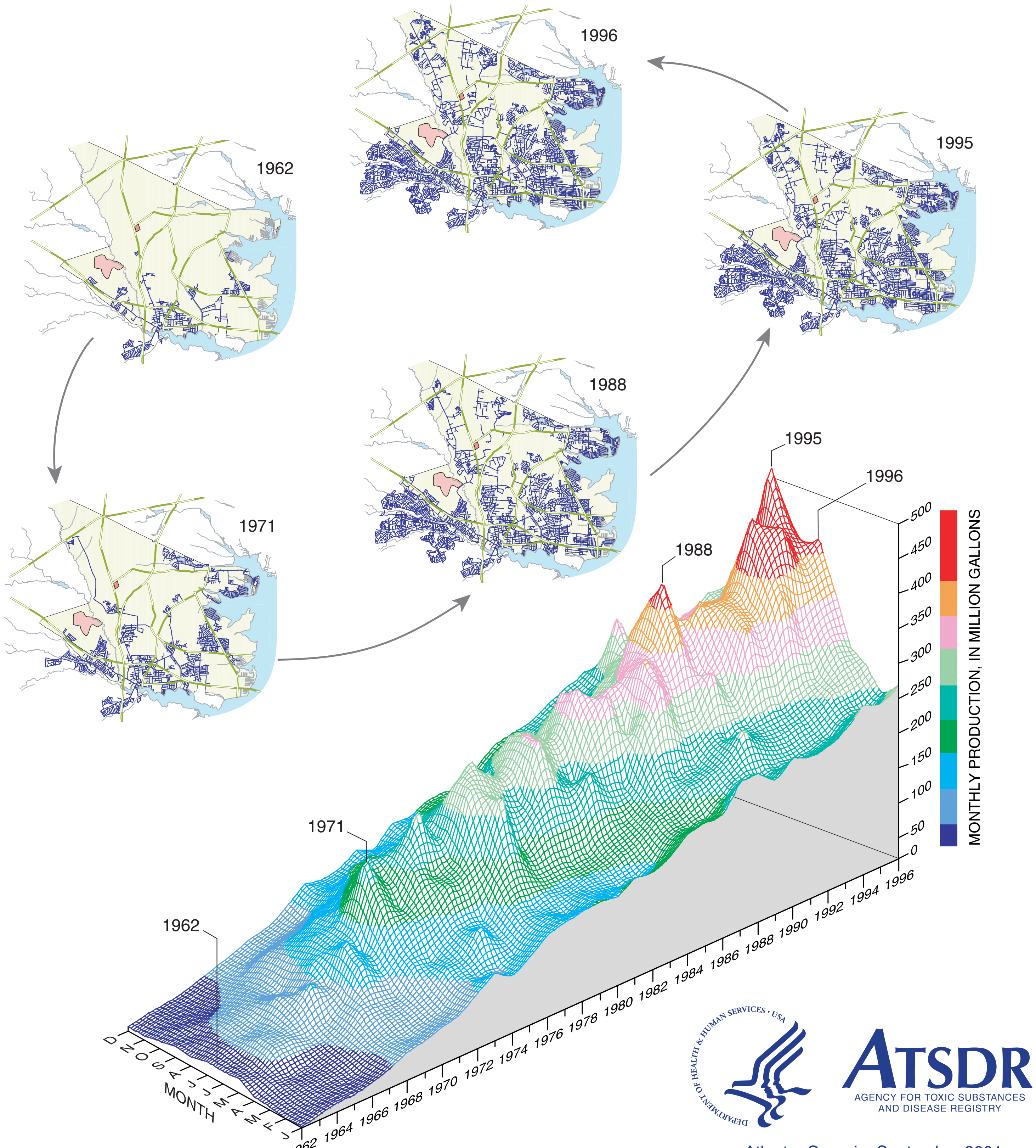
Summary of Findings

Historical Reconstruction of the Water-Distribution System Serving the Dover Township Area, New Jersey: January 1962–December 1996



DEPARTMENT OF HEALTH & HUMAN SERVICES · USA

ATSDR
AGENCY FOR TOXIC SUBSTANCES AND DISEASE REGISTRY

Atlanta, Georgia–September 2001

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Front Cover Illustrations:

Upper Images: Maps showing configuration and expansion of the historical water-distribution system networks serving the Dover Township area, New Jersey: 1962, 1971, 1988, 1995, and 1996.

Lower Image: Plot showing three-dimensional representation of monthly water-supply well production for the Dover Township area, New Jersey, January 1962–December 1996.

SUMMARY OF FINDINGS

HISTORICAL RECONSTRUCTION OF THE WATER-DISTRIBUTION SYSTEM SERVING THE DOVER TOWNSHIP AREA, NEW JERSEY: JANUARY 1962 – DECEMBER 1996

Agency for Toxic Substances and Disease Registry
U.S. Department of Health and Human Services
Atlanta, Georgia

September 2001

FOREWORD

The New Jersey Department of Health and Senior Services (NJDHSS), with support from the Agency for Toxic Substances and Disease Registry (ATSDR), is conducting an epidemiologic study of childhood cancers in Dover Township, Ocean County, New Jersey. In 1996, ATSDR and NJDHSS developed a Public Health Response Plan in cooperation with the Ocean County Health Department and the Citizens' Action Committee on Childhood Cancer Cluster. The plan outlines a series of public health activities including assessments of potential environmental exposures in the community. In 1997, ATSDR and NJDHSS determined that an epidemiologic study was warranted, and that the study would include assessments of the potential for exposure to specific drinking-water sources.

To assist the epidemiologic efforts, ATSDR developed a work plan to reconstruct historical characteristics of the water-distribution system serving the Dover Township area by using water-distribution system modeling techniques. The numerical model chosen for this effort, EPANET 2, is available in the public domain and is described in the scientific literature. To test the reliability of model simulations, water-distribution system data specific to the Dover Township area were needed to compare with model results. Lacking such data, a field-data collection effort was initiated to obtain pressure measurements, storage-tank water levels, and system operation schedules (the on-and-off cycling of wells and pumps) during winter-demand (March 1998) and peak-demand (August 1998) operating conditions. Using these data, the water-distribution system model was calibrated to present-day (1998) conditions. ATSDR released a report and a technical paper in June 2000 describing the field-data collection activities and model calibration results.

Having established the reliability of the model and the modeling approach, the model was used to examine (or reconstruct) historical characteristics of the water-distribution system. For this purpose, monthly simulations were conducted from January 1962 through December 1996 to estimate the proportionate contribution of water from points of entry (well or well fields) to various locations throughout the Dover Township area.

This summary of findings was developed to provide an overview of the historical reconstruction analysis conducted by ATSDR and NJDHSS. A full description of the analysis is forthcoming in a comprehensive report. For the historical period, the following topics are presented in the full report: (1) data sources and requirements, (2) methods of analysis, (3) simulation approaches, (4) selected simulation results of the historical reconstruction analysis, and (5) the use of sensitivity analysis to address issues of uncertainty and variability of historical system operations. Readers interested in details of the historical reconstruction methodology, simulation approaches, or results for specific years and locations for the Dover Township area should refer to the full report that is available over the Internet at the ATSDR Web site at URL: *www.atsdr.cdc.gov*.

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GLOSSARY AND ABBREVIATIONS

Definition of terms and abbreviations used throughout this report are listed below:

Term or Abbreviation	Definition
ATSDR	Agency for Toxic Substances and Disease Registry
Consumption	The use of water by customers of a water utility; is also known as demand. In a water-distribution system, consumption should equal production if there are no losses through leaks or pipe breaks
Direct measurement or observation	A method of obtaining data that is based on measuring or observing the parameter of interest.
EPA	U.S. Environmental Protection Agency
EPANET 2	A water-distribution system model developed by the EPA
Epidemiologic study	A study to determine whether a relation exists between the occurrence and frequency of a disease and a specific factor such as exposure to a toxic compound found in the environment
GA	Genetic Algorithm; a method of optimization that attempts to find the most optimal solution by mimicking the mechanics of natural selection and genetics
Historical reconstruction	A diagnostic analysis used to examine the historical characteristics of a water-distribution system
Manual adjustment process	A modeling approach whereby a balanced flow condition is achieved through the repeated modification and refinement of modeling parameters by the analyst
Master Operating Criteria	Guidelines developed for operating a water-distribution system that are based, in part, on hydraulic engineering principles
Maximum-demand month	A time during a prescribed year when water usage is greatest; is also known as a peak- or summer-demand period
Minimum-demand month	A time during a prescribed year when water usage is least; is also known as a low- or winter-demand period
NJDHSS	New Jersey Department of Health and Senior Services
NPL	National Priorities List; the EPA's official list of hazardous waste sites which are to be cleaned up under the Superfund
Point of entry	The location where water enters a water-distribution system from a source such as an aquifer, lake, stream, or river. For the Dover Township area, the points of entry are the wells and well fields
Production	The processing of potable water by a water utility and the delivery of the water to locations serviced by the water-distribution system. In a water-distribution system, production should equal consumption if there are no losses through leaks or pipe breaks

Proportionate contribution	The derivation of water from one or more sources in differing proportions. The sum of the proportionate contribution at any location in the water-distribution system should equal 100%
Qualitative description	A method of estimating data that is based on inference or is synthesized using surrogate information
Quantitative estimate	A method of estimating data by using computational techniques
Sensitivity analysis	A method of characterizing or quantifying uncertainty and variability. This involves conducting a series of model simulations, changing specific parameter values, and comparing the effect of the changed parameter(s) with reference to a base condition
Source-trace analysis	A method used to identify the source of delivered water using a water-distribution model. A source-trace analysis can be used to track the percentage of water reaching any point in a distribution system over time from a specified location or source
System operations	The on-and-off cycling of wells and high-service and booster pumps, and the operational extremes of water levels in storage tanks over a 24-hour period
TIGER	Topologically integrated, geographic encoding and referencing system; a database developed by the U.S. Department of Commerce that describes in a digital format the locations of roadways, hydrography, landmarks, places, cities, and geographic census boundaries
Water-distribution system	A water-conveyance network consisting of hydraulic devices such as wells, reservoirs, storage tanks, and high-service and booster pumps; and a series of pipelines for delivering potable water

DISCLAIMER

For additional information, write to:

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SUMMARY OF FINDINGS

HISTORICAL RECONSTRUCTION OF THE WATER-DISTRIBUTION SYSTEM SERVING THE DOVER TOWNSHIP AREA, NEW JERSEY: JANUARY 1962–DECEMBER 1996

BACKGROUND

Contamination of groundwater resources in Dover Township, Ocean County, New Jersey (Figure 1), including the contamination of water-supply wells, was identified in the 1960s (Toms River Chemical Corporation 1966) and subsequently documented in the 1970s (ATSDR 2001a,b,c,d). Based on public health assessments conducted for the Dover Township area, the Agency for Toxic Substances and Disease Registry (ATSDR) and the New Jersey Department of Health and Senior Services (NJDHSS) have determined that completed human exposure pathways to groundwater contaminants have occurred through private and community water supplies (ATSDR 2001a,b,c,d). As a result, NJDHSS and ATSDR are conducting an epidemiologic study of childhood leukemia and nervous system cancers that occurred in Dover Township. The epidemiologic study is exploring a variety of possible risk factors, including environmental exposures. To assist NJDHSS with the environmental exposure assessment component of the epidemiologic study, ATSDR developed a water-distribution model using the EPANET 2 software (Rossman 2000). Results obtained from the model will be used to assess exposure to drinking water sources that are being investigated as potential risk factors in the epidemiologic investigation.

Because of the lack of appropriate historical data, the EPANET 2 model was calibrated to the present-day (1998) water-distribution system characteristics using data collected during March and August 1998. The reliability of the calibrated model was demonstrated by successfully conducting a water-quality simulation of the transport of a naturally occurring conservative element—barium—and comparing results with data collected at 21 schools and 6 points of entry to the water-distribution system during March and April 1996. Results of the field-data collection activities, model calibration, and reliability testing were described previously (Maslia *et al.* 2000a,b). Following calibration, the model was used to simulate historical characteristics of the water-distribution system serving the Dover Township area from 1962 through 1996.

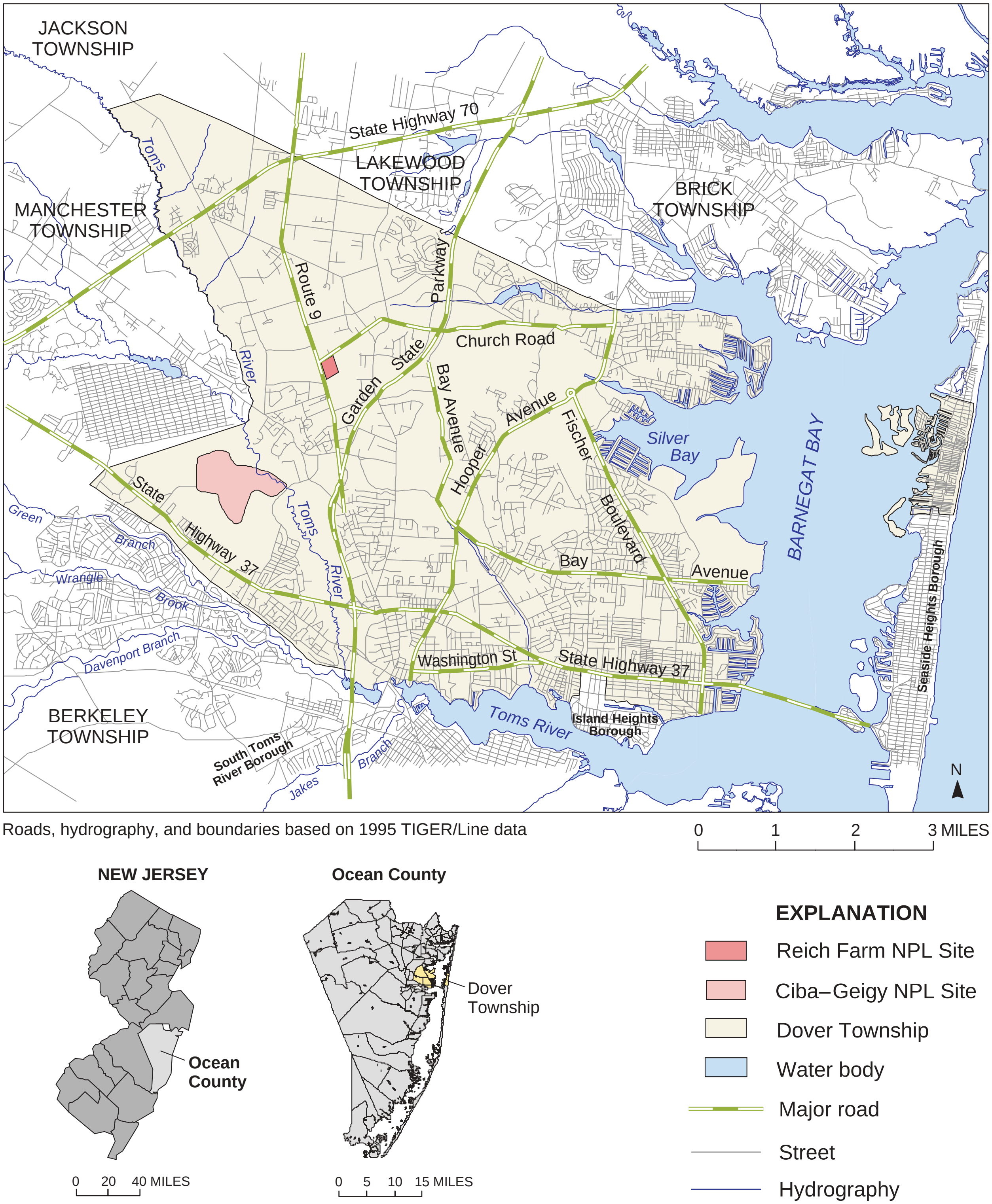


Figure 1. Investigation area, Dover Township, Ocean County, New Jersey.

This document is a summary of a detailed report that describes the historical reconstruction analysis. This summary and the full report are viewed as companion documents to Maslia *et al.* (2000a) which describes the analysis of the 1998 water-distribution system serving the Dover Township area. The full report focuses on the historical reconstruction analysis of the water-distribution system including: (1) data sources and requirements, (2) methods of analysis, (3) simulation strategies, (4) selected simulation results, and (5) the use of sensitivity analysis to address issues of uncertainty and variability of historical system operations.

METHODS AND APPROACH

Given the paucity of historical contaminant-specific concentration data during most of the period relevant to the epidemiologic study, ATSDR and NJDHSS decided that modeling efforts should concentrate on estimating the percentage of water that a study subject might have received from each point of entry (well or well fields) to the water-distribution system (Figure 2). This approach uses the concept of "proportionate contribution" described in Maslia *et al.* (2000a, p. 4) wherein at any given point in the distribution system, water may be derived from one or more sources in differing proportions.

Databases were developed from diverse sources of information and were used to describe the historical distribution-system networks specific to the Dover Township area. These data were applied to EPANET 2 and simulations were conducted for each month of the historical period—January 1962 through December 1996 (420 simulations or "model runs"). After completing the 420 monthly analyses, source-trace analysis simulations were conducted to determine the percentage of water contributed by each well or well field operating during each month. Results of these analyses—the percentage of water derived from the different sources that historically supplied the water-distribution system—were provided to health scientists for their analysis in assessing the environmental factors being considered by the epidemiologic investigation.

SPECIFIC DATA NEEDS

A simulation approach to the historical reconstruction of the water-distribution system in the Dover Township area required knowledge of the functional as well as the physical characteristics of the distribution system. Accordingly, six specific types of information were required: (1) pipeline and network configurations for the distribution system; (2) potable water-production data including information on the location, capacity, and time of operation of the groundwater production wells; (3) consumption or demand data at locations throughout the distribution system; (4) storage-tank capacities, elevations, and water-level data; (5) high-service and booster pump characteristic curves; and (6) system-operations information such as the on-and-off cycling schedule of wells and high-service and booster pumps, and the operational extremes of water levels in storage tanks.

Examples of the historical network configurations for 1962, 1971, 1988, and 1996 are shown in Figures 2 through 5, respectively. (Yearly historical network configurations maps for the period 1962 through 1996 are presented in the full report.) Figures 2 through 5 show the complexity of the system increased significantly over the time span of the historical period. For example, the 1962 water-distribution system served nearly 4,300 customers from a population of about 17,200 persons (Board of Public Utilities, State of New Jersey 1962) and was characterized for modeling by (Figure 2):

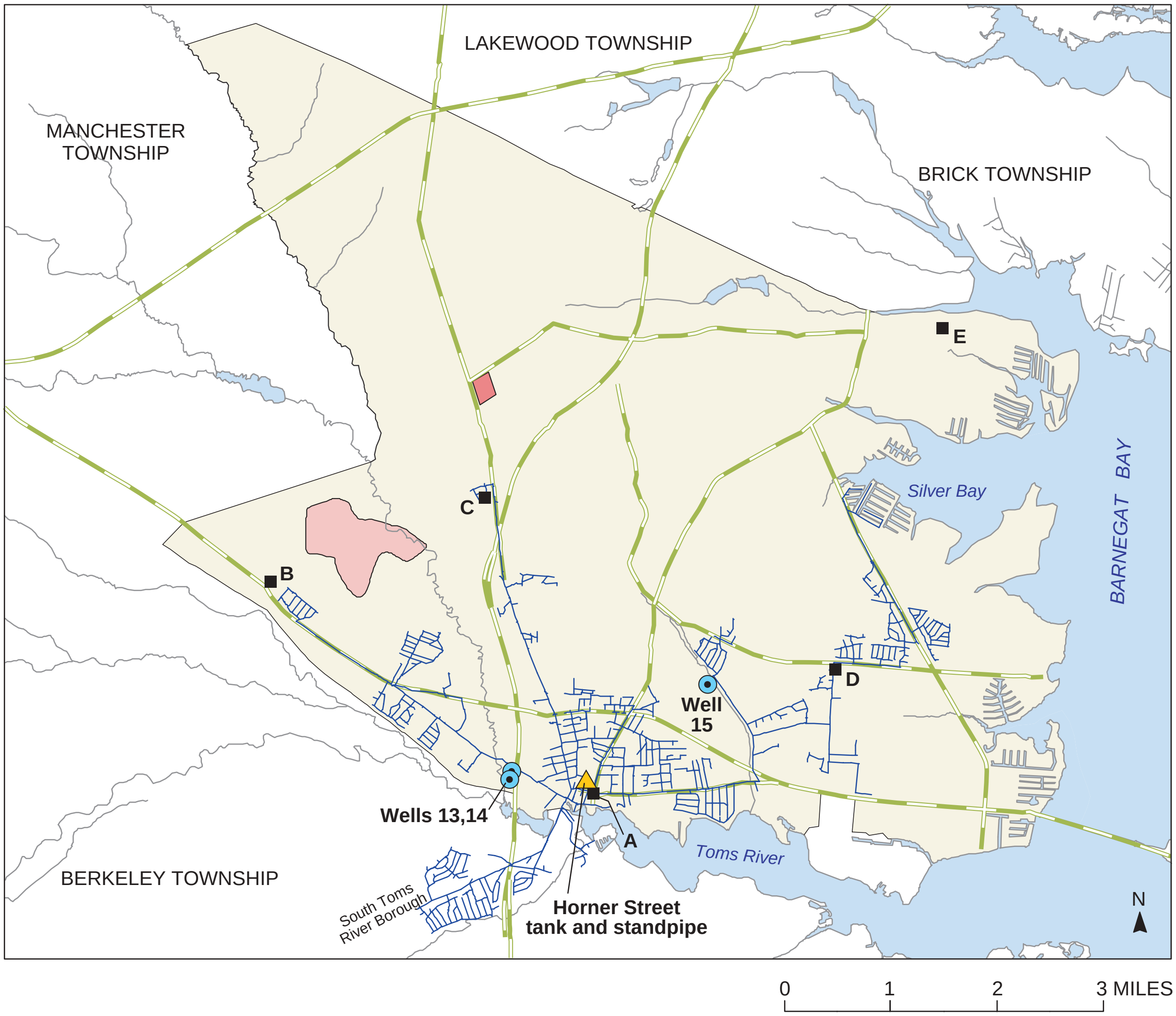
- approximately 2,400 pipe segments ranging in diameter from 2 to 12 inches and comprising a total service length of 77 miles;
- 3 groundwater extraction wells with a rated capacity of 1,900 gallons per minute;
- 1 elevated storage tank and standpipe with a combined rated storage capacity of 0.45 million gallons; and
- production of about 1.3 million gallons per day during the peak-production month of May.

By contrast, in 1996—the last year of the historical reconstruction period—the water-distribution system served nearly 44,000 customers from a population of about 89,300 persons (Board of Public Utilities, State of New Jersey 1996) and was characterized for modeling by (Figure 5):

- more than 16,000 pipe segments ranging in diameter from 2 to 16 inches and comprising a total service length of 482 miles;
- 20 groundwater extraction wells with a rated capacity of 16,550 gallons per minute;
- 12 high-service or booster pumps;
- 3 elevated and 6 ground-level storage tanks with a combined rated capacity of 7.35 million gallons; and
- production of about 13.9 million gallons per day during the peak-production month of June.

Analysis of production data indicates that the historical distribution systems could be characterized by three typical demand periods each year: (1) a low- or winter-demand period, generally represented by the month of February—designated as the minimum-demand month; (2) a peak- or summer-demand period, represented by one of the months of May, June, July, or August—designated as the maximum-demand month; and (3) an average-demand period, generally represented by the month of October—designated as the average-demand month.

Water-production data were gathered, aggregated, and analyzed for each well for every month of the historical period. These data were obtained from the water utility (Flegal 1997), Board of Public Utilities, State of New Jersey, Annual Reports (1962–1996), and NJDHSS data searches (Michael P. McLinden, written communication, August 28, 1997). The production data were measured by using in-line flow meters at water-supply wells (George J. Flegal, Manager, United Water Toms River, Inc., oral communication, August 28, 2001).

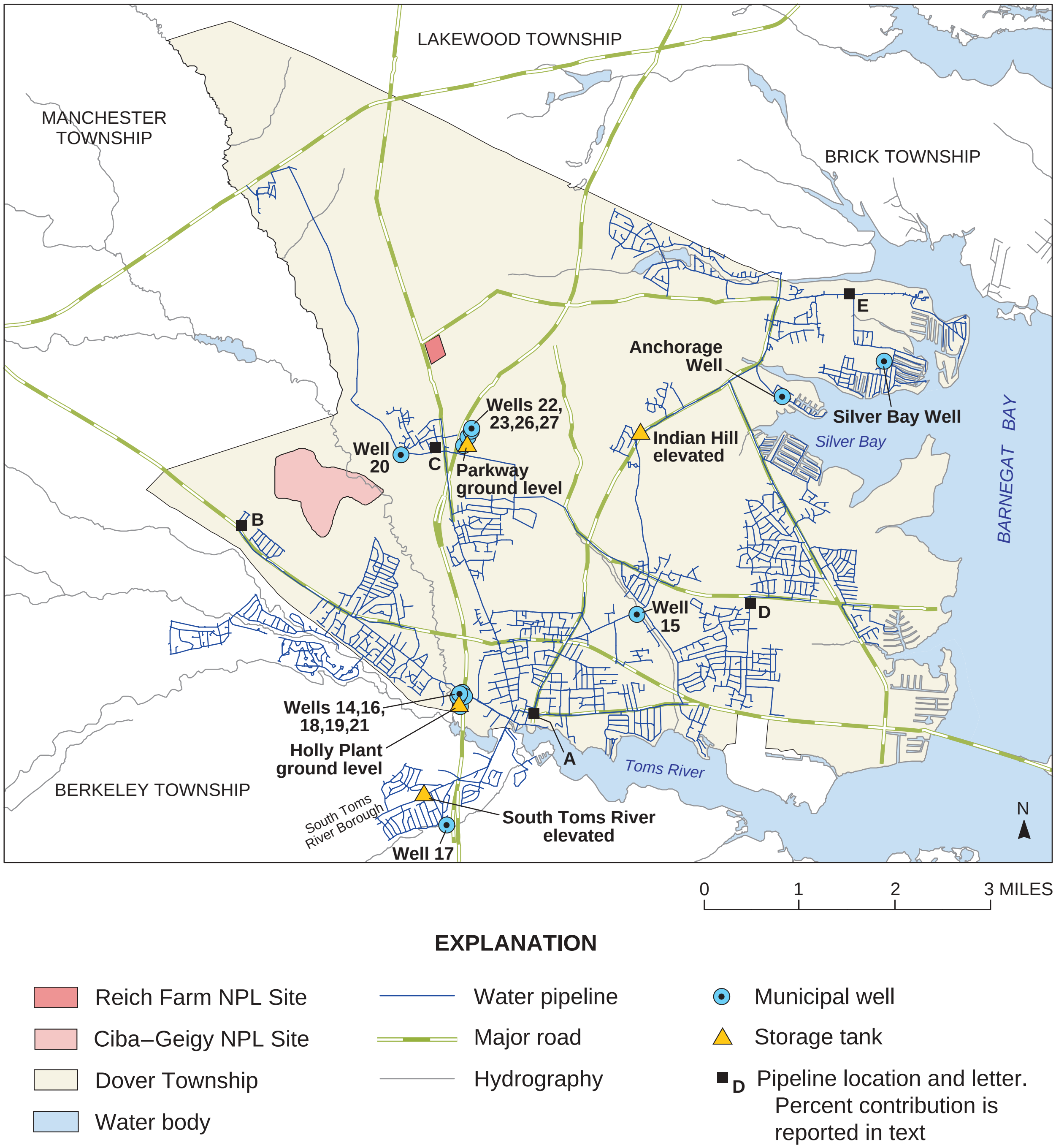


EXPLANATION

Reich Farm NPL Site
Ciba–Geigy NPL Site
Dover Township
Water body
Water pipeline
Major road
Hydrography
Municipal well
Storage tank
D Pipeline location and letter. Percent contribution is reported in text

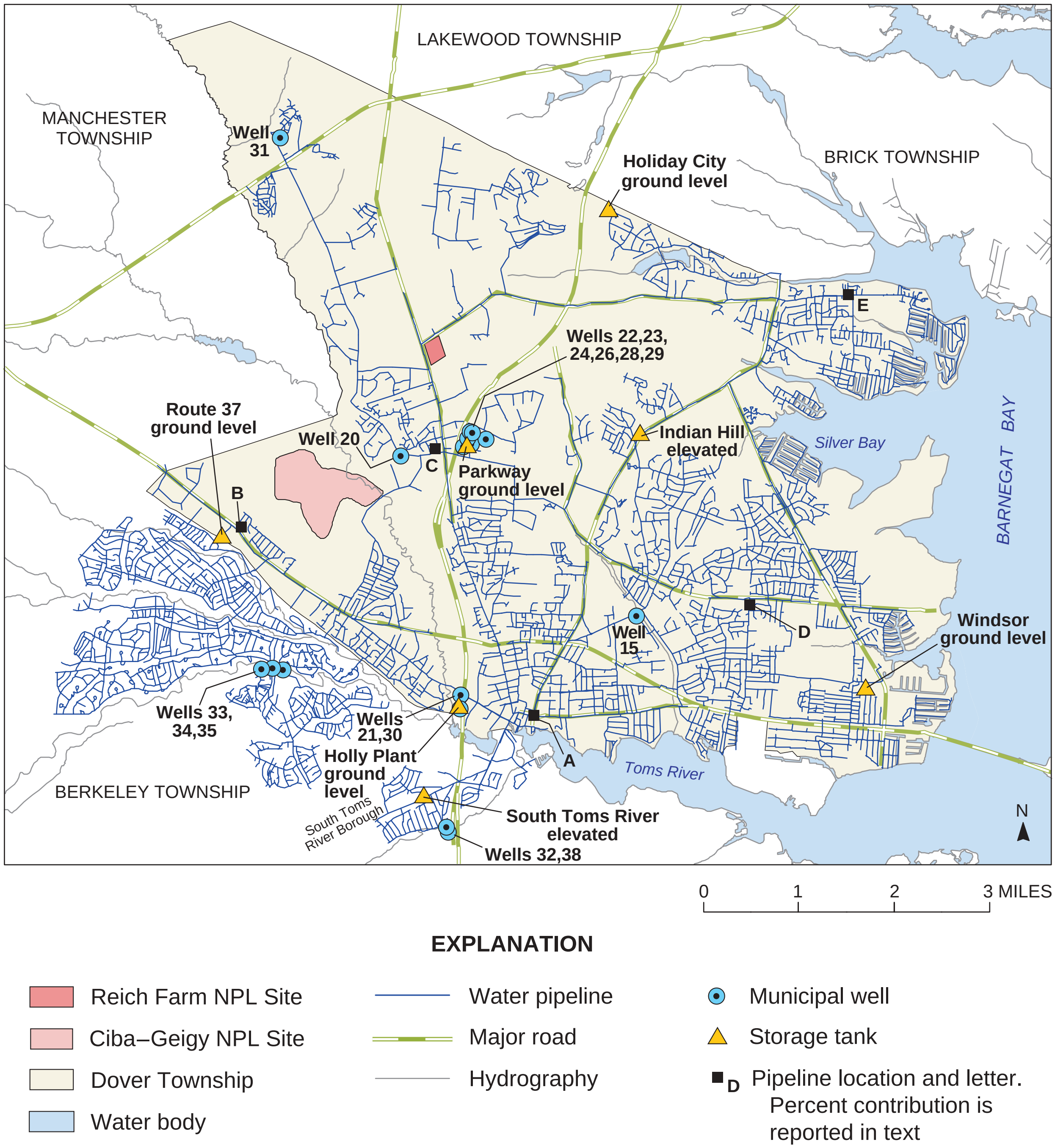
Notes: (1) Water pipelines range in diameter from 2 inches to 12 inches
(2) Roads, hydrography, and boundaries based on 1995 TIGER/Line data

Figure 2. Water-distribution system serving the Dover Township area, New Jersey, 1962.



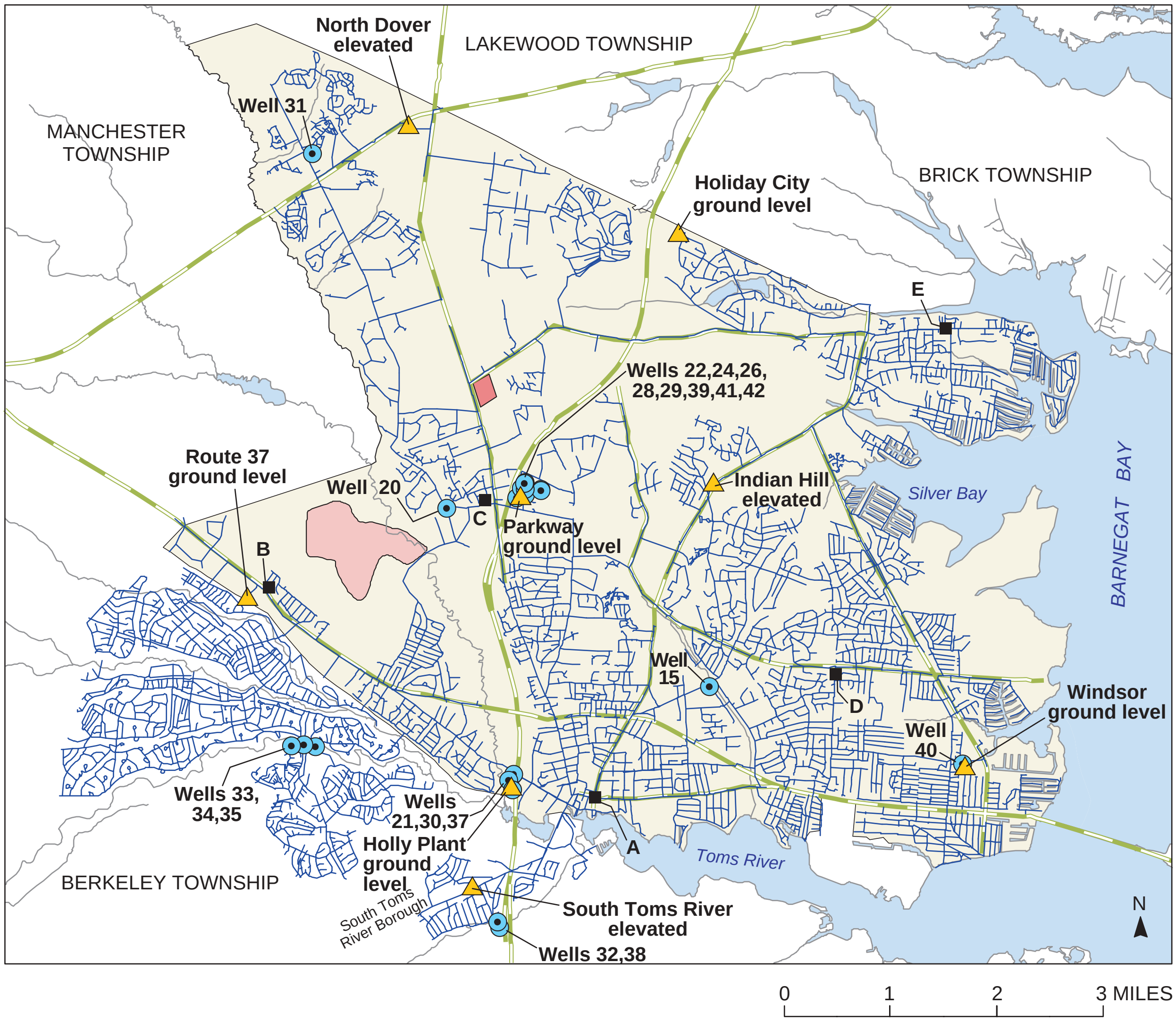
Notes: (1) Water pipelines range in diameter from 2 inches to 16 inches
(2) Roads, hydrography, and boundaries based on 1995 TIGER/Line data

Figure 3. Water-distribution system serving the Dover Township area, New Jersey, 1971.



Notes: (1) Water pipelines range in diameter from 2 inches to 16 inches
(2) Roads, hydrography, and boundaries based on 1995 TIGER/Line data

Figure 4. Water-distribution system serving the Dover Township area, New Jersey, 1988.



EXPLANATION

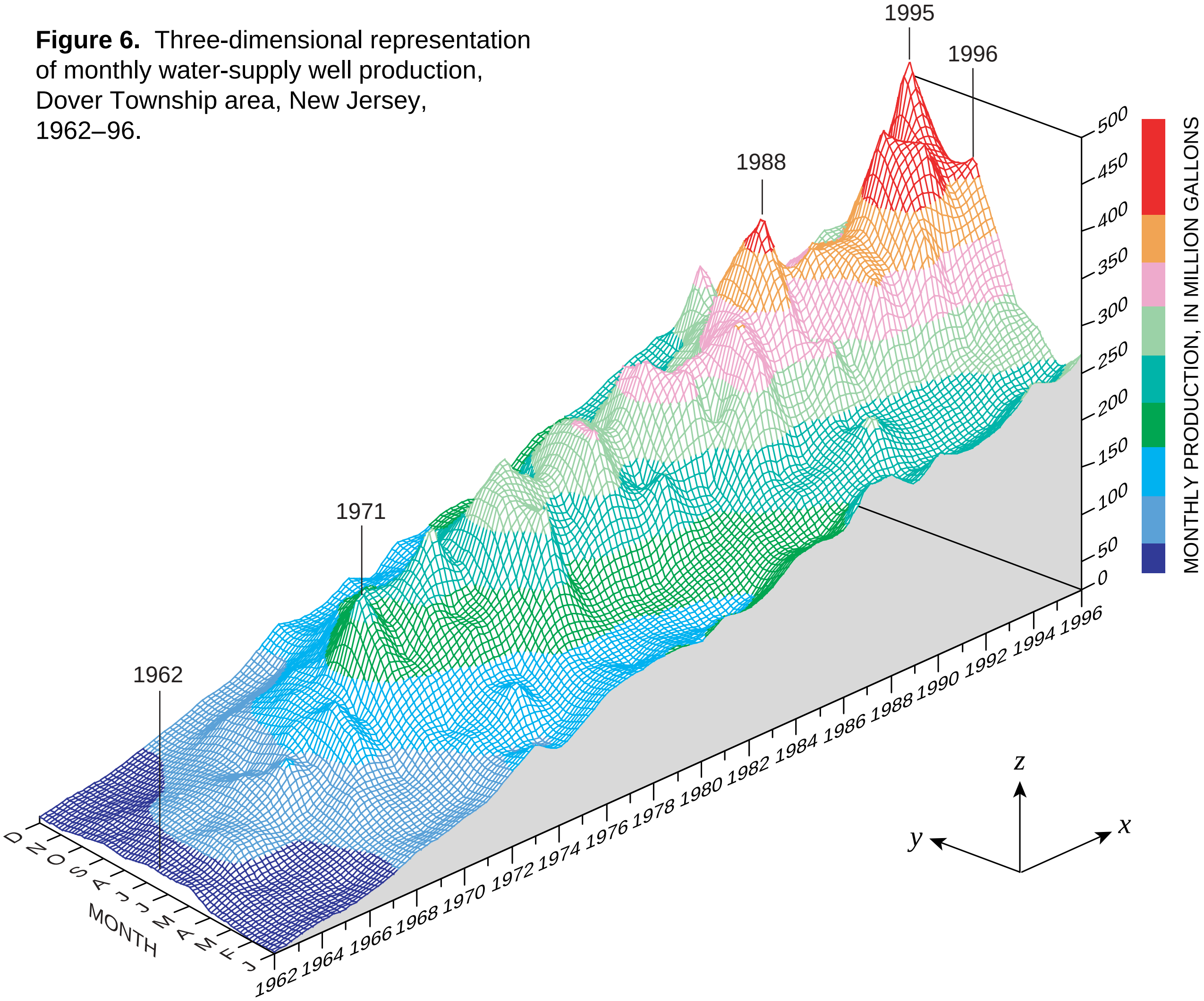
Notes: (1) Water pipelines range in diameter from 2 inches to 16 inches
(2) Roads, hydrography, and boundaries based on 1995 TIGER/Line data

Figure 5. Water-distribution system serving the Dover Township area, New Jersey, 1996.

Monthly production data can be represented graphically as shown in a three-dimensional plot (Figure 6). Referring to this plot, the x-axis is the year (1962–1996), the y-axis is the month (January–December), and the z-axis is the total monthly production in million gallons. Maximum production is shown to occur in the months of May, June, July, or August. In addition, considerable production increases occurred in 1971, 1988, and 1995. These years are characterized on the plot by sharp peaks.

As noted previously, to simulate the distribution of water for each of the 420 months of the historical period, network configuration, demand, and operational information were required. Before 1978, operational data were unavailable requiring development of system-operation parameters—designated as "Master Operating Criteria." These are based on hydraulic engineering principles necessary to successfully operate distribution systems similar to the one serving the Dover Township area (Table 1). From 1978 forward, for selected

Figure 6. Three-dimensional representation of monthly water-supply well production, Dover Township area, New Jersey, 1962–96.



years, operators of the water utility provided information on the generalized operating practices for a typical "peak-demand" (summer) and "non-peak demand" (fall) day. These guidelines were used in conjunction with the "Master Operating Criteria" to simulate a typical 24-hour daily operation of the water-distribution system for each month of the historical period.

Table 1. "Master Operating Criteria" used to develop operating schedules for the historical water-distribution system, Dover Township area, New Jersey

Parameter	Criteria
Pressure[1]	Minimum of 15 pounds per square inch, maximum of 110 pounds per square inch at pipeline locations, including network end points
Water level	Minimum of 3 feet above bottom elevation of tank; maximum equal to elevation of top of tank; ending water level should equal the starting water level
Hydraulic device on-line date	June 1 of year installed to meet maximum-demand conditions
On-and-off cycling: Manual operation	Wells and high-service and booster pumps cannot be cycled on-and-off from 2200 to 0600 hours
On-and-off cycling: Automatic operation	Wells and high-service and booster pumps can be cycled on-and-off at any hour
Operating hours	Wells should be operated continuously for the total number of production hours, based on production data[2]

[1]Generally, for residential demand, minimum recommended pressure is about 20 pounds per square inch. However, for some locations in the Dover Township area (mostly in areas near the end of distribution lines) lower pressures were simulated.

[2]See full report for historical monthly production data.

Examples of historical water-distribution system operating schedules for the maximum-demand months of May 1962, July 1971, July 1988, and June 1996 are shown in Tables 2 through 5, respectively. These tables indicate the hour-by-hour operation of wells and high-service and booster pumps during a typical day of the maximum-demand month for the given year. Note that in 1962 (Table 2), high-service and booster pumps were not part of the distribution system and, therefore, only groundwater wells were operated to supply demand by discharging water directly into the distribution system (wells 13–15, Figure 2). In 1968, high-service and booster pumps were added to the distribution system. From that year forward, some wells supplied storage tanks, then high-service and booster pumps were operated to meet distribution-system demands (wells 21–30, 40, and 42, Figure 5); other wells still discharged directly into the distribution system (refer to Tables 2 through 5 for details).

Data Availability, Quality, Methods, and Sources

In this type of study, the ideal or desired condition is to obtain all data required for model simulations through direct measurement or observation. In reality, however, necessary data are not routinely available by direct measurement or observation and must be synthesized using generally accepted engineering analyses and methods. Issues of data sources and the methods used to obtain data that cannot be directly measured reflect, ultimately, on the credibility of simulation results. To address these issues for historical reconstruction analysis, the methods for obtaining the necessary data were grouped into three categories (Table 6):

- *Direct measurement or observation*—Data included in this category were obtained by direct measurement or observation of historical data and are verifiable by independent means. Of the three data categories, these data were the most preferred in terms of reliability and least affected by issues of uncertainty.

Table 2. Water-distribution system operating schedule, Dover Township area, New Jersey, May 1962

[May is maximum-demand month for 1962; hour of day in color means well operating; ■ Groundwater well]

Well ID[1]	Hour of the Day[2]																							
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
	Groundwater Well																							
Holly (13)										■	■	■	■	■	■	■								
Holly (14)																	■	■	■	■	■	■		
Brookside (15)	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■						■	■

[1]Wells discharge directly into the distribution system.

[2]Hour of the day: 0 is midnight; 12 is noon, respectively.

Table 3. Water-distribution system operating schedule, Dover Township area, New Jersey, July 1971

[July is maximum-demand month for 1971; hour of day in color means well or pump operating; ■ Groundwater well; ■ High-Service or Booster pump]

Well ID[1]	Hour of the Day[2]																							
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
	Groundwater Well																							
Brookside (15)	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			
South Toms River (17)						■	■											■	■	■	■	■		
Indian Head (20)											■	■	■	■	■	■	■	■	■	■	■	■		
Anchorage[3]	■	■	■	■	■	■	■	■	■	■								■	■	■	■	■	■	■
Silver Bay[3]	■	■	■	■	■	■	■	■	■	■								■	■	■	■	■	■	■
	High-Service or Booster Pump																							
Pump ID																								
Holly pump 1[4]	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Holly pump 2[4]	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Holly pump 3[4]																								
Parkway pump 1[5]								■	■	■	■	■	■	■	■	■	■							
Parkway pump 2[5]																								

[1]Wells discharge directly into the distribution system.

[2]Hour of the day: 0 is midnight; 12 is noon, respectively.

[3]Anchorage and Silver Bay do not have well numbers designated by water utility.

[4]Holly pump 1, Holly pump 2, and Holly pump 3 supplied by Holly ground-level storage tanks and Holly wells 14, 16, 18, 19, and 21.

[5]Parkway pump 1 and Parkway pump 2 supplied by Parkway ground-level storage tank and Parkway wells 22, 23, 26, and 27.

Table 4. Water-distribution system operating schedule, Dover Township area, New Jersey, July 1988

[July is maximum-demand month for 1988; hour of day in color means well or pump operating; Groundwater well; High-Service or Booster pump]

Well ID[1]	Hour of the Day[2]																							
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
	Groundwater Well																							
Brookside (15)																								
Indian Head (20)																								
Route 70 (31)																								
South Toms River (32)																								
Berkeley (33)																								
Berkeley (34)																								
Berkeley (35)																								
South Toms River (38)																								
	High-Service or Booster Pump																							
Pump ID																								
Holly pump 1 [3]																								
Holly pump 2 [3]																								
Holly pump 3 [3]																								
Parkway pump 1 [4]																								
Parkway pump 2 [4]																								
Holiday City Pump [5]																								
St. Catherine's pump [6, 7]																								
South Toms River pump 1																								
South Toms River pump 2																								
Windsor pump 1 [8]																								
Windsor pump 2 [8]																								

[1]Wells discharge directly into the distribution system.

[2]Hour of the day: 0 is midnight; 12 is noon, respectively.

[3]Holly pump 1, Holly pump 2, and Holly pump 3 supplied by Holly ground-level storage tanks and Holly wells 21 and 30.

[4]Parkway pump 1 and Parkway pump 2 supplied by Parkway ground-level storage tank and Parkway wells 22, 23, 24, 26, 28, and 29.

[5]Pump operated from 0630 to 1130 hours and 1630 to 2030 hours.

[6]Also known as Route 37.

[7]Pump operated from 0930 to 1445 hours.

[8]Windsor pump 1 and Windsor pump 2 supplied by Windsor ground-level tank.

Table 5. Water-distribution system operating schedule, Dover Township area, New Jersey, June 1996

[June is maximum-demand month for 1996; hour of day in color means well or pump operating; Groundwater well; High-Service or Booster pump]

Well ID[1]	Hour of the day[2]																							
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
	Groundwater Well																							
Brookside (15)	■	■	■	■																				
Route 70 (31)	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
South Toms River (32)								■	■	■	■	■	■	■	■	■	■	■						
Berkeley (33)	■	■	■	■	■	■	■	■	■	■	■	■					■	■	■	■	■	■	■	■
Berkeley (34)	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Berkeley (35)	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
South Toms River (38)								■	■	■	■	■	■	■	■	■	■							
Pump ID	High-Service or Booster Pump																							
Holly pump 1 [3]							■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			
Holly pump 2 [3]	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Holly pump 3 [3]																								
Parkway pump 1 [4]						■						■	■	■	■	■	■							
Parkway pump 2 [4]							■	■	■	■	■	■						■	■	■	■	■		
Holiday City pump							■	■	■	■	■													
St. Catherine's pump [5]																								
South Toms River pump 1																								
South Toms River pump 2																								
Windsor pump 1 [6]	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Windsor pump 2 [6]																								
Windsor pump 3 [6]																								

[1]Wells discharge directly into the distribution system.

[2]Hour of the day: 0 is midnight; 12 is noon, respectively.

[3]Holly pump 1, Holly pump 2, and Holly pump 3 supplied by Holly ground-level storage tanks and Holly well 30.

[4]Parkway pump 1 and Parkway pump 2 supplied by Parkway ground-level storage tank and Parkway wells 22, 24, 26, 28, 29, and 42.

[5]Also know as Route 37.

[6] Windsor pump 1, Windsor pump 2, and Windsor pump 3 supplied by Windsor ground-level storage tank and Windsor well 40.

- *Quantitative estimates*—Data included in this category were estimated or quantified using computational methods.
- *Qualitative description*—Data included in this category were based on inference or were synthesized using surrogate information. Of the three data categories, data derived by qualitative description were the least preferred in terms of reliability and the most affected by issues of uncertainty.

Of the six specific types of information required for the historical reconstruction analysis, the network pipeline data, groundwater well-location data, groundwater well-production data, and storage-tank data were obtained by direct measurement or observation (Table 6). These data were available throughout the entire historical period and they could be assessed for quality and verified by independent means such as state reports or field observations. For example, groundwater well-production data were available for every well for every month of the historical period and these data were measured by the water utility using in-line flow-metering devices at groundwater wells (George J. Flegal, Manager, United Water Toms River, Inc., oral communication, August 28, 2001).

Data for historical consumption (or demand) consisted of two components—monthly volumes (quantity) and spatial distribution (location). The monthly volumes were obtained by using a quantitative estimation method. Data were available from metered billing records for October 1997 through April 1998 and verified through the calibration process described in Maslia *et al.* (2000a,b); the magnitude of monthly historical production was known based on measured flow data. Using these data, estimates of historical demand were quantified by imposing the requirement that total consumption must equal total production.

Direct measurement or quantitative estimates of the spatial distribution of historical demand were not available for the Dover Township area. Therefore, qualitative description methods were used to estimate historical data values. In doing so, estimates of the spatial distribution of historical demand (demand patterns) were based on two assumptions: (1) historical demand patterns were similar to the present-day demand patterns which are known from available metered billing records (Table 6); and (2) demand patterns could be inferred from land-use classification using historical land-use classification as a surrogate indicator. To assess the validity of this approach, historical land-use classification or zoning maps for Dover Township were used in conjunction with distribution-system network maps for 1962, 1967, 1978, 1990, and 1996 (network maps like the ones shown in Figures 2 through 5). Using information obtained from the land-use classification and distribution-system network maps, geospatial and comparative analyses were conducted. Results of these analyses indicated that the distribution of land-use classification in Dover Township was relatively static and changed little during the historical period. These analyses substantially validated the qualitative description method used to estimate the spatial distribution of historical demand.

Table 6. Data availability and method of obtaining data for historical reconstruction analysis, Dover Township area, New Jersey

Data Type	Time Frame of Availability	Source	Method of Obtaining Data[1]: Direct Measurement or Observation	Quantitative Estimate	Qualitative Description	Notes
Pipeline location and geometry	1962–1996	Water utility database[2]	X			In-service date assigned to be January 1 of in-service year
Groundwater well location	1962–1996	Water utility database[2], Board of Public Utilities reports[3], ATSDR and NJDHSS field verification	X			In-service date assigned to be June 1 of in-service year
Groundwater well production	1962–1996	Water utility database[2], Board of Public Utilities Annual Reports[3], NJDHSS data search[4]	X			Water utility data, 1962–1996; NJDHSS data, 1962–1979; data from in-line flow meters[5], hourly values available for 1996; prior to 1996, monthly values available; average daily operation estimated from monthly data and well capacity
Storage tank geometry, capacity, and location	1962–1996	Water utility database[2], Board of Public Utilities Annual Reports[3], ATSDR and NJDHSS field verification	X			In-service date assigned to be June 1 of in-service year
Estimation of consumption (demand)	October 1997–April 1998	Water utility billing records, ATSDR calibrated model[6]		X		Prior to October 1997, data not available to investigators; quantitative estimate based on assumption that demand must equal production
Spatial distribution of consumption (demand)	October 1997–April 1998	Water utility billing records, ATSDR calibrated model[6]			X	Prior to October 1997, data not available to investigators; estimates based on qualitative assessment of land-use and geospatial analysis
Pump-characteristic curves	1998	Water utility data[2], ATSDR calibrated model[6]		X		None
System operations, 1962–1977	None	"Master Operating Criteria," hydraulic engineering principles, water utility operating practices			X	Daily hours of operation for wells from production data
System operations, 1978–1987	Typical peak day (summer) and non-peak day (fall) for selected years	Water utility operational notes[7], "Master Operating Criteria," hydraulic engineering principles		X	X	High-service and booster pump discharge estimated from water utility notes
System operations, 1988–1996	Typical peak day (summer) and non-peak day (fall) for selected years; all of 1996; and March and August 1998	Water utility operational notes[7], "Master Operating Criteria," hydraulic engineering principles, observed water-utility operating practices[6]	X	X	X	High-service and booster pump discharge estimated from water utility notes; hourly operations data for 1996

[1]Direct measurement or observation—measured or observed data available for some or throughout historical period; data verifiable by independent means; Quantitative estimate—direct measurement or observation of historical data not available for some or most of historical period; data estimated by computational methods; Qualitative description—direct measurement or observation of historical data not available for most or all of historical period; data based on inference or synthesized using surrogate information.

[2]Flegal (1997).

[3] Board of Public Utilities, State of New Jersey, Annual Reports (1962–1996).

[4]Michael P. McLinden, written communication, August 28, 1997.

[5]George J. Flegal, Manager, United Water Toms River, Inc., oral communication, August 28, 2001.

[6]Maslia *et al*. (2000a, b).

[7]Richard Ottens, Jr., Production Manager, United Water Toms River, Inc., written communication, 1998.

The high-service and booster pump-characteristic data were derived using information obtained from the water utility (Flegal 1997). This information consisted of head values versus flow values which were refined during the model calibration process (Maslia *et al.* 2000a,b).

The historical system-operation data were obtained using each of the three methods of obtaining data described previously—depending on the time frame (Table 6). For the early historical period (1962-1977), investigators relied on hydraulic engineering principles and the "Master Operating Criteria" (Table 1). Because data describing specific operational practices were not available, operating schedules developed for these early historical networks (for example, Table 2 and Table 3) were based on qualitative descriptions of system operations. To maintain a balanced flow condition however, water-distribution systems of similar configuration and facilities as the historical Dover Township area system, generally operate using on-and-off cycling schedules of limited variability. That is, wells and high-service and booster pumps must be cycled on-and-off within a limited or narrow operating range. Simulations conducted on the water-distribution system serving the Dover Township area confirmed the limited variability of the on-and-off cycling operating schedule.

For the 1977–1987 period, system-operation data were developed from quantitative estimates and qualitative descriptions of the operating schedules (Table 6). These data were derived using hydraulic engineering principles, the "Master Operating Criteria," and from information provided by the water utility that described the general operations of the water-distribution system for a typical "peak" day (summer) and a "non-peak" (fall) day. For some of the years, the water utility also provided estimates of discharge to the distribution system from the high-service and booster pumps (Richard Ottens, Jr., Production Manager, United Water Toms River, Inc., written communication, 1998).

System-operation data for the most recent historical systems (1988–1996) were obtained from direct measurement or observation, quantitative estimates, and qualitative descriptions of operating schedules (Table 6). Data sources used to develop these operating schedules (for example, Table 5) included the generalized operating notes from the water utility (Richard Ottens, Jr., Production Manager, United Water Toms River, Inc., written communication, 1998), hourly operations data for 1996 (Flegal 1997), notes taken by ATSDR and NJDHSS staff during field-data collection activities in March and April 1998 (Maslia *et al.* 2000a), and the observation that the distribution system had previously operated in a manner very similar to the present-day system (1998) for which detailed information was available.

EXAMPLES OF SIMULATION RESULTS

Analysis of the proportionate contribution of water from wells and well fields to selected network locations in the Dover Township area illustrates the increasing complexity and operational variability of the distribution system throughout the historical period. As previously described, these results were obtained by conducting source-trace analysis simulations. The annual variation of the simulated proportionate contribution of water from all active wells and well fields to selected locations in the Dover Township area is shown for the minimum-demand month of February (Figure 7), the maximum-demand months of May, June, July, or August (Figure 8), and the average-demand month of October (Figure 9). For each of these examples, five geographically distinct pipeline locations were selected from the historical networks to represent the spatial distribution of proportionate contribution results. These locations are identified on Figures 2 through 5, and Figures 7 through 9 as locations A, B, C, D, and E.

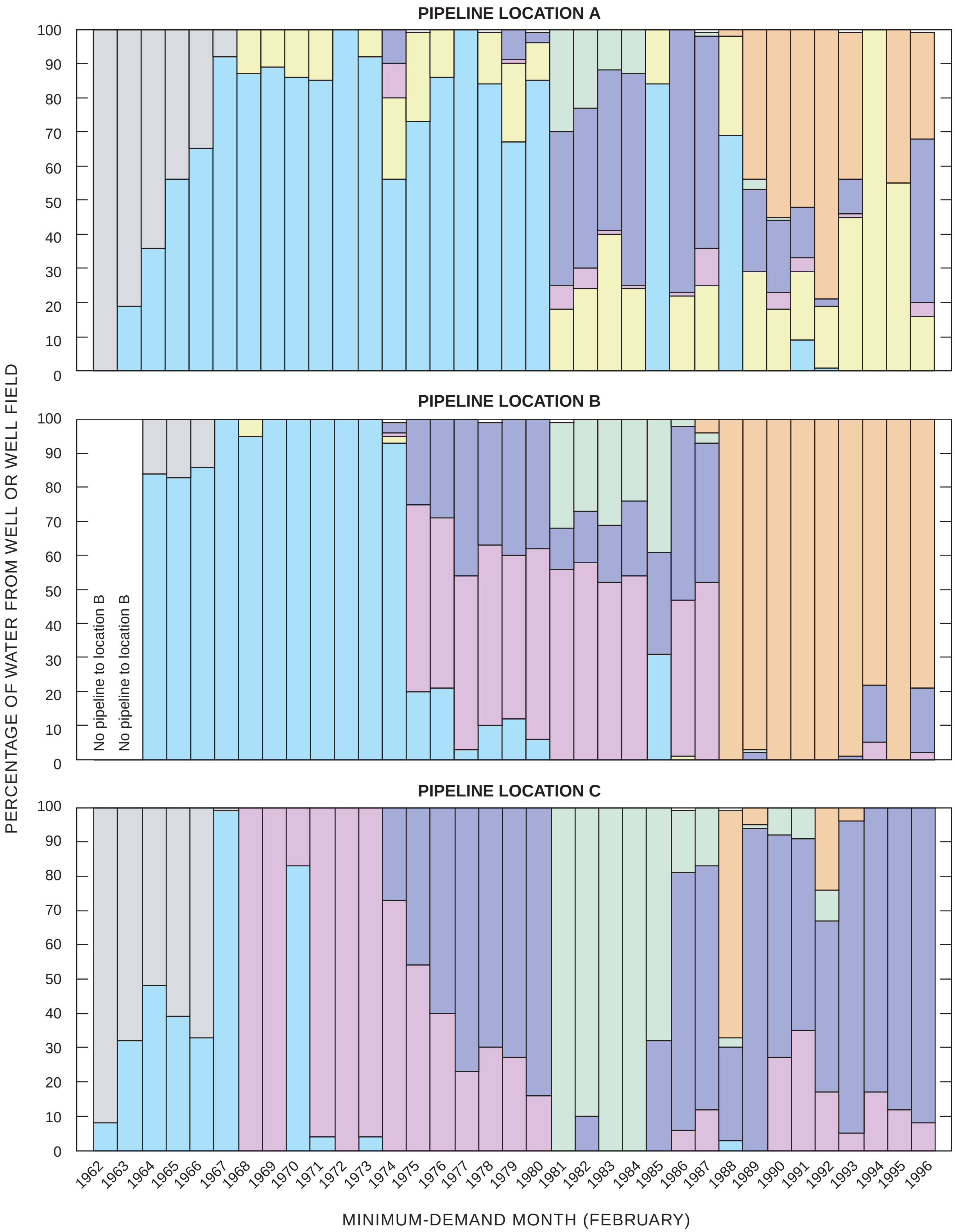
Comparison of the May 1962 results with the June 1996 results (Figure 8), indicates the increasing complexity of the network and distribution-system operations and how such operations influenced the proportionate contribution of water to specific locations. In May 1962, only two well fields (Holly and Brookside) provided water to any one location; whereas, in June 1996, as many as seven well fields provided water to the distribution system (for example, pipeline location E in Figure 8).

In Figures 7 through 9, the sum of the proportionate contribution of water from all wells and well fields to any pipeline location should be 100%. Because of numerical approximation and roundoff, however, the total contribution from all wells and well fields may sum to slightly less or slightly more than 100% at some locations. This is expected when using numerical simulation techniques. In the historical reconstruction analysis conducted for the distribution system serving the Dover Township area, the sum of the proportionate contribution at any location ranges from 98% to 101%.

In reviewing the simulation results, the annual and seasonal variation of the proportionate contribution of water is evident by inspecting, for example, the results for pipeline location D. Annual variation is determined by selecting a certain demand condition (minimum, maximum, or average—Figures 7, 8, or 9, respectively) and comparing the proportionate contribution results over the historical period (1962–1996). Seasonal variation is determined by choosing a specific year and comparing the proportionate contribution results for the minimum-, maximum-, and average-demand months (Figures 7, 8, and 9, respectively).

Simulation results for the maximum-demand months of May 1962, July 1971, July 1988, and June 1996 for pipeline location D exemplify the annual variation in the contribution of water to this location and indicate the following (see Figure 8 for the proportionate contribution results and Figures 2 through 5 for well and well field locations):

- *May 1962*—100% of the water was provided by the Brookside well (15);
- *July 1971*—30% of the water was provided by the Holly wells (14, 16, 18, 19, and 21); 54% by the Brookside well (15); 3% by the Indian Head well (20); and 14% by Parkway wells (22, 23, 26, and 27);


PIPELINE LOCATION A
PIPELINE LOCATION B
PIPELINE LOCATION C
PERCENTAGE OF WATER FROM WELL OR WELL FIELD
No pipeline to location B
No pipeline to location B
0
10
20
30
40
50
60
70
80
90
100
1962
1963
1964
1965
1966
1967
1968
1969
1970
1971
1972
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MINIMUM-DEMAND MONTH (FEBRUARY)

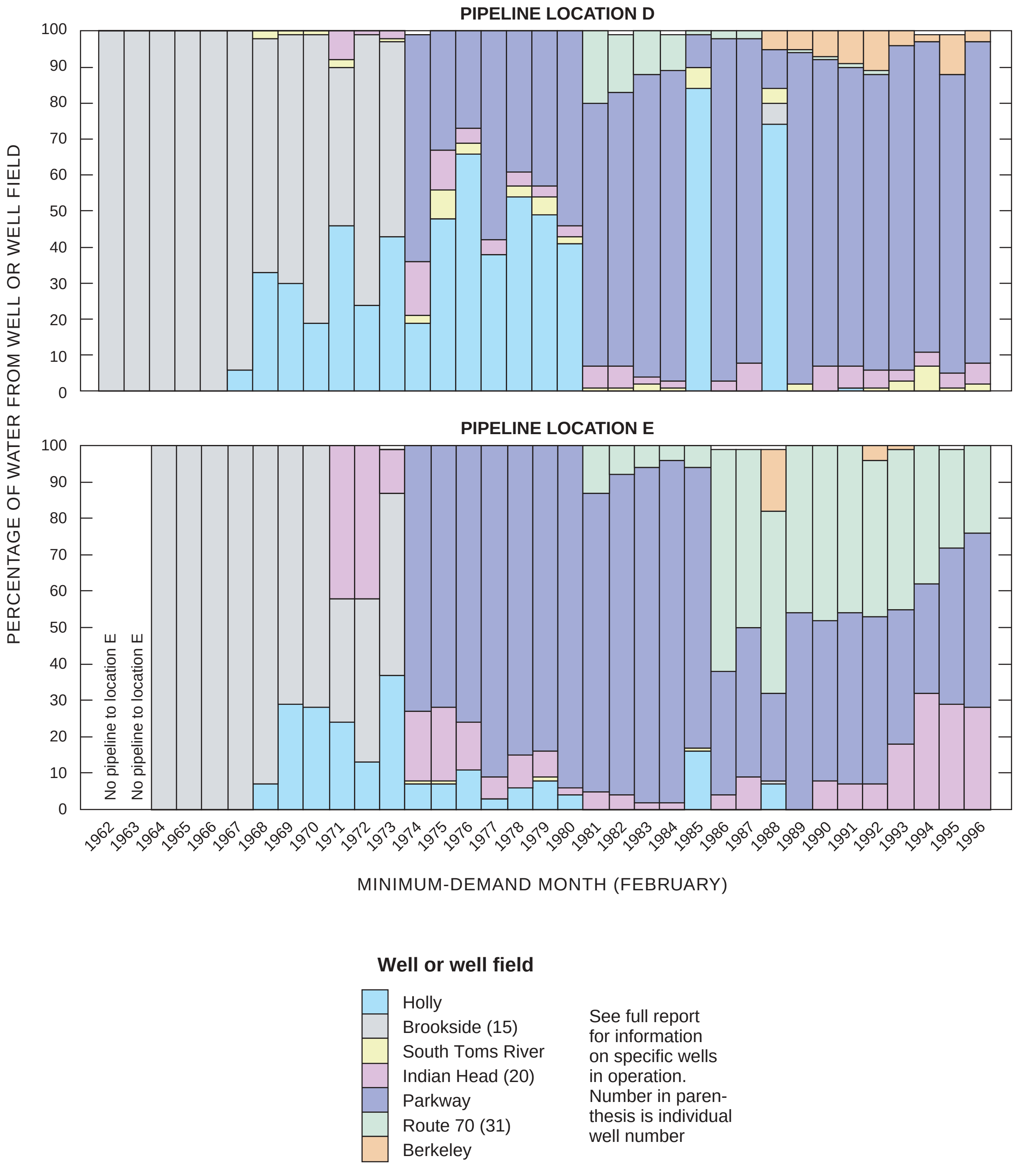
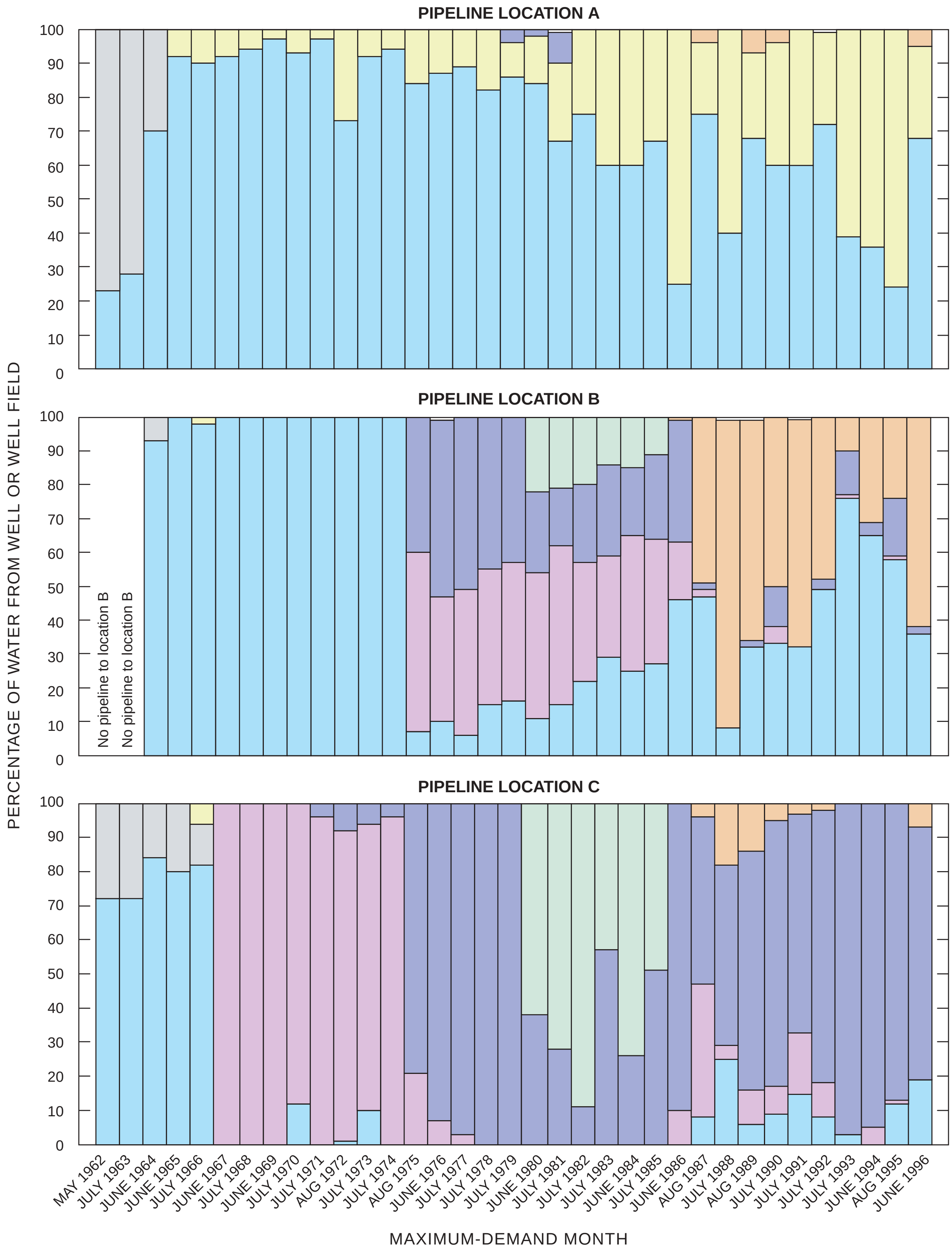


Figure 7. Annual variation of simulated proportionate contribution of water from wells and well fields to selected locations in the Dover Township area, New Jersey, minimum-demand months, 1962–96.


PIPELINE LOCATION A
PIPELINE LOCATION B
PIPELINE LOCATION C
PERCENTAGE OF WATER FROM WELL OR WELL FIELD
No pipeline to location B
No pipeline to location B
0
10
20
30
40
50
60
70
80
90
100
MAY 1962
JULY 1963
JUNE 1964
JUNE 1965
JULY 1966
JUNE 1967
JULY 1968
JUNE 1969
JULY 1970
JULY 1971
AUG 1972
JULY 1973
JULY 1974
AUG 1975
JUNE 1976
JULY 1977
JULY 1978
JULY 1979
JUNE 1980
JULY 1981
JULY 1982
JULY 1983
JUNE 1984
JULY 1985
JUNE 1986
AUG 1987
JULY 1988
AUG 1989
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JUNE 1994
AUG 1995
JUNE 1996
MAXIMUM-DEMAND MONTH

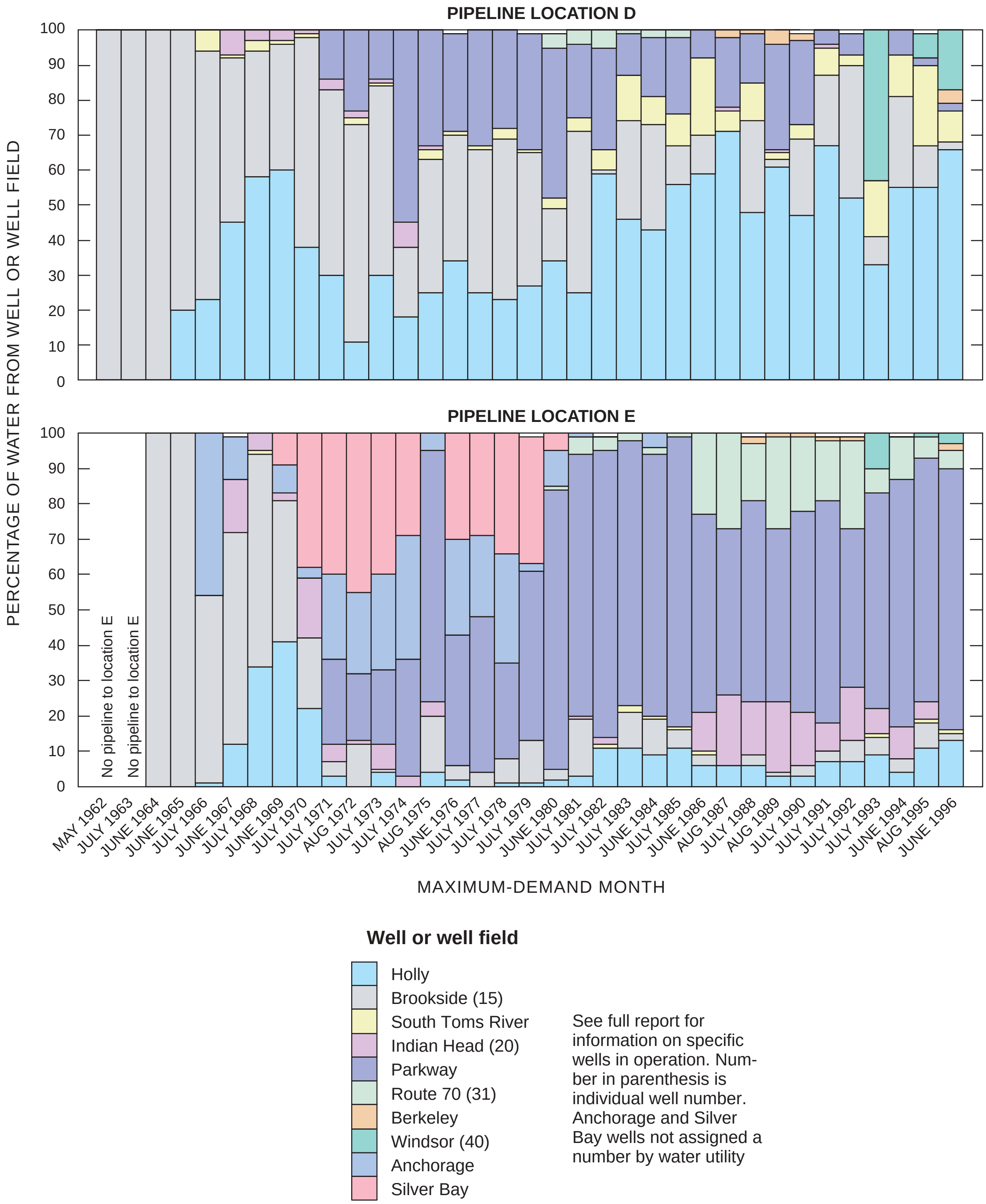
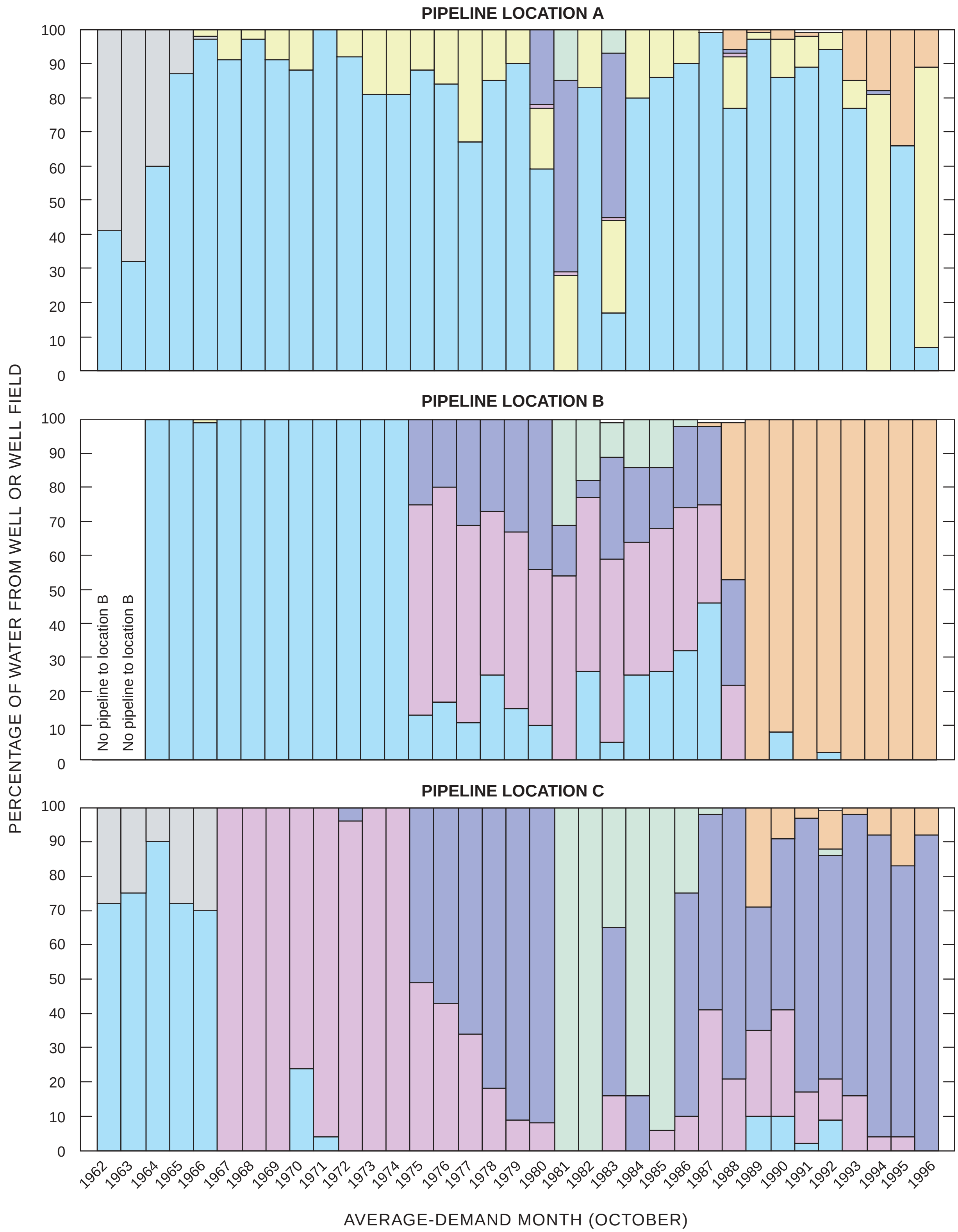


Figure 8. Annual variation of simulated proportionate contribution of water from wells and well fields to selected locations in the Dover Township area, New Jersey, maximum-demand months, 1962–96.



PIPELINE LOCATION A
PIPELINE LOCATION B
PIPELINE LOCATION C
PERCENTAGE OF WATER FROM WELL OR WELL FIELD
No pipeline to location B
No pipeline to location B
0
10
20
30
40
50
60
70
80
90
100
1962
1963
1964
1965
1966
1967
1968
1969
1970
1971
1972
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1978
1979
1980
1981
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1993
1994
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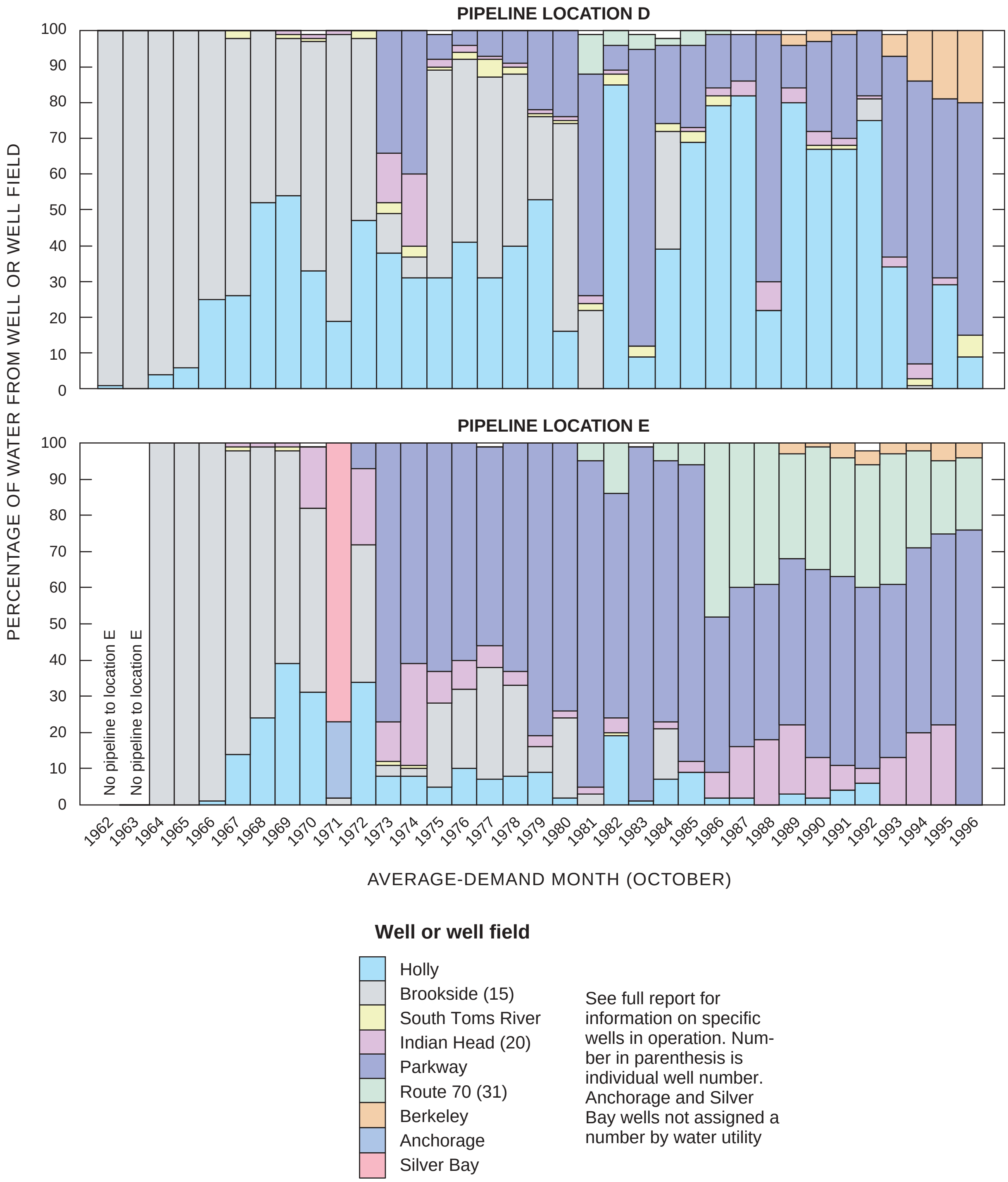
1996
AVERAGE-DEMAND MONTH (OCTOBER)



See full report for information on specific wells in operation. Number in parenthesis is individual well number. Anchorage and Silver Bay wells not assigned a number by water utility

Figure 9. Annual variation of simulated proportionate contribution of water from wells and well fields to selected locations in the Dover Township area, New Jersey, average-demand months, 1962–96.

- *July 1988*—49% of the water was provided by Holly wells (21 and 30); 26% by the Brookside well (15); 11% by the South Toms River wells (32 and 38); 14% by the Parkway wells (22, 23, 24, 26, 28, and 29); and 1% by the Berkeley wells (33-35); and

- June 1996—66% of the water was provided by the Holly well (30); 2% by the Brookside well (15); 9% by the South Toms River wells (32 and 38); 2% by the Parkway wells (22, 24, 26, 28, 29, and 42); 4% by the Berkeley wells (33-35), and 17% by the Windsor well (40).

The simulation results shown in Figures 7, 8, and 9 demonstrate that the contribution of water from wells and well fields varied by time and location. However, the results also show that certain wells provided the predominant amount of water to locations throughout the Dover Township area. Readers who are interested in the proportionate contribution of water from specific water sources at specified times during the historical period of 1962 through 1996 should refer to the full report.

Sensitivity Analysis

The proportionate contribution results described above were obtained from trace-analysis simulations conducted on the historical distribution-system networks whereby balanced flow conditions were achieved through the manual refinement of modeling parameters. The adjusted parameters were the on-and-off cycling pattern values of wells (pattern factor values assigned in EPANET 2) and the operational extremes of water levels in the storage tanks. This modeling approach was designated as the "manual adjustment process." Simulation results presented in this summary were obtained using the manual adjustment process and were the bases of comparisons for all sensitivity analyses.

To address the issue of uncertainty and variability of system operations, and specifically to test the sensitivity of the proportionate contribution results to variations in model-parameter values, a technique was required that would "search" for and select a set of alternate operating conditions different from those determined using the manual adjustment process. These alternate operating conditions needed to also result in the satisfactory operation of the historical water-distribution system. Such a technique was found in the Genetic Algorithm optimization (GA) method. Simply put, a GA refers to a method of optimization that attempts to find the most optimal solution by mimicking (in a computational sense) the mechanics of natural selection and natural genetics. (Aral *et al.* [2001] discuss GAs and their application to water-distribution system analysis; the full report also presents additional references on the development and application of GAs.)

Changes in simulated proportionate contribution results were compared using results obtained through the manual adjustment process and the GA approach. The sensitivity analysis simulations were grouped into three categories (Figure 10): (1) variation of pattern factors assigned to wells (operational variation in the value and the time of day—designated as sensitivity simulations

SENS0, SENS1, SENS2, and SENS3); (2) variation in the operational minimum pressure criteria at pipeline locations (designated as sensitivity simulations SENS4 and SENS5); and (3) variation in the operational storage tank water-level differences between the starting time (0 hours) and ending time (24 hours) of a simulation (designated as sensitivity simulations SENS6 and SENS7). Sensitivity analysis simulation SENS0 and SENS1 applied the GA approach to every historical network (420 simulations) using the balanced flow conditions obtained from the manual adjustment process as the initial starting conditions. The remaining sensitivity analysis simulations (SENS2–SENS7) were conducted for distribution-system networks for selected years of 1962, 1965, 1971, 1978, 1988, and 1996. For these historical networks, the previously described parameters were varied with respect to the minimum-, maximum-, and average-demand months. Readers desiring specific details pertaining to the definition of each of the sensitivity analysis simulations should refer to the full report.

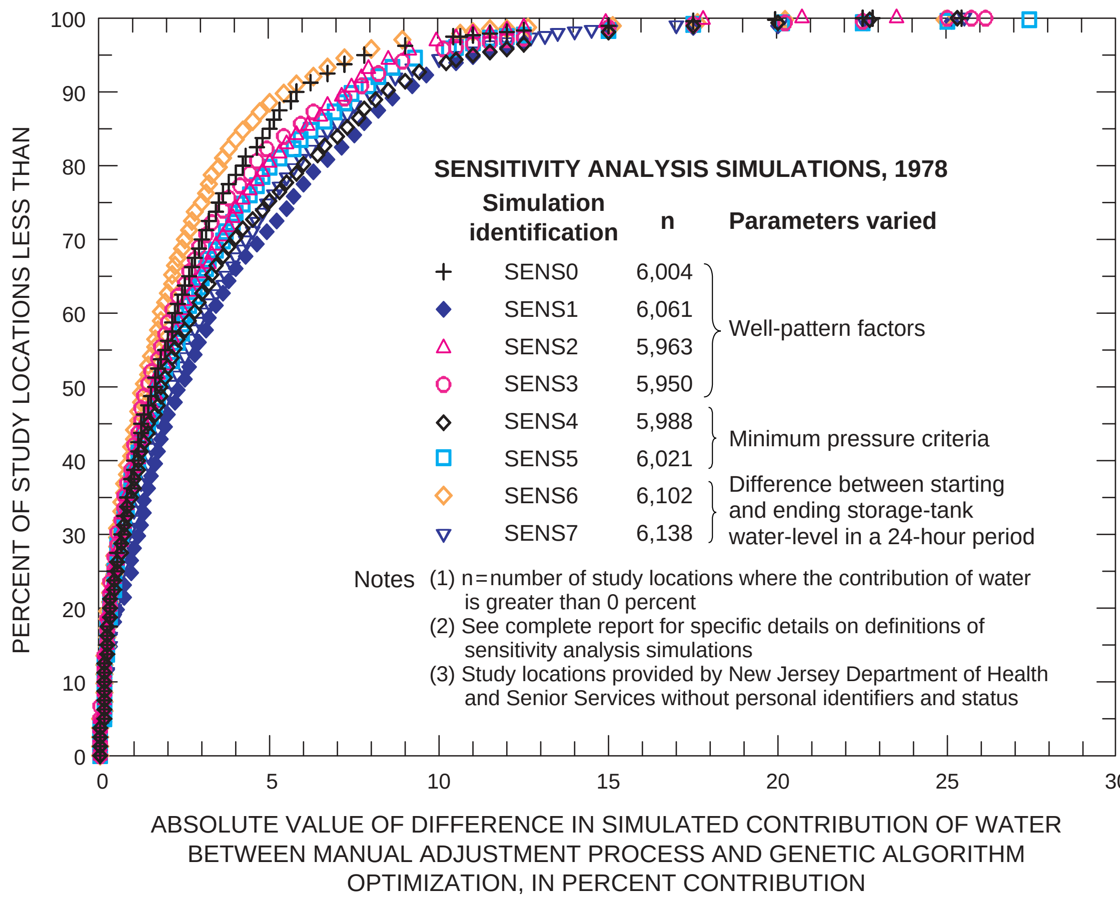


Figure 10. Results of sensitivity analyses using the manual adjustment process and Genetic Algorithm (GA) optimization for maximum-, minimum- and average-demand months, 1978.

Figure 10 shows examples of results for the sensitivity analysis simulations representing 1978 conditions. These results indicate small variations when comparing the proportionate contribution results from the manual adjustment process to results obtained using the GA approach. Figure 10, however, also shows that the simulated proportionate contribution of water from wells and well fields is relatively insensitive to changes in system operational parameters. For a 24-hour period, the average percentage of water over all study locations derived from all wells or well fields using either the manual adjustment process or any of the GA simulations does not vary appreciably. For example, the results in Figure 10 indicate that more than 90% of study locations show a difference of 10% or less in the simulated proportionate contribution results derived from either the manual adjustment process or any of the GA simulations. These results (Figure 10) indicate that there was a narrow range within which the historical water-distribution system could have successfully operated to maintain a balanced flow condition and satisfy the "Master Operating Criteria" previously described. Results for other historical networks (such as 1988 and 1996) show less variation when comparing simulated proportionate contribution results obtained using either the manual adjustment process or any of the GA optimization approaches.

For the historical reconstruction analysis, investigators assumed that daily system operations over a period of 1 month could be represented by a "typical" 24-hour day for each month of the historical period. To test the validity of this assumption, additional sensitivity analyses using hourly operational data obtained from the water utility for 1996 were conducted. For the maximum-demand month of June 1996, a 30-day analysis—720 hours—was conducted by simulating the hourly operation according to the data supplied by the water utility. When results for the hourly operation simulation for 30 days (average over the 30-day period) were compared with results from the "typical" 24-hour day for the month of June, differences in the proportionate contribution of water to the five pipeline locations (A, B, C, D, and E) showed only slight variations. As an example, the difference in the contribution of water from the Parkway well field for the two methods of simulating the daily system operations were 0% for location A, 1% for location B, 4% for location C, 2% for location D, and 3% for location E. Therefore, sensitivity analysis assisted in confirming that the day-to-day operations of the water-distribution system were highly consistent over a 30-day period (based on available 1996 hourly data) and could be represented by a "typical" 24-hour operational pattern.

The sensitivity analysis conducted as part of the historical reconstruction of the water-distribution system serving the Dover Township area indicate that: (1) there was a narrow range within which the historical water-distribution systems could have successfully operated and still satisfy hydraulic engineering principles and the "Master Operating Criteria," and (2) daily operational variations over a month did not appreciably change the proportionate contribution of water from specific sources when compared to a typical 24-hour day representing the month. Thus, the reconstructed historical water-distribution systems and operating criteria—based on applying the "Master Operating Criteria" and using generalized water-utility information—are believed to be the most probable and realistic scenarios under which the historical water-distribution systems were operated.

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What is in the ATSDR report?

The report presents and describes the approach ATSDR and NJDHSS used for conducting the historical reconstruction analysis of the water-distribution system serving the Dover Township area for the period of 1962 through 1996. Specifically, the report focuses on: (a) data requirements, (b) methods of analysis, (c) the simulation approach, (d) results of simulation of historical networks in terms of proportionate contribution of water from wells and well fields to locations throughout the Dover Township area, and (e) issues of uncertainty and variability in system operations.

What is a water-distribution system model and which one did ATSDR use?

A water-distribution model is a computer program that solves a set of mathematical equations that describe the flow of water from reservoirs, wells, and storage tanks through a network of pipelines. The model developed for the Dover Township area contains information specific to the water-distribution system serving that area. The computer model software used by ATSDR is called EPANET 2 and it is available in the public domain over the Internet on the EPA Web site at URL: *www.epa.gov/ORD/NRMRL/wswrd*.

How are ATSDR and NJDHSS using water-distribution system modeling?

ATSDR and NJDHSS are using water-distribution system modeling to estimate the percentage of water a study subject might have received from each of the well fields in the water-distribution system operating from 1962 through 1996. This approach provides epidemiologists with information they can use to assess the association between the occurrence of childhood cancers and exposure to each of the sources of potable water entering the distribution system.

What type of information did ATSDR and NJDHSS need to conduct the historical reconstruction analysis?

To conduct the analysis, six types of information were required for the historical period:

- pipeline and network configurations;
- potable water-production data including information on the location, capacity, and time of operation of the groundwater wells producing the water;
- information on the distribution of water consumption at locations throughout the distribution system;
- high-service and booster pump-characteristic curve data;
- storage-tank and water-level data; and
- system operations information such as the on-and-off cycling of wells and high-service and booster pumps.

What procedures did ATSDR and NJDHSS use to reconstruct historical water-distribution system conditions?

Water-distribution system networks representing the location of pipelines from 1962 through 1996 were derived from a pipeline database obtained from the water utility. Analyses were conducted for each month from January 1962 through December 1996 (420 simulations or "model runs"). For each of the 420 monthly analyses, additional simulations were conducted to determine the percentage of water contributed by each well or well field operating during the month.

What type of information did ATSDR and NJDHSS have regarding historical operations of the water-distribution system serving the Dover Township area?

Before 1978, system operation information such as the on-and-off cycling of wells and high-service and booster pumps was not available. For selected years from 1978–1996, ATSDR investigators obtained generalized guidelines from the water utility describing operations of the water-distribution system on a typical "peak" day in the summer and typical "non-peak" day in the fall. Additionally, some system operations information on operator standard practice procedures were gathered during ATSDR and NJDHSS field-data collection activities in March and August 1998. Except for 1996, specific data such as hourly on-and-off cycling of wells and pumps over a 24-hour period for each month of the historical period were not available. Therefore, ATSDR and NJDHSS investigators developed “Master Operating Criteria” to guide the approach of developing hourly operating data to be used for simulating monthly system operations. These “Master Operating Criteria” allowed investigators to develop specific operating conditions by cycling wells and high-service and booster pumps on and off to meet specific demand, pressure, and storage tank water-level requirements.

Given the lack of historical system operating information, could the system have operated in a vastly different manner than was used in the model?

First, in developing and simulating operating conditions, investigators used accepted engineering and water-utility industry methods of practice (such as minimum pressure and minimum storage tank water-level requirements). Second, investigators used state-of-the-art simulation techniques (such as Genetic Algorithm optimization) in attempting to simulate the operation of the historical systems in different ways. Results obtained by investigators using these techniques indicated that the distribution system could only be realistically operated in a certain manner. Third, investigators found that by operating the historical distribution system in different ways, the calculated percentage of water contributed by wells or well fields to locations in the Dover Township area did not change appreciably.

Has the proportion of water contributed by different well fields to my street remained about the same over the years?

At any given point in the distribution system, water is derived from one or more sources in differing proportions depending on demand conditions, water levels in the storage tanks, and which wells are pumping. The percentage of water contributed by the different wells or well fields to any location in the distribution system can vary monthly, seasonally, and annually. However, as shown in the example results provided in this summary, certain wells did provide the predominant amount of water to locations throughout the Dover Township area.

What kind of oversight and input from independent experts did ATSDR have for the historical reconstruction approach it used and for review of its findings?

Throughout this investigation, ATSDR sought outside technical input and expert peer review. In November 2000, ATSDR convened a technical work group of outside experts to review the approach taken in conducting the historical reconstruction analysis and to review preliminary modeling results. The technical work group was composed of experts with professional backgrounds from government, academia, industry, and consulting. Areas of expertise included (a) numerical model development and simulation; (b) hydraulic and water-quality analysis of water-distribution systems; (c) model calibration; and (d) water-distribution system optimization. Overall, the experts indicated that the approach used by ATSDR was technically sound given the data limitations, and provided some recommendations for improving the modeling approach and reconstruction analysis (which ATSDR implemented). In August 2001, six nationally and internationally recognized experts from outside the agency met to discuss their review of the full report. Panel members agreed that given the available data, the technical approach and methodology used by ATSDR to reconstruct the historical operation of the water-distribution system for the Dover Township area were reasonable and followed accepted engineering and modeling practices.

Where and how can I obtain a copy of the ATSDR report?

A limited number of printed copies of the full report are being made available to area stakeholders and placed at public repositories. Electronic versions of this summary and the full report are available over the Internet at the ATSDR Web site at URL: *www.atsdr.cdc.gov*.