒	▒	■	■	■	■	▒	▒	▒	▒	▒	■
9/25/02	▒	▒	■	■	■	■	▒	▒	■	■	■	■
10/2/02	▒	▒	■	■	■	■	▒	░	■	■	■	■
10/9/02	▒	▒	■	■	■	■	▒	▒	■	■	■	■
10/16/02	▒	▒	■	▒	▒	▒	□	□	▒	□	▒	▒
10/23/02	░	▒	■	□	▒	▒	□	□	▒	□	▒	▒
10/30/02	░	▒	▒	□	░	▒	□	□	▒	□	▒	▒
11/6/02	░	░	▒	□	░	▒	□	□	▒	□	□	▒
11/13/02	░	░	▒	□	░	▒	□	□	▒	□	□	▒
11/20/02	□	░	□	□	□	□	□	□	░	□	□	▒
11/27/02	□	░	□	□	□	□	□	□	░	□	□	▒
12/4/02	□	□	□	□	□	□	□	□	░	□	□	▒
12/11/02	□	□	□	□	□	□	□	□	░	□	□	▒
12/18/02	□	□	□	□	□	□	□	□	░	□	□	▒

□ near or above normal

░ moderately dry

▒ severely dry

■ extremely dry

Table 11. Drought watch, warning, and emergency declarations in New Jersey by drought region, 2001-2003

Region	Drought Status and Date Entered			Drought Status and Date Left			Comment
	Watch	Warning	Emergency	Emergency	Warning	Watch	
Northeast	10/31/01	1/24/02	3/4/02	1/8/03	1/8/03	1/8/03	
Central	10/31/01	---	3/4/02	1/8/03	1/8/03	1/8/03	No warning phase
Coastal North	10/31/01	1/24/02	3/4/02	1/8/03	1/8/03	1/8/03	
Coastal South	10/31/01	11/21/01	3/4/02	1/8/03	3/21/03	3/21/03	
Northwest	10/31/01	11/21/01	3/4/02	1/8/03	1/8/03	1/8/03	
Southwest	10/31/01	11/21/01	3/4/02	1/8/03	3/21/03	3/21/03	

determining which regions went on drought watch and warning.

Winter 2001-2002 was abnormally dry (fig. 16) and this is seen in the streamflow and unconfined ground-water drought indicators (table 10). This lead to moving the northeast and northwest regions to drought warning on January 24, 2002. The central region stayed in watch because storage in the large reservoirs there (Spruce Run and Round Valley) had not significantly declined. However, declining reservoir levels in northeast New Jersey and the Delaware River Basin, as well as low streamflows and ground-water levels, led to a state-wide declaration of drought emergency on March 4, 2002. The central drought region was included in this declaration because it receives some water from the northwest region via the Delaware & Raritan Canal, and can supply water to the northeast region via interconnections. The interconnected nature of water-distribution systems in New Jersey means some drought regions can supply water to, or receive water from, a neighboring region.

Near-normal precipitation in the spring of 2002 resulted in more normal conditions by the summer of 2002 and a filling of reservoirs in the northeast to near-normal levels. Water levels in unconfined aquifers recovered to normal conditions in the spring in 2002 in all regions except the southwest and coastal south regions. However streamflow conditions remained extremely or severely dry in the southwest, coastal north and coastal south drought regions. These considerations led to the decision to keep the drought emergency declaration in place.

In the fall of 2002 increased rainfall resulted in greater streamflows and higher reservoir and ground-water levels. The State's drought emergency was lifted on January 8, 2003 and most of New Jersey returned to a normal drought status. Due to still-lower-than-normal water levels in the unconfined aquifers, the Coastal South and Southwest drought regions were put into drought warning status. These two southern drought regions were returned to normal status on March 26, 2003 as ground-water levels rose in response to spring precipitation.

SUMMARY

A suite of drought indicators has been created for each of New Jersey's six drought regions. The indicators summarize the condition of streamflow, ground-water levels in unconfined aquifers, precipitation, reservoir levels in New Jersey, and reservoirs levels in the Delaware River basin. The indicators are designed to effectively communicate this information to the public and decision makers.

The streamflow indicator is based on comparing the 90-day cumulative flow deviation to a statistical analysis of historical 3-month flow deviations at three gages per region. On a given day the value of the 90-day cumulative flow deviation is compared to a frequency analysis of the historical 3-month flow deviation values for that month. The exceedence frequency of the 90-day deviation is estimated and then averaged with the frequencies from the other stream gages in the drought region. If this average frequency is less than 10%, then the streamflow drought indicator signals that conditions in that drought region are extremely dry; between 10% and 30% is severely dry, between 30% and 50% moderately dry, and over 50% near or above normal.

The ground-water indicator is based on comparing observed water levels to a statistical analysis of historical monthly water levels. The water level on a given day is compared to a frequency analysis of historical monthly water levels and exceedence frequency estimated. If the frequency is less than 10% then that well is considered to reflect extremely dry conditions; between 10% and 30% severely dry, between 30% and 50% moderately dry, and over 50% near or above normal. The ground-water drought indicator for a region is based on all wells in that region and in neighboring regions in a similar hydrogeologic setting.

While other approaches are possible this approach to correlating streamflows and ground-water levels with droughts has proven to be a useful and efficient tool in tracking water-supply shortages in New Jersey on a regional basis on a near real-time basis.

A precipitation drought indicator has not yet been fully developed due to the difficulty of obtaining statewide real-time rainfall data. When these data are available it is anticipated that an approach similar to that done for streamflow data will prove to be useful.

Reservoir drought indicators are based on reservoir storage and previously-developed operating rule curves. These data are made available to the DEP by reservoir operators.

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The drought indicators are updated biweekly during normal periods and weekly during dry times. The results are made available to the public on the Internet at:

http://www.njdrought.org/

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GLOSSARY

aquifer - A formation, group of formations, part of a formation or interconnected fractured bedrock, capable of supplying useful quantities of water to wells and springs.

confined aquifer (artesian) - An aquifer bounded above and below by layers of significantly lower permeability.

drought - A condition of dryness due to lower than normal precipitation, resulting in reduced streamflows, reduced soil moisture, lowering of the water table, and lower reservoir levels.

drought emergency - As applied to New Jersey, a time during which the Governor has declared a threat exists to the water supply of the State. Various emergency actions may be required.

drought indicator - A statistical summary of a water-supply factor that incorporates or summarizes many factors to indicate water-supply conditions.

drought warning - As applied to New Jersey, a time during which water supplies are dangerously low and that the public is encouraged to conserve water.

drought watch - A time during which water supplies are not yet threatened but conditions indicate this may occur in the near future.

N% exceedence frequency - For a given set of ordered numbers, it is that value which separates the lower n% of the set from the upper (100-n)%.

real-time data - Data available for analysis within a short time of being measured.

rule curve - A set of curves showing expected water levels in a reservoir under normal, drought warning, and drought emergency conditions at different times of the year.

salt-water front - A line in a tidal river upstream of which the water is considered to be fresh and downstream salt.

streamflow deviation - The volume by which streamflow is greater or lesser than normal over a defined time period.

unconfined aquifer - An aquifer which has a water table.

water level - The level to which water rises in a well tapping an aquifer.

water-supply emergency - A time during which the water supply is threatened and steps must be taken to reduce demand.

water table - The upper surface of the zone of saturation at which the water pressure in the porous medium equals atmospheric pressure.

water-table aquifer - See unconfined aquifer

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(New Jersey Geological Survey Open-File Report OFR 04-2)