U.S. Department of the Interior
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Model Simulation of the Manasquan Water-Supply System in Monmouth County, New Jersey

Water-Resources Investigation Report 01-4172

Prepared in cooperation with the

New Jersey Water Supply Authority

USGS
science for a changing world

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By Ming Chang, Gary Tasker, and Steven Nieswand

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West Trenton, New Jersey

2001

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CONVERSION FACTORS

Multiply	By	To obtain
inch (in.)	2.54	centimeter
inch (in.)	25.4	millimeter
inch (in.)	25,400	micrometer
square mile (mi^2)	2.590	square kilometer
gallons per day (gal/d)	0.003785	cubic meters per day
million gallons per day (Mgal/d)	0.04381	cubic meters per second

MODEL SIMULATION OF THE MANASQUAN WATER-SUPPLY SYSTEM IN MONMOUTH COUNTY, NEW JERSEY

By Ming Chang, Gary Tasker, and Steven Nieswand

ABSTRACT

Model simulation of the Manasquan Water Supply System in Monmouth County, New Jersey, was completed using historic hydrologic data to evaluate the effects of operational and withdrawal alternatives on the Manasquan reservoir and pumping system. Changes in the system operations can be simulated with the model using precipitation forecasts.

The Manasquan Reservoir system model operates by using daily streamflow values, which were reconstructed from historical U.S. Geological Survey streamflow-gaging station records. The model is able to run in two modes--General Risk Analysis Model (GRAM) and Position Analysis Model (POSA). The GRAM simulation procedure uses reconstructed historical streamflow records to provide probability estimates of certain events, such as reservoir storage levels declining below a specific level, when given an assumed set of operating rules and withdrawal rates. POSA can be used to forecast the likelihood of specified outcomes, such as streamflows falling below statutory passing flows, associated with a specific working plan for the water-supply system over a period of months.

The user can manipulate the model and generate graphs and tables of streamflows and storage, for example. This model can be used as a management tool to facilitate the development of drought warning and drought emergency rule curves and safe yield values for the water-supply system.

INTRODUCTION

The Manasquan Water Supply System (MWSS), under the management of the New Jersey Water Supply Authority (NJWSA), is composed of the Manasquan Reservoir and the Manasquan River pumping station. The MWSS supplies potable water to the residents of Monmouth County and northern Ocean County, New Jersey. The system also supplies raw water to a water purveyor for treatment and distribution in Monmouth and Ocean Counties. The U.S. Geological Survey (USGS), in cooperation with the NJWSA, developed a computer model of the Manasquan Water Supply System to evaluate the effects of operational and withdrawal alternatives on the reservoir and pumping system.

Purpose and Scope

This report describes (1) the components of the computer model of the Manasquan Water Supply System, (2) the methodology used to develop the input data, and (3) the development of drought warning and emergency rule curves. The graphical and tabular outputs of the model are shown in illustrations. Reconstructed historical streamflow records, approximately 68 years, were used to provide probability estimates of drought events. Rule curves were created by using model outputs to aid in the development of safe yield for the Manasquan Reservoir system.

Description of Study Area and Water-Supply System

The Manasquan Reservoir, which covers 770 acres and has a capacity of 4.7 Ggal (billion gallons), is on Timber Swamp Brook, a tributary of the Manasquan River in Howell Township, Monmouth County, New Jersey (fig. 1) (New Jersey Water Supply Authority, 1997). Water is withdrawn from the Manasquan River at an intake facility located near Allenwood, Wall Township, Monmouth County (fig. 1). The water then is pumped to settling facilities where it can be pumped to the reservoir or can flow by gravity to a distribution chamber. If the water is sent to the distribution chamber, it can be diverted directly to the Manasquan Water Treatment Plant and to the New Jersey-American Water Company (NJ-AWC) treatment facility.

Water can be pumped at the intake facility only when the passing flow requirement of 8 Mgal/d is met. The minimum pumping rate that the intake facility can use to withdraw water is 26 Mgal/d; the maximum rate is 150 Mgal/d. The maximum pumping rate for the reservoir pumping system is 120 Mgal/d. This pump is operated only during off-peak electrical usage hours to reduce operational costs. A maintenance flow of 200,000 gal/d is required to sustain flows at Timber Swamp Brook.

THE MANASQUAN RESERVOIR SYSTEM MODEL

The model functions as a continuity accounting model (Dunne and Tasker, 1996), consisting of a series of interconnected nodes. At each node the monthly total of the daily averages of

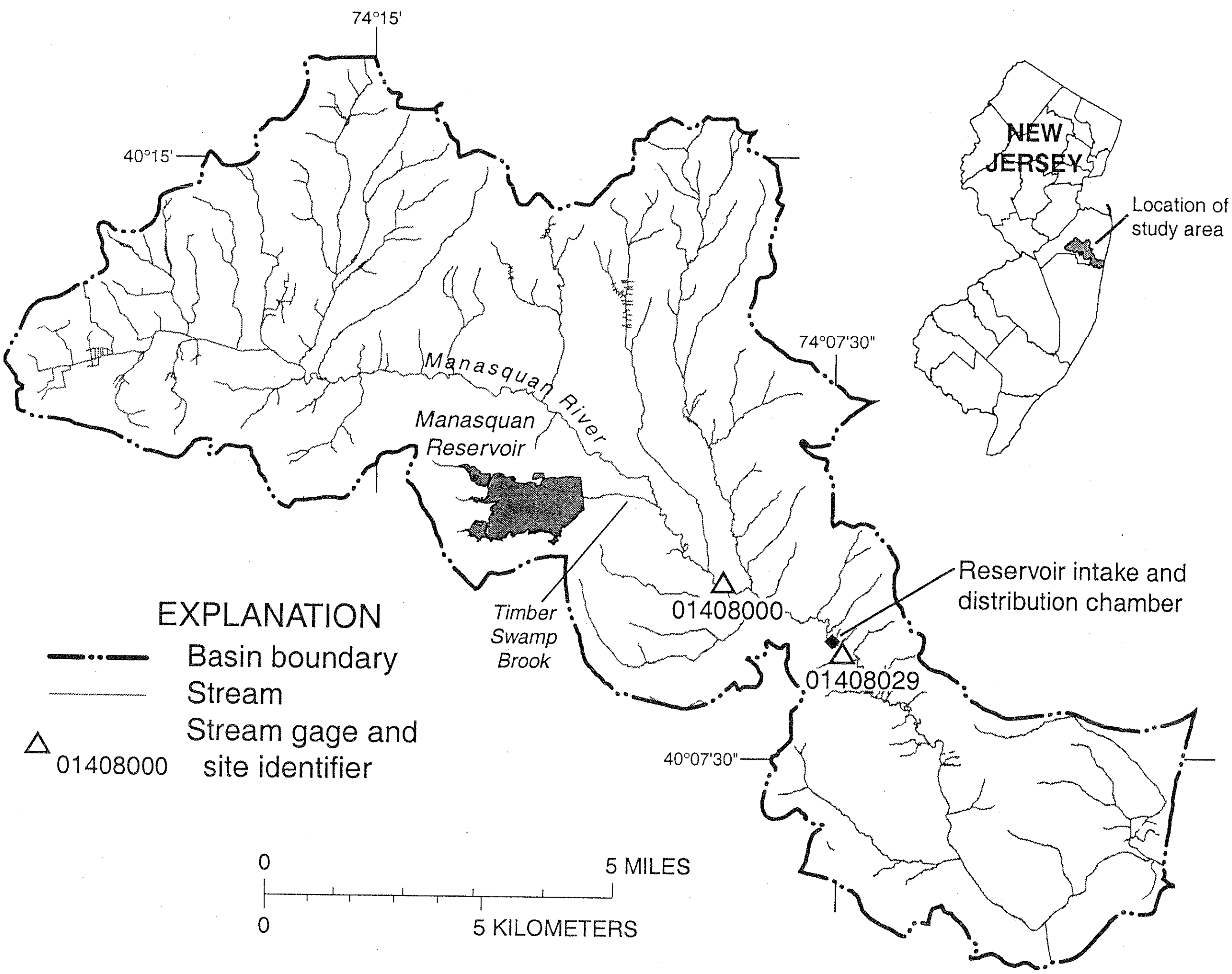

Figure 1. The Manasquan River Basin, Monmouth County, N.J. [Station 01408000, Manasquan River at Squankum, N.J.; station 01408029, Manasquan River near Allenwood, N.J.]

inflow volume, outflow volume, and change in storage are determined and recorded. The model input is the estimated daily streamflow for each node that has been reconstructed from records of water use and estimated from flows observed at the gaging station (01408000) at Squankum (fig. 1). A set of operating rules is used to control the reservoir releases and pumpages to meet the passing flow requirement and the withdrawal demands. The default operating rules can be changed in order to evaluate the effects of alternatives on the reservoir system. The general direction of flow in the model is shown in figure 2.

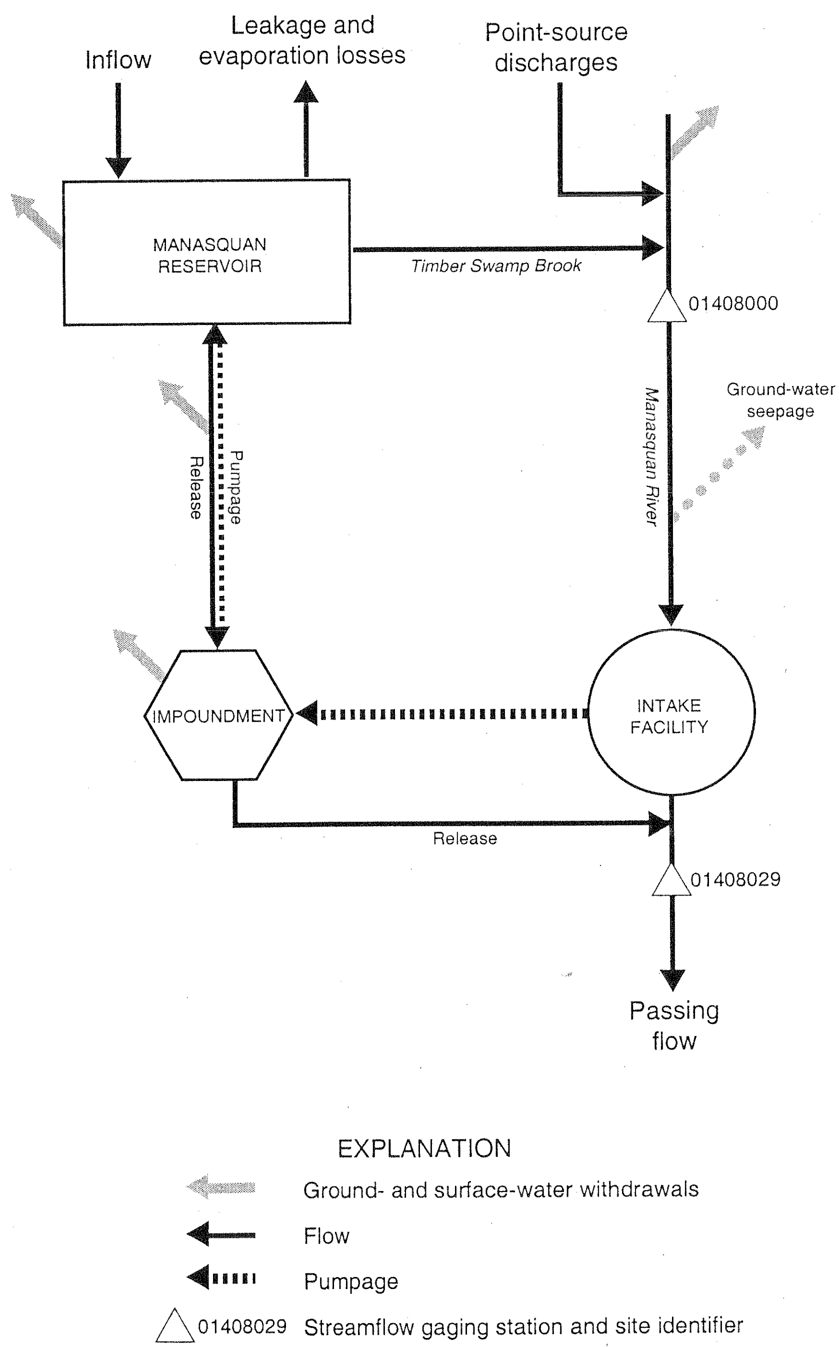

Figure 2. Schematic diagram of the Manasquan Water Supply System, Monmouth County, New Jersey. [Station 01408000, Manasquan River at Squankum, N.J.; station 01408029, Manasquan River near Allenwood, N.J.]

Historical Streamflow Reconstruction

The Manasquan Reservoir System model uses daily natural streamflow values that were reconstructed by use of historical USGS streamflow-gaging station records and adjusted for the effects of human activities, such as water withdrawals and wastewater discharges (table 1). The period of streamflow record used for the streamflow-gaging station located at Manasquan River at Allenwood begins in June 1990. In order to create a record of streamflow prior to 1990 at the Allenwood stream gage, mean daily streamflow values were reconstructed using streamflow during the period of record (July 1931 to December 1999) at the station upstream from Allenwood at Manasquan River at Squankum (table 1).

The reconstruction of the streamflow at Allenwood took into account a number of human activities that influence the flow in the Manasquan River. These activities include point-source discharges from wastewater-treatment facilities; withdrawals of surface water from the river or ponds in the watershed for irrigation and industrial use; withdrawals of ground water from surficial aquifers (100 meters or less) for irrigation and water supply; withdrawals of ground water from confined aquifers for water supply; and infiltration and inflow (I/I) into wastewater-collection systems. Withdrawals from surficial aquifers were considered to have a direct relation (1:1) to streamflow. Withdrawals from confined aquifers increased the leakage from shallow aquifers; therefore, the leakage was considered to have a direct relation (1:1) to streamflow. I/I is defined as the leakage of shallow ground water and storm runoff into wastewater-collection systems. Because I/I is water that would go into the river if the wastewater-collection system was not present, it also has a direct relation (1:1) to streamflow. These activities and the methodology for estimating them are described in Appendix A.

Rule Curves

The safe yield of a surface source of water is defined by the New Jersey Department of Environmental Protection (NJDEP) as "the yield maintainable by a water system continuously throughout a repetition of the most severe drought of record, after compliance with requirements for maintaining minimum passing flows" (The Water Supply Management Act Rules, N.J.A.C.7: 19-6.1 and the following ones). In any given year, a drought that is more severe than the drought of record may occur; therefore, rule curves are developed for water-supply reservoirs to provide indicators to water-supply-system managers that actions may be warranted to preserve the integrity of the water-supply system.

Long-term records (approximately 20 or more years) can be used to establish a range for normal reservoir levels. Rule curves are established below the normal range to give the water manager time to institute actions, usually to reduce demand on the system and maintain an adequate water supply. Typical drought rule curves have three levels -- drought watch, drought warning, and drought emergency. During the drought watch phase, the water manager begins initial preparations for the drought warning phase and advises water users to use water wisely. The drought warning phase is more serious; a much greater effort is made to motivate water users to conserve water voluntarily. In some cases, mandatory restrictions are put into effect. Under a drought emergency, mandatory restrictions usually are put into effect.

Table 1. Streamflow-gaging stations and period of record, Monmouth County, New Jersey [mi^2; square miles; refer to figure 1 for station locations]

Station number	Station name	Drainage area (mi^2)	Period of record
01408000	Manasquan River at Squankum, N.J.	44	7/1931 to 12/1999
01408029	Manasquan River near Allenwood, N.J.	63.3	6/1990 to 12/1999

Three approaches were tested in developing the rule curves for the Manasquan Water Supply model. All approaches are based on procedures created by the NJDEP for developing rule curves (Joint Board of Public Utilities and NJDEP Water Emergency Planning Team Final Report, June 1989). An example of a typical rule curve is shown in figure 3. NJDEP procedures were used to adjust the curves to fit a trapezoid in order to smooth the curve.

Approach 1

The first approach is similar to the approach used by the New Jersey Water Supply Authority in establishing rule curves for their Raritan reservoirs (M.H. McRee, New Jersey Water Supply Authority, unpublished report, undated). This approach uses the General Risk Analysis Model (GRAM) for the period of record (1930-99) with appropriate edits to the specified water demand, reservoir operating rules, and the required passing flow. GRAM is discussed in the section Model Simulation later in the report.

The simulation output included the end of the month storage levels, in billion gallons, for the Manasquan Reservoir for the period of record. The rule curves developed for the MWSS were based on frequency analysis with use of the 10- and 30-percent non-exceedance values for monthly reservoir storage for the period of record. This approach is similar to the method used by NJDEP, which has used the 10- and 30-percent non-exceedance streamflow values to define drought emergency and drought warning, respectively, in their procedures for developing rule curves. An example of the rule curves developed for approach 1 is shown in figure 4 and discussed in Appendix B.

Approach 2

The second approach uses both the Position Analysis (POSA) mode and GRAM mode of the Manasquan model. An iterative process was used that began with the POSA mode. (Position Analysis Model is discussed in Model Simulation later in the report.) First, an operating mode is determined for the water-supply system under drought conditions so that the minimum storage will not be less than the dead storage (minimum useful storage of a reservoir). After this curve is calculated, the 10-percent and 30-percent non-exceedance curves can be determined, tested, and refined by use of the GRAM mode (fig. 5). The methodology for approach 2 is discussed in Appendix B.

Approach 3

Approach 3 is based on streamflows for the period of record rather than reservoir storage and is similar to the procedures developed by NJDEP. This approach uses the GRAM mode with the 10- and 30-percent non-exceedance flows calculated for different time segments during the period of record. The resulting curves then are compared with drought rule curves for other reservoirs to determine the best representative curve (fig. 6). The methodology for approach 3 is discussed in Appendix B.

Another approach that could be used to develop rule curves is a trial-and-error method using the GRAM and POSA modes. By reviewing rule curves developed for other reservoirs and using these curves as input to the GRAM mode, curves can be developed that meet the policies of the operating agency.

No matter which approach is used to develop drought rule curves, the curves should be adjusted to reflect policy issues. For example, the low points of the rule curves can reflect the risk that the water manager is willing to take during different drought conditions. The minimum storage that a water manager would be comfortable with at different times of the year can be determined on a case-by-case basis. The curves also can be adjusted to reflect the amount of time the water manager wants a system to be in the drought warning or the drought emergency phase. These decisions are associated with different levels of risk. The GRAM and POSA modes allow the water manager to test a large number of alternatives.

Model Simulation

The model can be run in one of two modes--General Risk Analysis Model (GRAM) or Position Analysis Model (POSA).

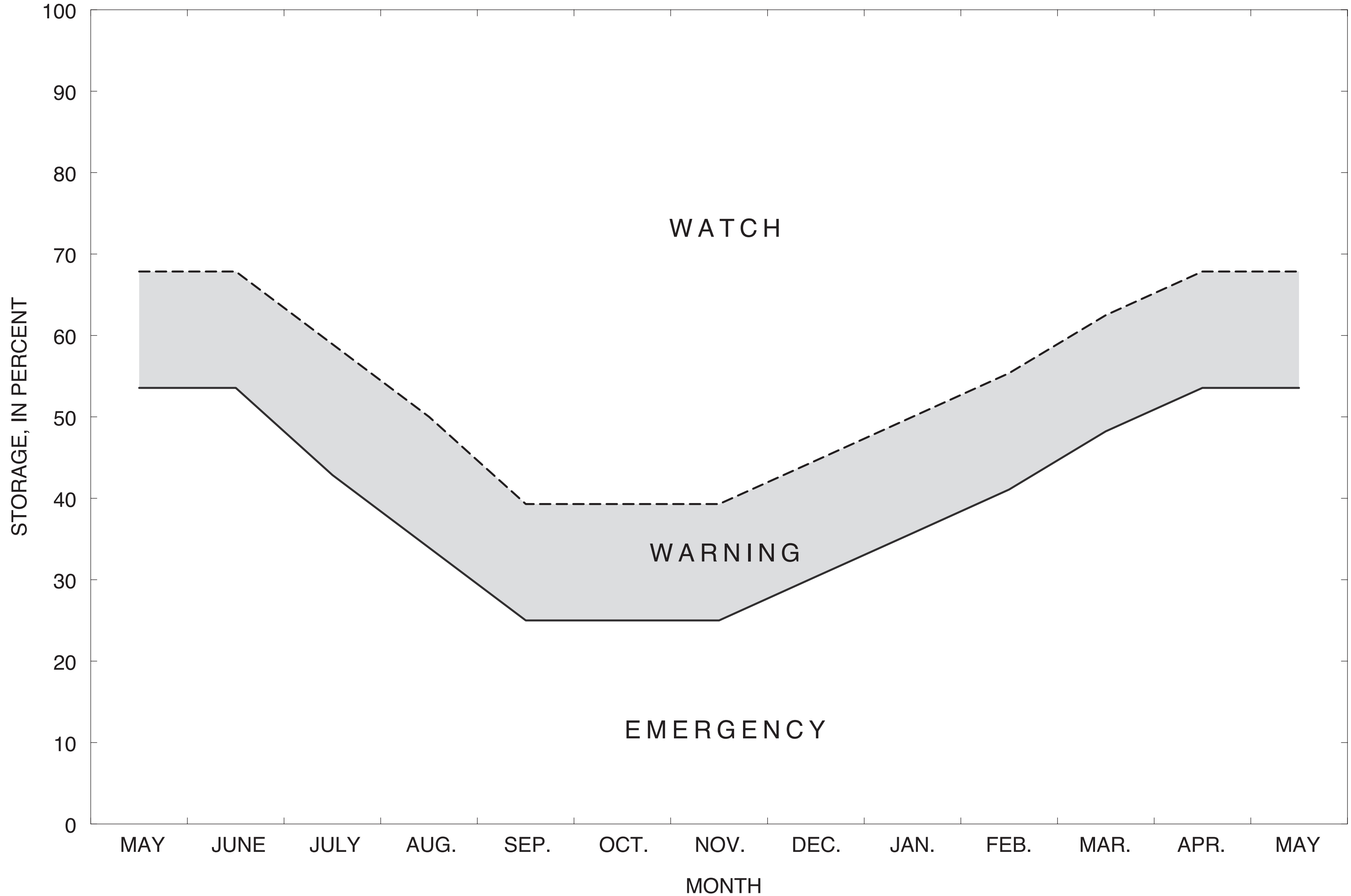

Figure 3. Example of a typical rule curve for New Jersey.

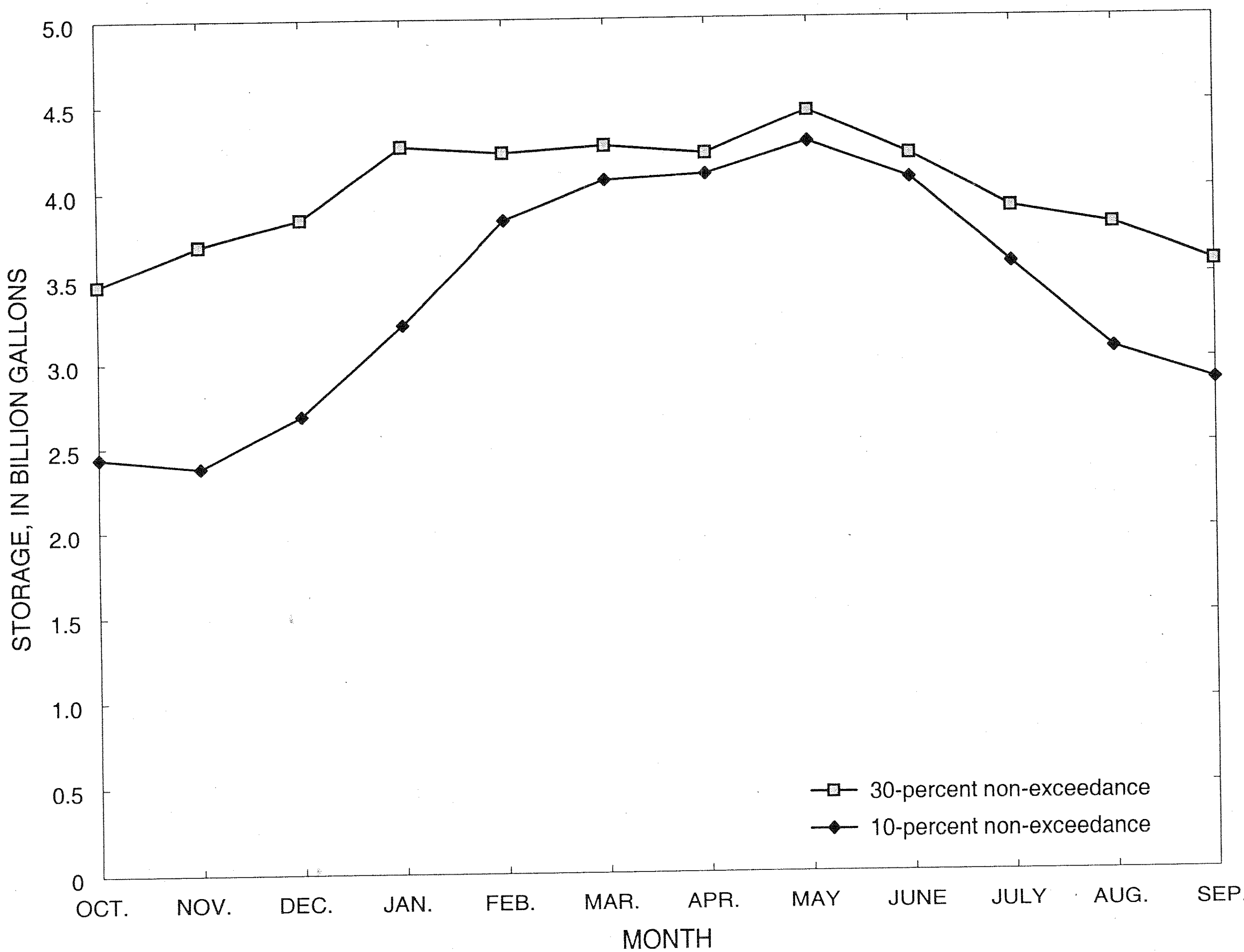

Figure 4. Approach 1 rule curves for management model used in New Jersey.

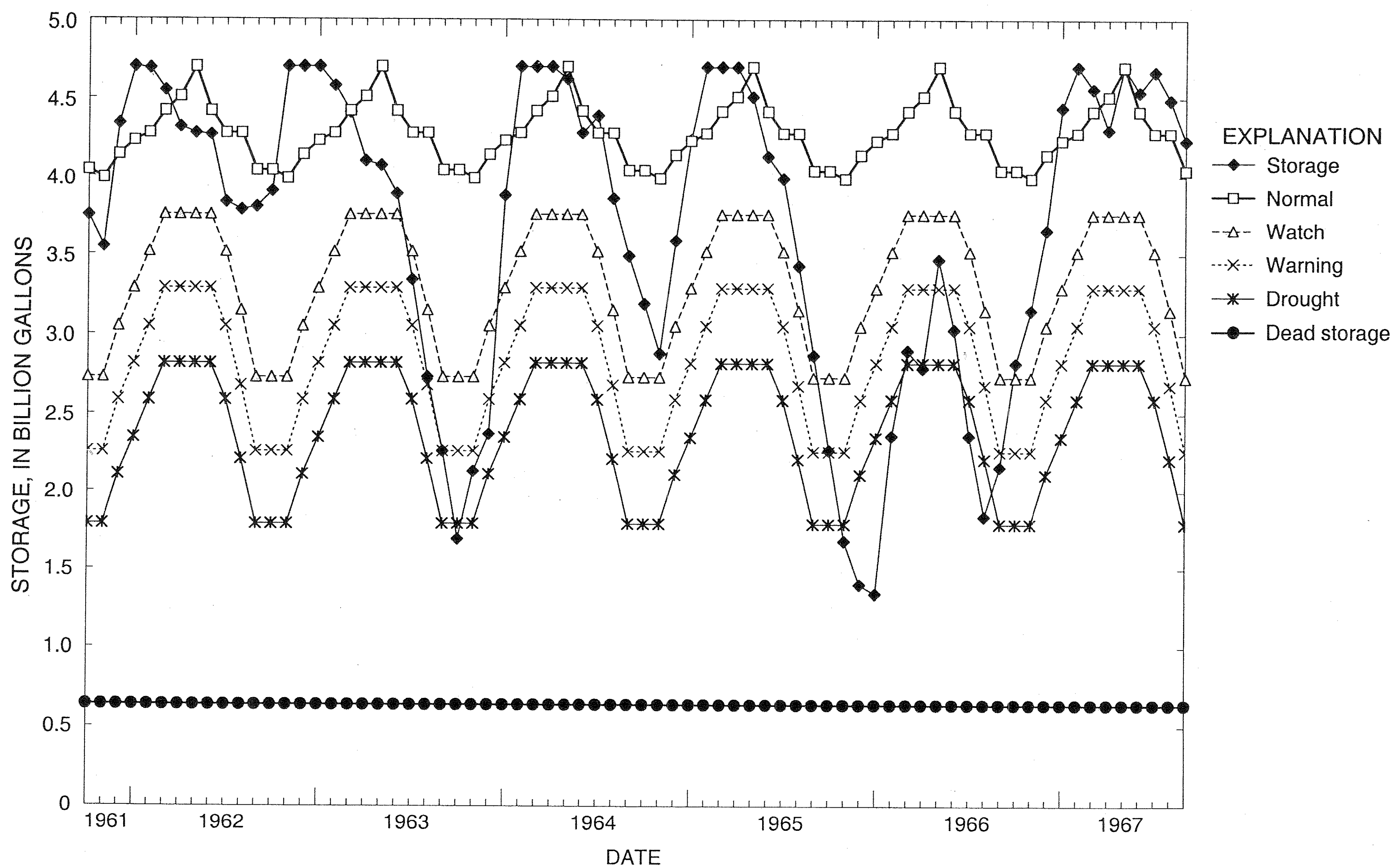

Figure 5. Approach 2 rule curves for management model used in New Jersey.

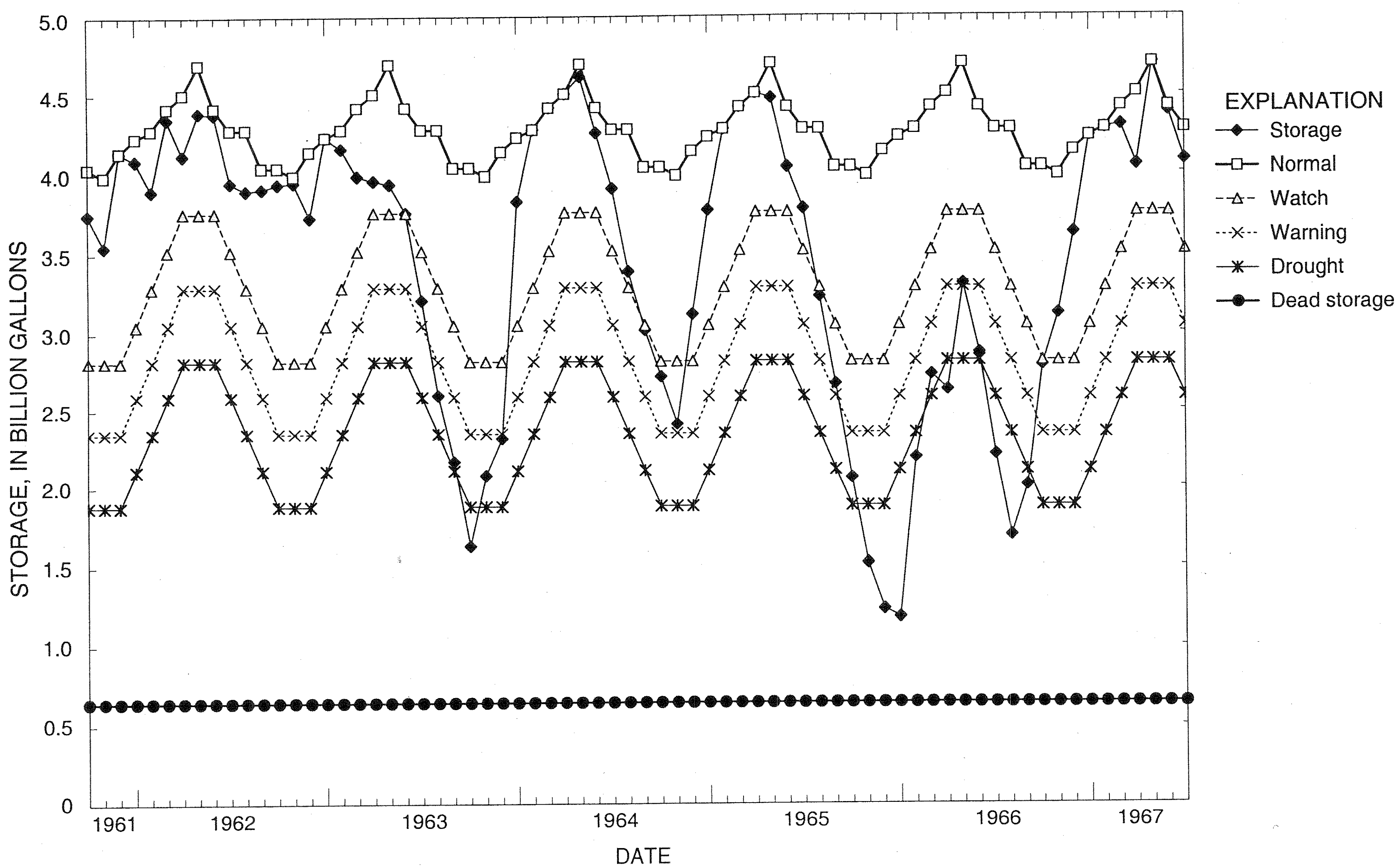

Figure 6. Approach 3 rule curves for management model used in New Jersey.

General Risk Analysis Model

The GRAM simulation procedure (Hirsch, 1978) was used with the reconstructed historical streamflow records for the base period from 1931 to 1999. GRAM can be used to evaluate the effects of operational and withdrawal alternatives on the reservoir and pumping system. It also can be used to determine the safe yield of the system and to develop drought warning and drought emergency rule curves. The model can be used in conjunction with rule curves to review the performance of the system under streamflow conditions from previous years. This type of analysis can give water managers a general representation of system reliability.

The GRAM mode was used to compute daily streamflows at Manasquan River at Allenwood by adding the historical reconstructed streamflows at Allenwood, for the base period from 1931 to 1999, and point-source flows and releases from the reservoir to Timber Swamp Brook, then deducting ground- and surface-water withdrawals, infiltration and inflow, and evaporation and seepage losses. The model included default values for the point-source discharges, releases from Timber Swamp Brook, ground- and surface-water withdrawals, and infiltration and inflow that were calculated with 1998 data. If current values (late 1990s) are used for these variables, the GRAM model can simulate reservoir operations under present human-induced conditions with historic flows.

Because pumping capacity is limited, GRAM attempts to satisfy daily demands at the distribution chamber with withdrawals from the river. Withdrawals from the river are limited by the passing flow requirement at Allenwood. If demand cannot be met by withdrawals from the river, water is released from the reservoir to make up the difference. Demand from the reservoir pipe also is met by reservoir releases. If the pumping trigger is turned on, GRAM will fill the reservoir to the pumping target, which is constrained by pumping a minimum and maximum quantity of water and by the amount of water in the river. GRAM accumulates the daily streamflow values for each month and, in a monthly format, saves an output that reports the storage at month's end (in Ggal), the average daily withdrawals from the river and streamflow to the reservoir (in Mgal/d), the average daily releases from the reservoir (in Mgal/d), and the average daily flow (in Mgal/d) that passed the intake. Detailed schematics and statistics of the GRAM model are presented in Appendix B.

Position Analysis Model

Position analysis (POSA) is a tool that water managers can use to forecast the likelihood of specified outcomes, such as reservoir levels falling below a specified level or streamflows falling below statutory passing flows, associated with a specific operating plan for the basin over a period of a few months (Hirsch, 1978). It can aid the water manager in deciding which plan of operation to implement by providing a means to evaluate and rank each proposed plan of operation in terms of future drought risks (Dunne and Tasker, 1996). POSA also can be used to develop drought warning and drought emergency rule curves by allowing the user to specify operating rules, current streamflows, and the current reservoir level.

The POSA mode operates by activating a series of subprograms that load the data into a cyclic model. A month with observed streamflow data is randomly chosen within the same season and with monthly conditions similar to those of the specified month. Monthly values then are calculated by the program and reported as output in the same method used for GRAM. Detailed schematics and statistics of the POSA model are described in Appendix B.

Graphical User Interface

A graphical user interface (GUI) was designed for the Manasquan model for use in a Windows 95/NT or higher environment in conjunction with a FORTRAN program. The GUI was created using Visual Basic 6.0 and consists of various screens in which the user can manipulate data entries (Refer to Appendix B for a detailed instruction manual.) Four category screens are available that can be used to direct the model. These categories are physical dimensions, basin adjustments, demands, and reservoir operating rules (fig. 7).

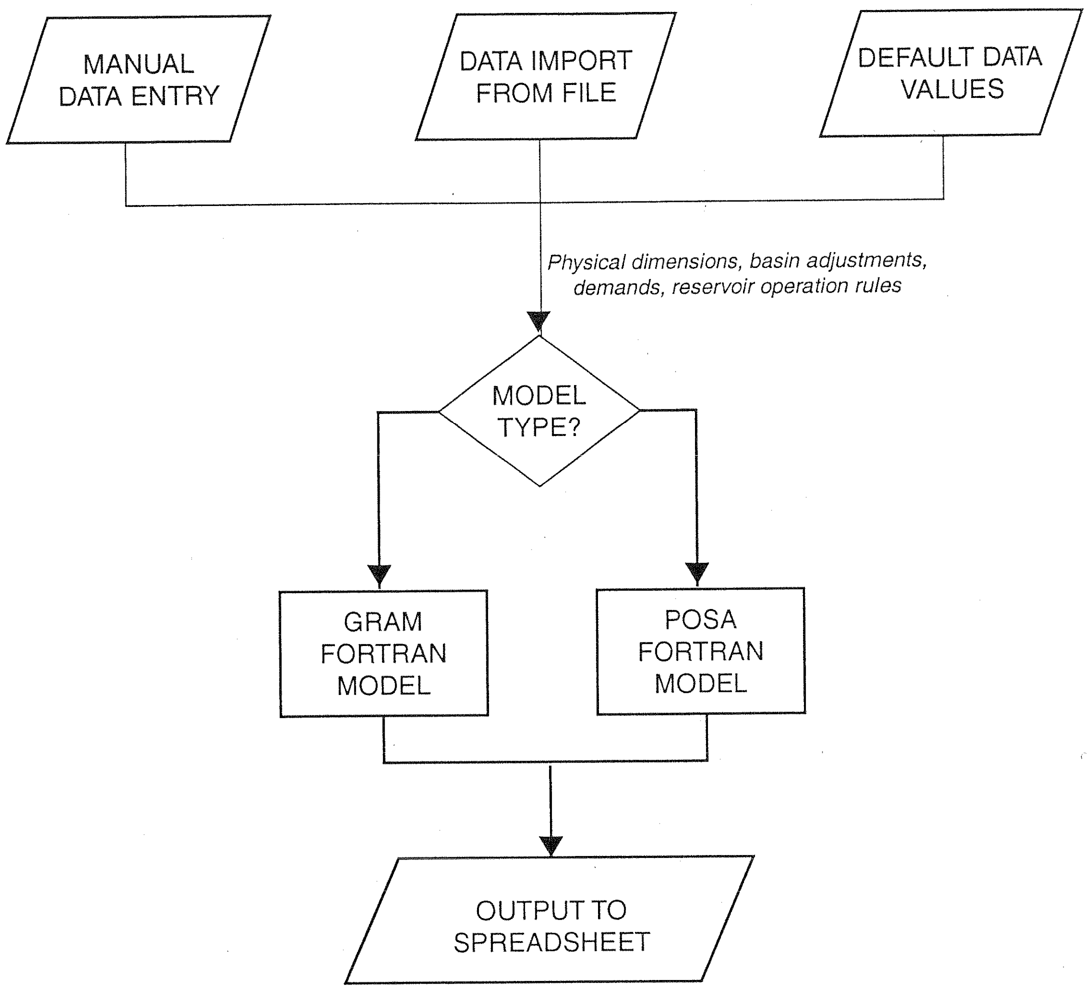

Figure 7. Flow chart of Manasquan Reservoir System Model used for the study in New Jersey.

Physical Dimensions

The capacity, dead storage, and pumping factors of the reservoir system can be altered in the Manasquan model to affect reservoir operation. Definitions of the variables that can be altered are listed below.

- *Total reservoir capacity* – The maximum volume, in Ggal, in the reservoir.
- *Dead storage* – The minimum volume, in Ggal, in the reservoir that is not available for use by the water supply.
- *River intake pump maximum* – The maximum flow, in Mgal/d, that can be pumped from the Manasquan River.
- *River intake pump minimum* – The minimum flow, in Mgal/d, that can be pumped from the Manasquan River.
- *Reservoir pump maximum* – The maximum flow, in Mgal/d, that can be pumped to the reservoir.
- *Reservoir pump minimum* - The minimum flow, in Mgal/d, that can be pumped to the reservoir.
- *Intake pumping factor* – The rate, as a fraction, at which the river intake pump will operate. For example, a value of 0.5 indicates a 50-percent pumping rate.
- *Reservoir pumping factor* – The rate, as a fraction, at which the reservoir pump will operate.

Basin Adjustments

Point sources and withdrawals from the Manasquan River Basin can be changed in the basin adjustments category. The variables that can be altered and their definitions are listed below.

- *Ground-water shallow withdrawals and change in leakage* – The ground-water shallow withdrawals term refers to the amount of water withdrawn from the shallow aquifers, usually for industrial and agricultural use. The change in leakage term refers to the human-induced seepage from surficial aquifers to confined aquifers caused by the pumping of confined aquifers. These two terms are combined to create one term for ground-water withdrawals, in Mgal/d, for use in the Manasquan River Basin.
- *Surface-water shallow withdrawals* – The amount of flow from surface-water withdrawals within the Manasquan River Basin, in Mgal/d.
- *Point source flows to basin* – The amount of flow from point-source discharges in the basin, in Mgal/d.
- *Evaporation and seepage losses* – Losses, in inches, resulting from evaporation and seepage from the reservoir. Data are obtained from the National Oceanic and Atmospheric Administration and Metcalf and Eddy (1985).
- *Manasquan River Regional Sewage Authority (MRRSA) flows* – The average yearly flow, in Mgal/d, at MRRSA. These data are used to calculate the I/I.
- *Percentage of total MRRSA flow from contributing municipalities* – The total wastewater flow, in Mgal/d, from municipalities in the contributing watershed area of the Manasquan River Basin. These data are used to calculate the I/I.
- *Percentage of contributing municipalities above Squankum streamflow gaging station* – The total percentage of municipalities contributing to MRRSA wastewater flow in the contributing watershed area of the Manasquan River Basin upstream from the Squankum streamflow gaging station.

Water Demands

The user can change the water-supply demand requirements to affect the model in the demands category. This category can be used to change the demand for drought conditions, the passing flow requirements, and the water-supply demand for various variables of the system. Definitions of the factors that can be altered are listed below.

- *Hospital Road Distribution Chamber* – The demand, in Mgal/d, at the distribution chamber located near Allenwood, Wall Township, Monmouth County.
- *Manasquan reservoir pipeline* – The demand, in Mgal/d, from the Manasquan Reservoir pipeline located at the treatment plant in Howell Township, Monmouth County.
- *Manasquan reservoir* – The demand, in Mgal/d, for withdrawals directly from the Manasquan Reservoir.
- *Phase I drought (Drought warning)* – The demand, as a fraction of normal, during a Phase I drought condition. During a drought warning, voluntary restrictions on water use may reduce demand on the system. The Phase I condition is determined by the New Jersey Water Supply Authority.
- *Phase II drought (Drought emergency)* – The demand, as a fraction of normal, during a Phase II drought condition. During a drought emergency, restrictions on water use may reduce the demand on the system. The Phase II condition is determined by the New Jersey Water Supply Authority.
- *Passing flow at the Allenwood streamflow gage*– The required passing flow of the Manasquan River at Allenwood streamflow gage (station 01408029).

Reservoir Operating Rules

In the Manasquan Model, the reservoir operating rules, which include drought levels, pumping targets and triggers, and releases to Timber Swamp Brook, can be manipulated to change or imitate actual system requirements. Changing actual system requirements allows efficiency and risk comparisons between alternative and actual conditions. Factors that can be altered and their definitions are listed below.

- *Timber Swamp Brook release* – The monthly releases to Timber Swamp Brook, in Mgal/d.
- *Normal reservoir level* – The normal level of the reservoir, as a fraction of full.
- *Pumping target level* – The level of the reservoir at which pumping to the reservoir will cease, as a fraction of full.
- *Pumping trigger level* – The level of the reservoir at which pumping to the reservoir will begin, as a fraction of full.
- *Drought watch level* – The level of the reservoir at which a drought watch will result, as a fraction of full.
- *Phase I and II drought* – The level of the reservoir at which a Phase I or II drought will result, as a fraction of full.

Model Output

When all the above model variables have been entered, the user will be prompted to designate a name for the output file that will be created automatically. A table and related graphs will be produced in Microsoft Excel format.

General Risk Analysis Model (GRAM) Data Table and Graphs

The table that is produced as output and that lists the values for storages, releases, streamflows, and basin condition is shown in figure 8. Examples of the graphs of flow and storage that are produced as output are shown in figures 9 and 10. Detailed explanations of figures are in Appendix C.

Position Analysis Model (POSA) Data Table and Graphs

A data table produced as output lists values for non-exceedance probabilities (fig. 11). A non-exceedance probability is the likelihood, in percent, that the reservoir will be at or below a given capacity at the end of a month on the basis of entered model variables. An example of the graph that is produced of the storage in relation to the month is shown in figure 12. Detailed explanations of figures 11 and 12 are given in Appendix C.

Model Limitations

A sensitivity analysis was performed on the Manasquan model to determine how different adjustments to ground- and surface-water withdrawals and wastewater discharges in the basin, operational conditions, and changes to the reservoir system would affect reservoir storage. One model variable or a combination of variables was adjusted, while all others were kept constant. The GRAM mode of the model was used in this analysis.

The GRAM mode was run for different conditions for the drought of record, during 1960-69, in New Jersey to document how minimum storage would change during that period. Additional model runs were made with different conditions to determine whether water-supply demands could be increased or decreased while maintaining a minimum storage.

The categories that were adjusted for the analysis are listed below.

- Physical dimensions
  - The volume of the reservoir system storage was increased by 100 Mgal to reflect the original design of the system.
  - The maximum pumping capacity at the intake and to the reservoir was increased to 500 Mgal to maximize water capture at the intake.
  - The minimum pumping capacity to the reservoir was reduced to zero to maximize the amount of water that could be pumped to the reservoir.
- Water demands
  - Water demands were adjusted by 125,000 gal/d to 4 Mgal/d. Total demand varied from 26 to 30 Mgal/d.
  - The location of water withdrawals from the system was adjusted.

	A	B	C	D	E	F	G	H	I	J	K	L
46	GENERAL RISK ANALYSIS MODEL											
47				TO RES	FR RIV	PASSING						
48	MON/YEAR	STORAGE	RELEASE	PUMPING	PUMPING	FLOW	CONDITION	NORMAL	WATCH	WARN	DROUGHT	DEAD STORAGE
49	10/1961	3.75	10	0	16.25	29.64	Normal	4.04	2.73	2.26	1.79	0.64
50	11/1961	3.55	10	0.96	17.21	23.65	Normal	3.99	2.73	2.26	1.79	0.64
51	12/1961	4.34	10	32.36	48.61	10.32	Normal	4.14	3.05	2.59	2.11	0.64
52	1/1962	4.7	10	17.6	33.85	44.27	Normal	4.23	3.29	2.82	2.35	0.64
53	2/1962	4.69	10	6.63	22.88	55.41	Normal	4.28	3.52	3.05	2.59	0.64
54	3/1962	4.55	10	0	16.25	110.77	Normal	4.42	3.76	3.29	2.82	0.64
55	4/1962	4.32	10	0	16.25	69.38	Normal	4.51	3.76	3.29	2.82	0.64
56	5/1962	4.28	10	8.25	24.5	19.99	Normal	4.7	3.76	3.29	2.82	0.64
57	6/1962	4.27	10.16	10.03	26.12	10.15	Normal	4.42	3.76	3.29	2.82	0.64
58	7/1962	3.84	13.23	0.39	13.4	8.17	Normal	4.28	3.52	3.05	2.59	0.64
59	8/1962	3.79	13.17	10.95	24.03	9.36	Normal	4.28	3.15	2.68	2.21	0.64
60	9/1962	3.81	10.95	10.17	25.48	9.12	Normal	4.04	2.73	2.26	1.79	0.64
61	10/1962	3.91	10	11.37	27.62	11.72	Normal	4.04	2.73	2.26	1.79	0.64
62	11/1962	4.7	10	32.32	48.57	30	Normal	3.99	2.73	2.26	1.79	0.64
63	12/1962	4.7	10	7.03	23.28	30.16	Normal	4.14	3.05	2.59	2.11	0.64
64	1/1963	4.7	10	7.37	23.62	25.93	Normal	4.23	3.29	2.82	2.35	0.64
65	2/1963	4.58	10	3.07	19.32	51.59	Normal	4.28	3.52	3.05	2.59	0.64
66	3/1963	4.41	10	0	16.25	89.03	Normal	4.42	3.76	3.29	2.82	0.64

Flow / Storage / outputGRAM

Figure 8. Example table of a data output produced by the General Risk Analysis Model (GRAM) in Microsoft Excel for this study in New Jersey.

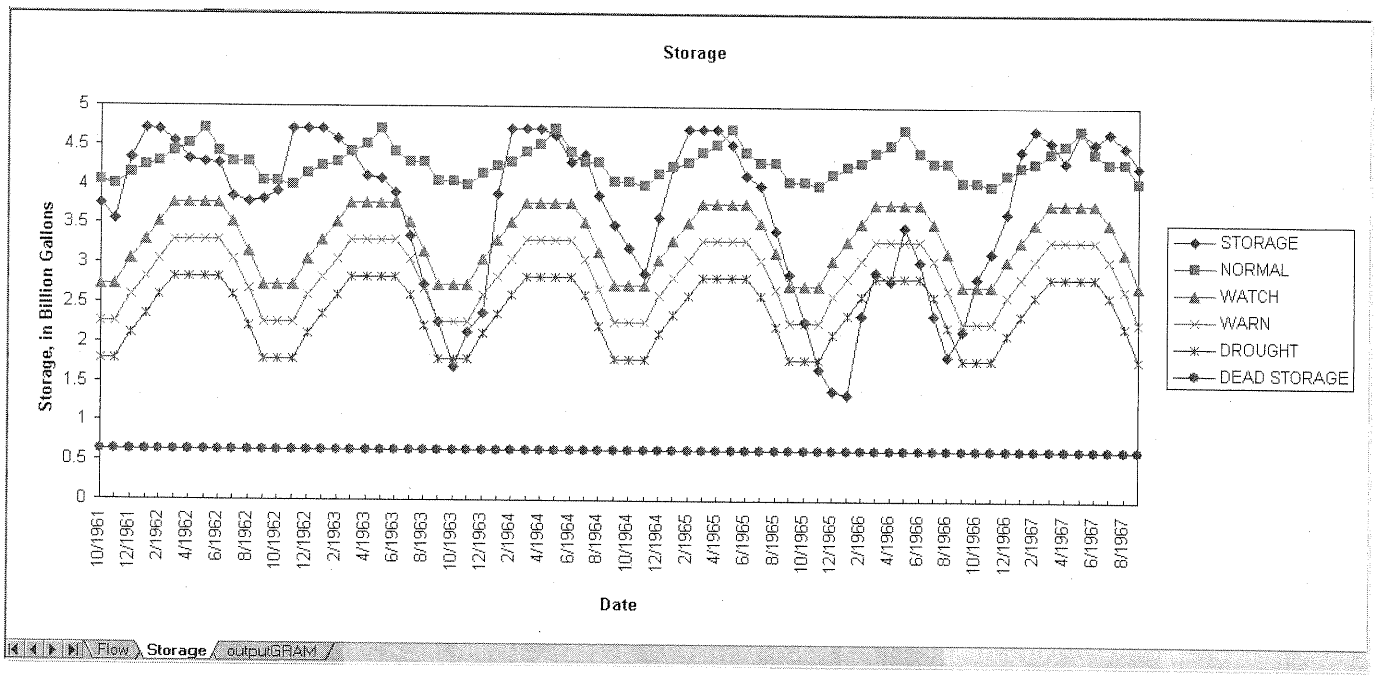

Figure 9. Example graph of storage data output produced by the General Risk Analysis Model (GRAM) in Microsoft Excel for this study in New Jersey.

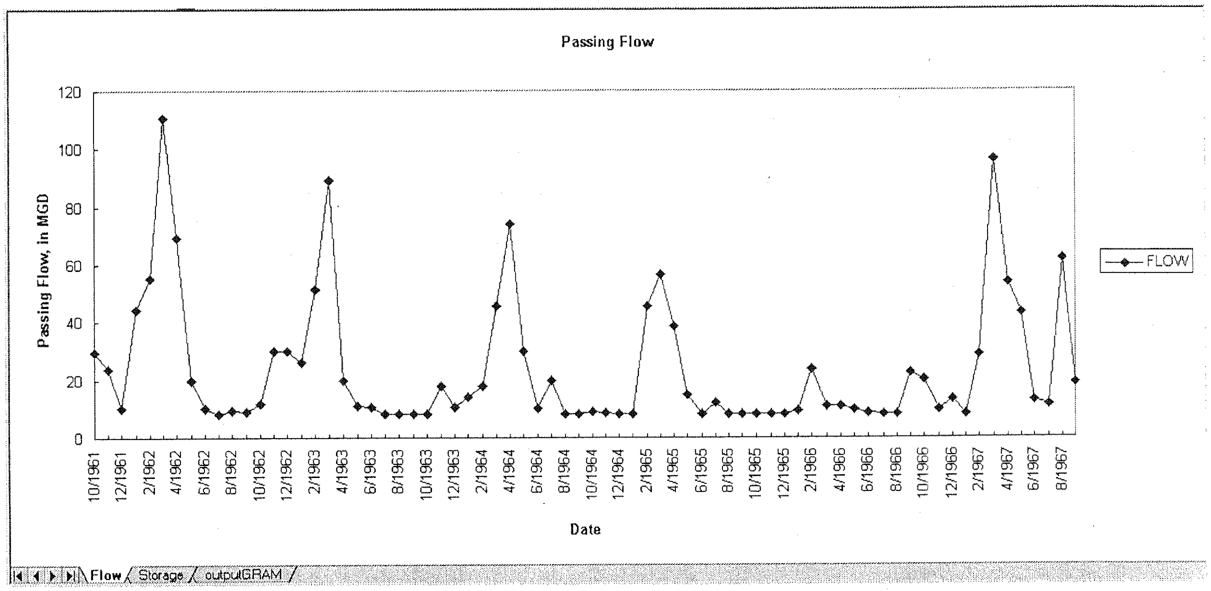

Figure 10. Example graph of passing flow output produced by the General Risk Analysis Model (GRAM) in Microsoft Excel for this study in New Jersey.

	A	B	C	D	E	F	G	H	I	J	K	L	M
50	NON- EXCEEDENCE PROBABILITY												
51	MONTH	MIN	0.01	0.05	0.1	0.25	0.5	0.75	0.9	0.95	0.99	MAX	DEAD STOR.
52	MAY	2.82	2.82	2.82	2.82	2.82	2.82	2.82	2.82	2.82	2.82	2.82	0.64
53	JUN	2.36	2.43	2.55	2.6	2.66	2.76	2.97	3.39	3.86	4.42	4.59	0.64
54	JUL	1.89	2.03	2.2	2.28	2.4	2.61	3.14	3.76	4.17	4.28	4.7	0.64
55	AUG	1.41	1.71	1.94	2.05	2.25	2.63	3.35	3.97	4.22	4.54	4.7	0.64
56	SEP	0.89	1.19	1.57	1.72	2.02	2.53	3.49	3.91	4.08	4.55	4.7	0.64
57	OCT	0.71	1.11	1.44	1.62	1.95	2.63	3.52	3.88	4.04	4.44	4.53	0.64
58	NOV	0.63	1.15	1.47	1.8	2.29	3.11	3.74	4	4.03	4.36	4.68	0.64
59	DEC	0.78	1.17	1.85	2.19	2.8	3.7	3.99	4.14	4.15	4.41	4.7	0.64
60	JAN	1.28	1.75	2.53	3	3.77	3.99	4.21	4.23	4.24	4.47	4.58	0.64
61	FEB	2.04	2.67	3.46	3.81	3.88	4.07	4.25	4.28	4.28	4.48	4.7	0.64
62	MAR	3.08	3.62	3.96	3.99	4.09	4.21	4.42	4.42	4.42	4.68	4.7	0.64
63	APR	3.84	3.93	4.1	4.15	4.21	4.27	4.51	4.51	4.51	4.69	4.7	0.64
64	MAY	3.74	4.14	4.25	4.28	4.3	4.47	4.69	4.7	4.7	4.7	4.7	0.64
65													

PosAnalysis | outputPOSA

Figure 11. Example table of data output produced by Position Analysis (POSA) in Microsoft Excel for this study in New Jersey.

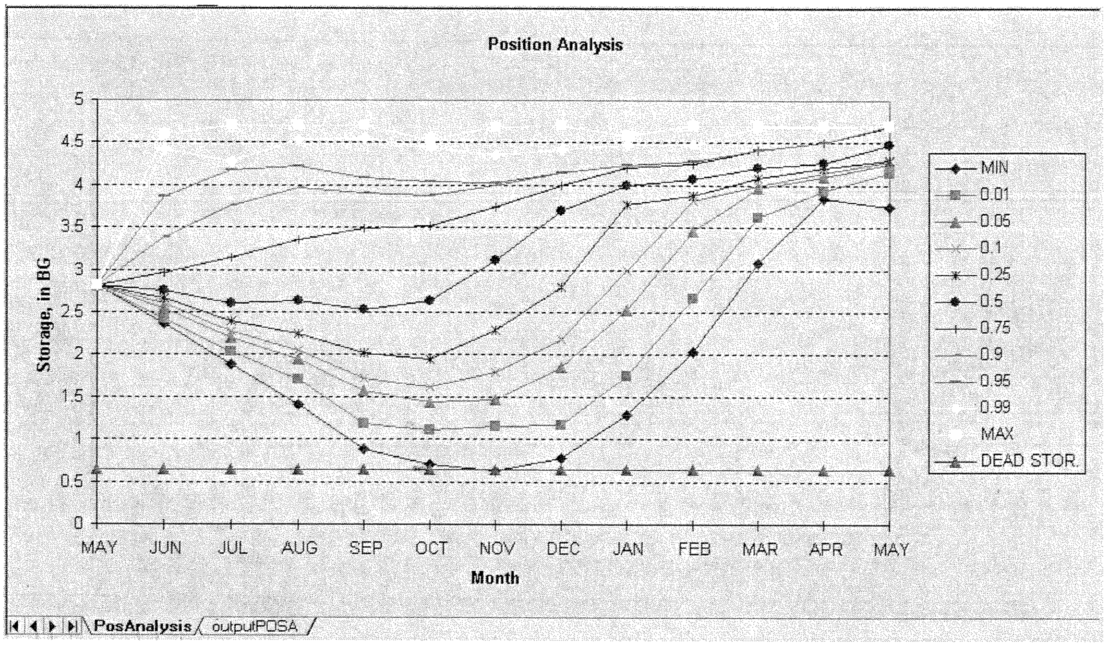

Figure 12. Example graph of data output produced by Position Analysis (POSA) in Microsoft Excel for this study in New Jersey.

- Basin adjustments
  - Wastewater discharge (S_d) was decreased to zero. S_d was increased by 0.25 Mgal/d, 0.5 Mgal/d, 1.0 Mgal/d, and 2.0 Mgal/d as a substitute for increasing the flow in the Manasquan River by these amounts.
  - Ground-water withdrawals and leakage (G_w), and surface-water withdrawals (S_w) were decreased to zero and to estimated withdrawals for the year 1965, respectively.
  - I/I was decreased to zero.
  - Evaporation and seepage from the reservoir were reduced to zero.
- Reservoir operating rules
  - The pumping trigger for pumping to the reservoir was adjusted.
  - The pumping target was adjusted within a range of 90 to 100 percent of full.

A base or default alternative was used for comparison with all other alternatives. The default alternative included the variables shown in table 2.

In the default alternative, approximately 60 percent of the system demand was supplied from the distribution chamber, and approximately 40 percent was supplied from the reservoir through a withdrawal from the release line (fig. 13).

Because there was a limit to the number of model runs made and the sensitivity analysis is an iterative process, some of the results presented below are estimates interpreted from the results of the model runs.

The results of the sensitivity analysis are presented below[1].

- Volume of the reservoir was increased by 100 Mgal. This resulted in an increase in minimum default alternative reservoir storage from 0.65 to 0.75 Ggal. The demand could be increased by approximately 0.250 Mgal/d while maintaining storage at 0.65 Ggal.
- The maximum pumping at the intake and to the reservoir was increased to 500 Mgal/d and the minimum pumping to the reservoir was

[1] Although 0.64 billion gallons is the actual dead storage volume, the alternatives used in the model runs resulted in a 0.65 billion gallons dead storage volume.

Table 2. Model input for the default alternative for sensitivity analysis of the Manasquan model, New Jersey.

[max, maximum; min, minimum; Mgal/d, million gallons per day; MRRSA, Manasquan River Regional Sewage Authority; A; demand at distribution chamber, in Mgal/d, B; demand from reservoir pipe (Howell Township), in Mgal/d; C, demand directly from reservoir, in Mgal/d; D, fraction of demand during Phase I drought condition; E, fraction of demand during Phase II drought condition; F, passing flow required at Allenwood, NJ, in Mgal/d; G, ground-water shallow withdrawals plus leakage, in Mgal/d; H, surface-water shallow withdrawals, in Mgal/d; I, point-source flows to basin, in Mgal/d; J, releases to Timber Swamp Brook, in Mgal/d; K, normal reservoir level as fraction of full; L, pumping target volume as fraction of full; M, pumping trigger volume as fraction of full; N, drought watch volume as fraction of full; O, Phase I drought volume as fraction of full; P, Phase II drought volume as fraction of full; Q, evaporation plus seepage losses from reservoir, in inches]

Variables of physical dimensions	Value
Total reservoir capacity, in billion gallons	4.7
Dead storage, in billion gallons	.64
River intake pump max, in Mgal/d	150
Reservoir pump max, in Mgal/d	120
Reservoir pump min, in Mgal/d	10
Intake pumping factor	1
Reservoir pumping factor	1
MRRSA flow, in Mgal/d	6.5
Percent MRRSA flow	66
Percent of sewage flow from contributing municipalities upstream from Squankum streamflow gaging station	50

Month	Variables of demands, basin adjustments, and reservoir operating rules																
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1	16.25	10	0	1	1	8	1.11	0.02	0	0.2	0.9	1	0.8	0.7	0.6	0.5	0.8
2	16.25	10	0	1	1	8	1.05	.02	.01	.2	.91	1	.81	.75	.65	.55	1.68
3	16.25	10	0	1	1	8	1.17	0	.02	.2	.94	1	.84	.8	.7	.6	2.32
4	16.25	10	0	1	1	8	1.13	.08	.02	.2	.96	1	.86	.8	.7	.6	3.86
5	16.25	10	0	1	1	8	1.15	.11	.01	.2	1	1	.9	.8	.7	.6	4.27
6	16.25	10	0	1	1	8	1.15	.2	.01	.2	.94	1	.84	.8	.7	.6	4.98
7	16.25	10	0	1	1	8	2.02	.36	.01	.2	.91	1	.81	.75	.65	.55	5.66
8	16.25	10	0	1	1	8	2.54	.28	.01	.2	.91	1	.81	.67	.57	.47	4.86
9	16.25	10	0	1	1	8	2.42	.19	.01	.2	.86	1	.76	.58	.48	.38	3.08
10	16.25	10	0	1	1	8	2.39	.09	.01	.2	.86	1	.76	.58	.48	.38	2.07
11	16.25	10	0	1	1	8	2.46	.01	.01	.2	.85	1	.75	.58	.48	.38	1.99
12	16.25	10	0	1	1	8	2.39	0	.01	.2	.88	1	.78	.65	.55	.45	1.08

reduced to zero. This alternative was run to determine the maximum demand that could be established for 1998 conditions. The minimum storage was increased from 0.64 Ggal to 1.18 Ggal. Demand was increased by 1.875 Mgal/d while maintaining storage at 0.64 Ggal.

- Point-source discharges (S_d) to the Manasquan River and the I/I were reduced to zero. The adjustment of S_d had no effect on minimum storage. Reducing I/I to zero increased the minimum storage from 0.64 Ggal to 0.67 Ggal. A change in demand was not tested because the changes in storage were considered negligible.
- S_d was increased by 0.25 Mgal/d, 0.5 Mgal/d, 1.0 Mgal/d, and 2.0 Mgal/d, which allowed for an increase in demand by the respective amounts while maintaining storage at approximately 0.70 Ggal for all alternatives.

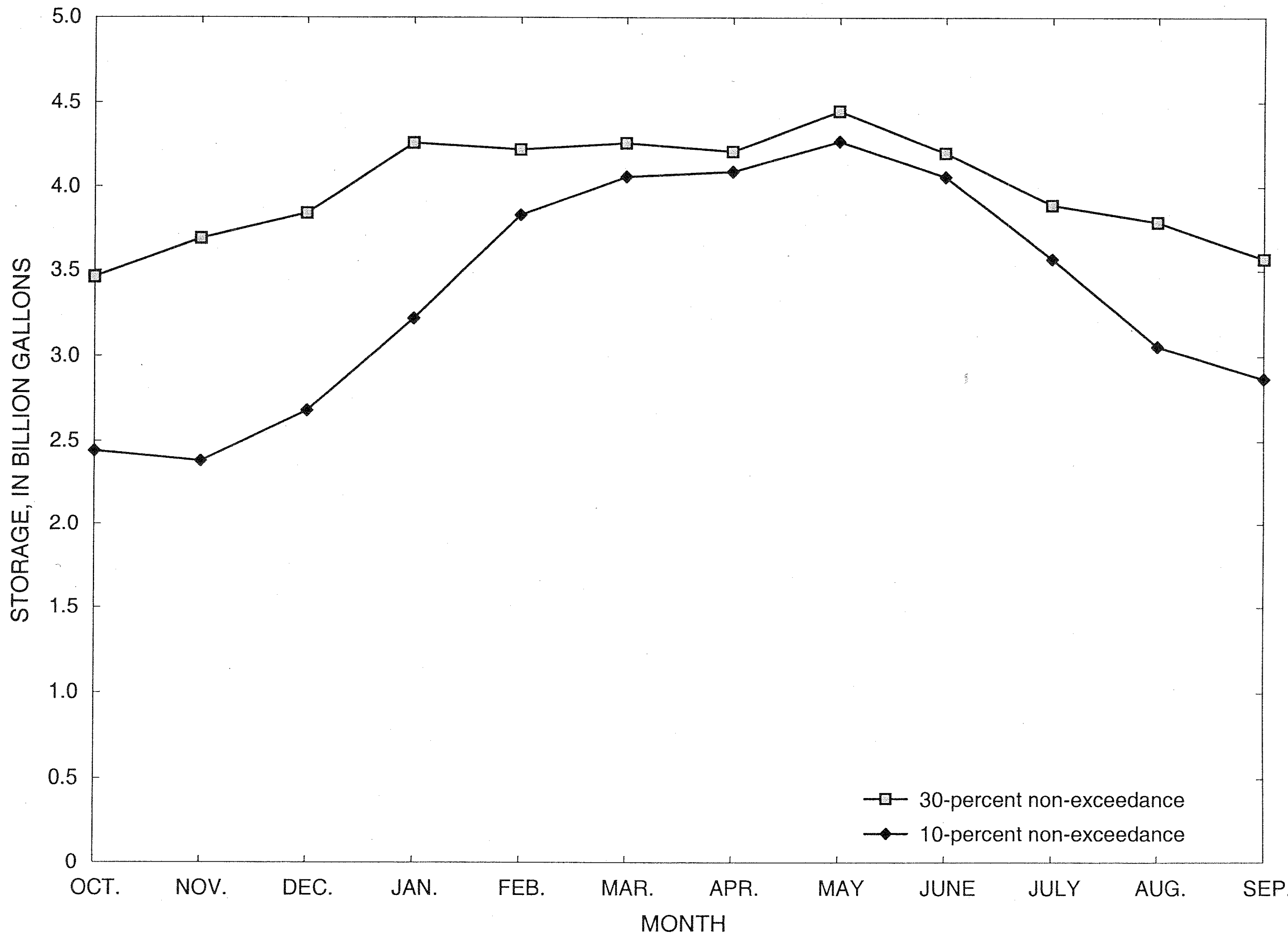

Figure 13. Rule Curve output for sensitivity analysis default alternative of the General Risk Analysis Model (GRAM) for management model used in New Jersey.

- Ground-water withdrawals (G_w) were reduced to zero. This resulted in an increase in the minimum storage from 0.64 Ggal to 1.01 Ggal. Demand could be increased by 1.75 Mgal/d while maintaining storage at 0.64 Ggal.
- Surface-water withdrawals (S_w) were reduced to zero. This resulted in an increase in the minimum storage from 0.64 Ggal to 0.71 Ggal. Demand could be increased approximately 0.125 Mgal/d while maintaining storage at 0.64 Ggal.
- Evaporation and leakage from the reservoir were reduced to zero, resulting in increased minimum storage from 0.64 Ggal to 1.04 Ggal. Demand was increased by 0.875 Mgal/d while maintaining storage at 0.64 Ggal.
- G_W and S_W were adjusted to estimated values for 1965. The maximum pumping rate at the intake and to the reservoir was increased to 500 Mgal/d, and the minimum pumping rate to the reservoir was decreased to zero. This alternative was run to simulate the factors considered when the system was designed. The demand could be increased to 29.25 Mgal/d while maintaining storage at 0.64 Ggal.
- The location of system withdrawals was changed for all water from the distribution chamber. The minimum storage was decreased from 0.64 Ggal to 0.50 Ggal. Demand could be reduced by 0.375 Mgal/d to maintain a minimum storage of 0.64 Ggal.
- The pumping target for the reservoir was decreased from 100 percent to 95 percent, which reduced the minimum storage from 0.64 to 0.44 Ggal. Decreasing the pumping target to 90 percent reduced minimum storage to 0.34 Ggal. The location of the system withdrawals was changed to the distribution chamber for pumping targets of 95 percent and 90 percent resulting in the minimum storage of 0.46 Ggal and 0.53 Ggal, respectively.

Increasing or decreasing any of the variables that have a direct effect on the flow in the Manasquan River would have effects similar to those described above on the model outputs. When similar factors were entered into a comparable model of the Manasquan Reservoir System, the results of runs from the Manasquan model were within 10 percent of the results from the previous model (Metcalf and Eddy, 1985).

SUMMARY

The computer model of the Manasquan Water Supply System (MWSS) can be used by water managers to evaluate or forecast drought conditions for the Manasquan River and Reservoir. For a given set of system and demand variables, the model is able to provide probability estimates of drought events. The use of a default alternative showed that changing the variables that affect the flow of the Manasquan River also affected the model outputs. The model also can be used to forecast the likelihood of specified outcomes associated with a specific operating plan for the MWSS.

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APPENDIXES

APPENDIX A. Method for Reconstructing Streamflow

Q_{rA} , Reconstructed streamflow at Allenwood, N.J.

The reconstructed flows at the Allenwood streamflow gaging station, Q_{rA}, were created with simple linear regression by determining the relation of flows at the Allenwood station to flows at the Squankum station from June 1990 to December 1999 (fig. 1a). The flow at Allenwood was adjusted to take into account the withdrawals by the MWSS upstream from the Allenwood gage. Because of the inaccuracy of the flow meters at the MWSS intake pumping station during extremely low flow, values less than 22 Mgal/d were removed from the analysis (Paul Krier, New Jersey Water Supply Authority, oral commun., 2000). Flows greater than 500 Mgal/d were not included in the analysis because of disputed streamflow records (R.D. Schopp, U.S. Geological Survey, oral commun., 2000).

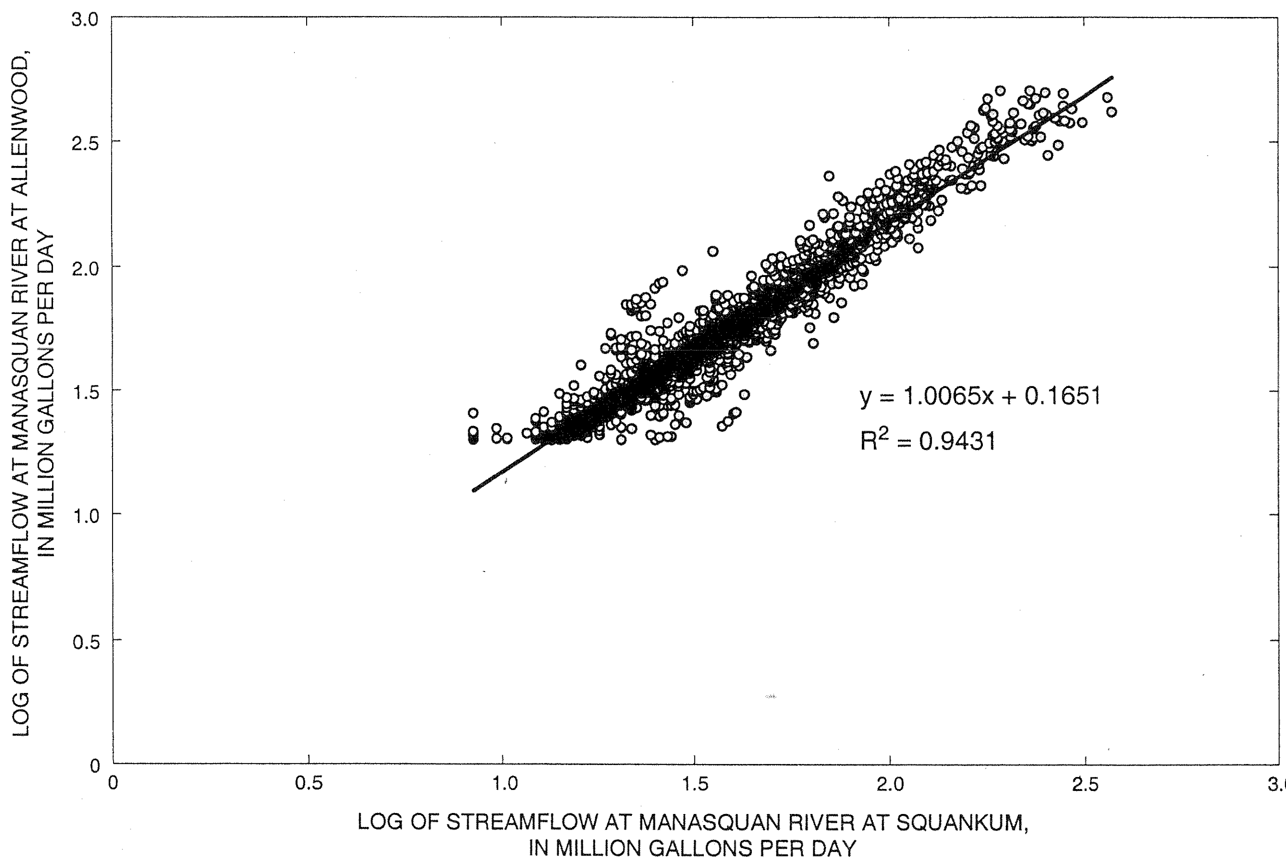

Figure 1a. Log relation of streamflow during 1990-99 at Manasquan River at Allenwood, N.J., and at Manasquan River at Squankum, N.J. [Values less than 22 Mgal/d and more than 500 Mgal/d were removed from the analysis. Mgal/d, million gallons per day]

The streamflows were reconstructed by applying a mass balance for two periods, 1930-89 and 1990-99. The mass-balance equation when applied for the period 1930-89 is

$$Q_{rS}=Q_{oS}-S_d+S_w+Gw_s+\Delta L+I/I ,$$

where

Q_{rS}	=	Reconstructed streamflow at Manasquan River at Squankum, N.J.,
Q_{oS}	=	Observed flow at Manasquan River at Squankum, N.J.,
S_d	=	Point source discharges,
S_w	=	Surface-water withdrawals,
GW_s	=	Surficial ground-water withdrawals,
ΔL	=	Change in leakage due to withdrawals from confined aquifers, and
I/I	=	Infiltration/Inflow.

Because Timber Swamp Brook contributes streamflow upstream from the Squankum streamflow gaging station, it is subtracted in order to replicate natural streamflow at the Allenwood stream gage subsequent to the operation of the Manasquan reservoir; therefore,

$$Q_{rT}=Q_{rS}(A_T) \text{ and}$$

$$Q_{rS1}=Q_{rS} - Q_{rT} ,$$

where

Q_{rT}	=	Streamflow at Timber Swamp Brook,
A_T	=	Contributing drainage area of Timber Swamp Brook ($3.18\ mi^2/40.917mi^2$), and
Q_{rS1}	=	Streamflow at Manasquan River at Squankum, N.J., minus streamflow at Timber Swamp Brook.

The relation developed from the regression analysis is applied to Q_{rS1} to calculate the reconstructed flow at Allenwood (fig. 1a).

$$Q_{rA1}=1.463Q_{rS1} ,$$

where

Q_{rA1}	=	Reconstructed flow at Manasquan River at Allenwood, N.J., minus streamflow at Timber Swamp Brook.

The equation when applied for the period 1990-99 is

$$Q_{rA}=Q_{oA}-S_d+S_w+Gw_s+\Delta L+I/I-M_r ,$$

where

Q_{oA} = Observed flow at Manasquan River at Allenwood, N.J., plus intake pumpage, not including runoff from Timber Swamp Brook upstream from the reservoir,

M_r = Manasquan Reservoir release to Timber Swamp Brook ($M_r = 0$ on overflow days),[1] and

Q_{rA} = Reconstructed flow at Manasquan River at Allenwood, N.J.

Q_o, Observed Flow values

Observed flow values from October 1931 to December 1999 were obtained from the National Water Information System (NWIS) [2].

S_d, Point-Source Discharge

Point source discharge data from 1931 to 1977 were obtained from Metcalf and Eddy (1985). Point-source discharge data from 1978 to 1999, which included data from 19 facilities, were obtained from the U.S. Environmental Protection Agency Permit Compliance System and New Jersey Department of Environmental Protection Permit Information. Data from 1978 to 1989 were incomplete for some facilities. Incomplete data were estimated by use of available data from the most recent year for the period that the facilities were known to be in operation.

S_w, Surface-Water Withdrawals

Surface-water-withdrawal data were obtained from NWIS. These included withdrawals for industrial, agricultural, and recreational uses. Withdrawal values for agricultural purposes and golf courses used in the model were 90 percent of actual values; it was assumed that 10 percent of the withdrawals eventually would be returned to the stream. Because surface- and ground-water use records were combined and reported as one value from 1945 to 1983, these combined records were used in the model as one surface-water variable.

GW_s, Ground-Water Withdrawals

Ground-water withdrawal data were obtained from the Site-Specific Water-Use Data System (SSWUDS)[3]. Agricultural water use was determined by applying water use coefficients (Clawges and Titus, 1993) to water-use data for crops and irrigated areas from 1929 to the present; for years between reports, irrigated areas were assumed to be the same (U.S. Department of Commerce, 1936, 1946, 1956, 1961, 1966, 1981, 1989, 1994). Withdrawals for livestock use were not included because they were found to be insignificant on the basis of the livestock water-use coefficient for the Manasquan Basin area. Reported irrigated acres within the county were prorated for the study area (16 percent of total irrigated acres in Monmouth County). Withdrawals for irrigation were estimated by multiplying the annual water demands per acre during a normal year by the percent of irrigated acres (Clawges and Titus, 1993). A percentage of annual water demands was assigned to monthly summer water demands (29 percent for June; 34 percent for July; and 37 percent for August) on the basis of reported values in SSWUDS.

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1 Although releases from the reservoir are still occurring, there is no need to calculate M_r during overflow days because passing flow requirements are met at Timber Swamp Brook.

2 USGS computer data base, West Trenton, N.J.

3 A data base of the National Water Information System (NWIS), West Trenton, N.J.

ΔL, Change in Vertical Leakage

The Manasquan River Basin overlies the Wenonah-Mount Laurel aquifer and the outcrop areas of the Vincentown aquifer and Kirkwood-Cohansey aquifer system. A model of the New Jersey Coastal Plain was used to calculate the vertical flow from the unconfined aquifer system to the confined aquifers (L.M. Voronin, U.S. Geological Survey, written commun., 2001). The change in vertical leakage term represents the amount of leakage induced by pumping from the confined aquifers beginning with prepumping conditions. In the Manasquan River Basin area, vertical leakage is from the outcrop areas of the Kirkwood-Cohansey aquifer system and the Vincentown aquifer to the confined Wenonah-Mount Laurel aquifer.

I/I, Inflow and Infiltration

Inflow and infiltration is the correlation of the amount of shallow ground water and stormwater runoff loss to the amount of water in wastewater collection systems. Because the wastewater system in the Manasquan River Basin has been regionalized, this water is lost from the basin and is not available for use. I/I was determined with simple linear regression by use of the relation of 1998-99 average monthly flows at the Squankum streamflow gaging station to total average monthly MRRSA wastewater flows from Freehold Borough and Township (fig. 2a; Manasquan Regional Sewage Authority, written commun., 2000).

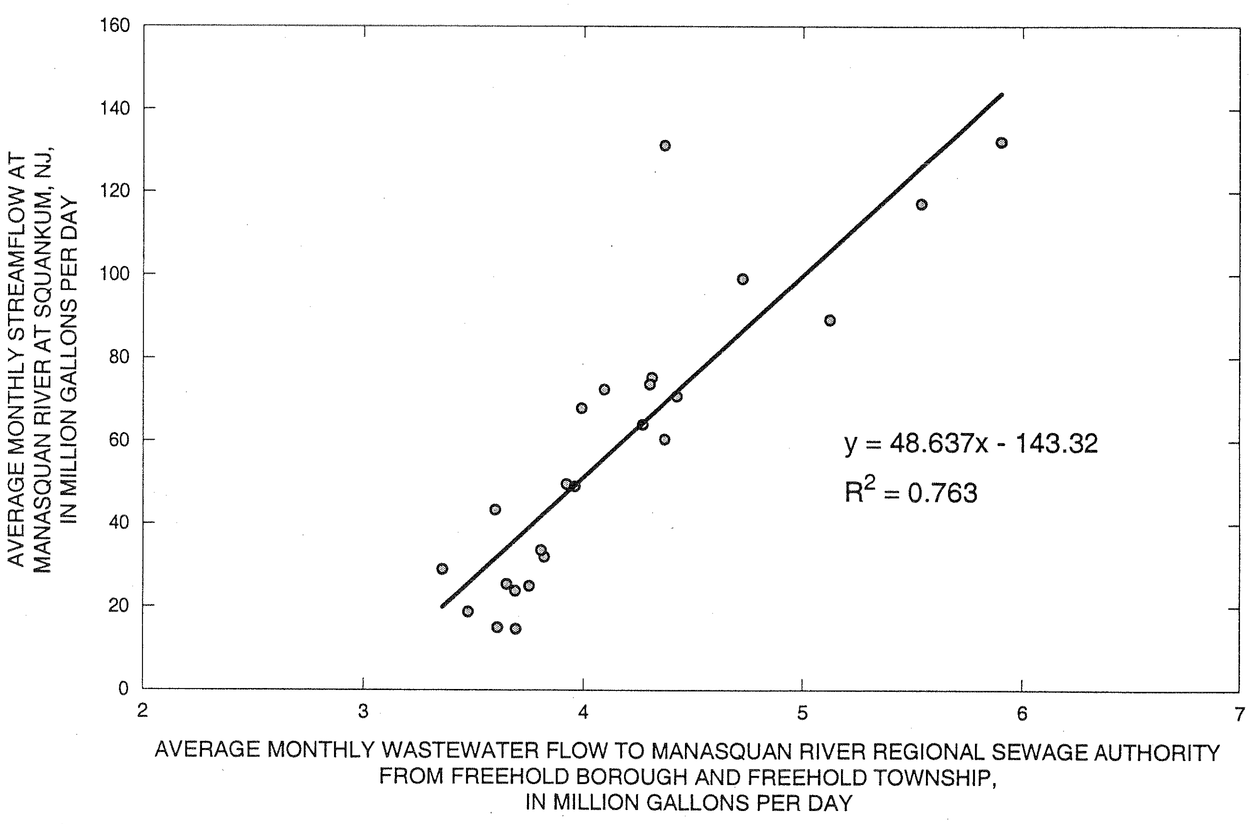


Figure 2a. Relation of 1998-99 average monthly streamflow at Manasquan River at Squankum, N.J., to average monthly wastewater flow to the Manasquan River Regional Sewage Authority (MRRSA) for Freehold Borough and Freehold Township.

The formula, in Mgal/d, was applied to streamflow from 1931 to 1999 as

$$I/I = \frac{((Q_{oS} - 19.905)/48.637)P_Y}{P_{98}}$$

$$I/I_M = \frac{I/I}{2} ,$$

where

I/I	=	Infiltration/Inflow ($I/I = 0$ for negative values),
Q_{oS}	=	Observed flow at Manasquan River at Squankum, N.J.,
P_Y	=	Wastewater flow from the upper Manasquan Basin for the corresponding year,
P_{98}	=	Wastewater flow from the upper Manasquan Basin for 1998, and
I/I_M	=	Infiltration/Inflow for the Manasquan Basin.

The value 19.905 Mgal/d represents streamflow where I/I does not contribute to the wastewater component. This value was based on the lowest base flow at the treatment facility (Manasquan River Regional Sewage Authority, written commun., 2000). Point-source data for 1931-85 were obtained from discharge data (Metcalf and Eddy, 1985). I/I_M for the Manasquan Basin in 1998 was based on the sewered area of Freehold Borough and Freehold Township and not the total basin area upstream from the Squankum streamflow gaging station. I/I was divided by two because approximately 50 percent of the sewered area is within the study area.

APPENDIX B. Rule Curve Development

Approach 1

Two methods are provided in the Manasquan model package to calculate the frequency distribution of reservoir storage. One method uses frequency analysis, the number or percentage of the pieces of data that fall into a particular class. The second method uses the log Pearson Type III distribution, a flexible distribution with three components with a limited range in the left direction and unlimited range in the right direction (Riggs, 1978). The log Pearson Type III Rule Curve program assumes that all the data will be of a log Pearson Type III distribution. Although this is a valid method, the data used for the Manasquan model did not conform to this log type; therefore, this method did not yield the best representation of rule curves. Because of the large quantity of data, the Frequency Analysis Rule Curve program was the appropriate option and yielded a more characteristic rule curve.

Approach 2

Position Analysis Model Mode

1. Streamflow during a drought of record was used for the 12 months preceding the drought. In New Jersey, the 1960's drought is considered the drought of record.

2. In New Jersey, the storage level of a reservoir during May and June is critical in meeting water-supply demands through the summer and fall; therefore, the model runs began with May.

3. A starting reservoir storage level was selected that produced a storage-level curve, the lowest point of which was equal to dead storage for the minimum non-exceedance probability. By comparing this rule curve with those of other reservoirs, the starting storage level can be estimated.

4. A future weather scenario was selected. To simulate drier than normal conditions, a 50-percent drier than normal, a 25-percent wetter than normal, and a 25-percent normal weather probability condition were used.

5. Reservoir operating rules were selected; demand, pumping factors, and passing flow requirements were edited.

6. During the simulation of drought emergency, normal demand was reduced by 25 percent. In New Jersey, a reduction in demand of approximately 25 percent would be expected if a drought emergency were declared.

7. From the POSA outputs, the 10-percent storage non-exceedance curve could be determined.

8. The above steps were repeated to estimate the 30-percent non-exceedance for drought warning. A 5-percent reduction in demand was used because, in New Jersey, a 5-percent reduction would be expected if a drought warning were declared.

General Risk Analysis Model Mode

1. The end-of-the-month storage values for the 10-percent non-exceedance curve were used to define Phase I drought curve (drought emergency).

2. The Phase II drought (drought warning) curve was adjusted to be 10 percent greater than the Phase I curve.

3. Reservoir operating rules were selected; demand, pumping factors, and passing flow requirements were edited.

4. The GRAM mode for the period of record and various drought periods was run to determine whether reservoir storage dropped below dead storage.

5. Rule curves were adjusted to fit the shape of a trapezoid.

6. The GRAM mode was run again. The number of occasions and length of time that the reservoir would be in drought warning and emergency was determined and drought curves were adjusted.

7. A drought watch curve was inserted at 10 percent above the Phase II curve.

**Note:* Steps 2, 6, 7, and adjustments of curves can be varied according to water-management policies.

Approach 3

1. Starting with the beginning of the period of record, the 10- and 30-percent non-exceedance cumulative flow was determined for eleven segments of time. Each segment was calculated by using flow data from June of a given year and adding one month for each segment until the final segment, June through May of the next year, was reached. For example, the first segment for June 1932 would include the flow for June 1932 and July 1932. The second segment would continue with June 1932 through August 1932. The final segment would include June 1932 through May 1933.

2. The GRAM mode was executed for each of the segments for the 10-percent non-exceedance flow with starting points similar to those used in the first two approaches. The reservoir operating rules were set to maximize reservoir storage.

3. The resultant curves were compared to determine which segment resulted in the lowest storage. The curves also were compared to drought rule curves from other reservoirs. The 8-month curve produced one of the lowest storage values and most resembled the rule curves for the other reservoirs.

4. The 8-month curve was adjusted to fit a trapezoid. Then the GRAM mode was executed with reservoir operating rules set at levels that would be similar to those water managers use to operate the system.

5. The curve was adjusted again because it appeared that the reservoir storage during various drought periods was approaching the dead storage level.

6. The drought warning curve was placed at 10 percent above the emergency curve, and the drought watch curve was placed at 10 percent above the warning curve. The 30-percent non-exceedance periods were not used in determining these curves.

**Note:* Steps 5 and 6, adjustments of the emergency curves and setting of the drought watch and warning curves can be varied according to water-management policies.

APPENDIX C. Model Statistics

Position analysis relies on the generation of a large number of possible monthly flow traces (six or more months in length), which have been initialized with the current reservoir storages and streamflows. These traces may be derived from a stochastic model of streamflows based on the historic record as described in Hirsch (1981). Use of a stochastic model allows separation of the observed runoff into a carryover component and a random error component. The stochastic runoff model used for this model is the log-transform autoregressive moving-average (LT-ARMA (1,1)) cyclic model described in Hirsch (1981). It also is referred to as a periodic ARMA (1,1) or PARMA (1,1) model (Salas, 1993). The runoff in year i and month j is denoted as $X_{i,j}$ and $Y_{i,j} = \log(X_{i,j})$. The variable is defined by

$$Z_{i,j} = \frac{(Y_{i,j} - \overline{Y}_{i,j})}{S_j} \quad , \qquad (1)$$

where $\overline{Y}_{i,j}$ and S_j are the sample mean and standard deviation, respectively, of the logarithms of the observed runoff values for month j. Therefore, $Z_{i,j}$ represents the standardized deviation for year i and month j from the log-transformed mean runoff for month j.

The serial dependence is modeled as a periodic moving average process or PARMA (1,1) model of the form

$$Z_{i,j} = \phi Z_{i,j-1} + E_{i,j} - \theta_j E_{i,j-1} \ , \qquad (2)$$

where $E_{i,j}$ represents independent errors with mean of zero. The 13 parameters, ϕ and θ_j, are estimated by the method described in Hirsch (1979). Note that when j = 1, $Z_{i,j-1}$ is taken to be $Z_{i-1,12}$ -- in other words, the month before January in a given year is taken to be December of the previous year.

Hirsch (1981) notes that in this model the lag one serial correlations among the runoff values for all 12 months are exactly preserved in the long run, and the lag 2-12 serial correlations are preserved in a least-squares sense. The first and third terms on the right-hand side of equation 2 can be thought of as the carryover components of runoff from antecedent moisture and delayed runoff in a basin, whereas $E_{i,j}$ is the random component from weather conditions in the current month, j. Equation (2) may be written as

$$Z_{i,j} = Z_{i,j} + \phi Z_{i,j-1} - \theta_j E_{i,j-1} \ . \qquad (3)$$

Given a long record of observed monthly runoff values, $Z_{i,j}$, the parameters for the model, ϕ and θ_j, and a reasonable starting value for the first value of $E_{i,j}$, a long record of "observed error components or residuals" can be computed from equation 3. These observed $E_{i,j}$'s represent the random component of monthly runoff for the period of record. If the standardized runoff values are broken into carryover and random components, one can generate synthetic runoff sequences by use of the error components in their historical sequence or by random resampling, with replacement, from the observed error components.

Bootstrap Method

The method of randomly resampling with replacement from the sample itself is called the bootstrap method (Efron, 1979). The advantage of the bootstrap is that it does not rely on the unverifiable assumption of normality of the error components. The method does rely on the nonparametric assumption that the maximum likelihood estimate of the population of error components is the sample of error components itself (Efron, 1982). In addition, the bootstrap method provides a means of including long-range weather forecasts in generating the traces.

For a given set of operating rules and water-use requirements for a system, water managers can use the basin model to forecast the likelihood of specified outcomes, such as reservoir levels falling below a specified level or streamflows falling below statutory passing flows, a few months in advance. Thus, the basin model can be used to determine the effectiveness of specified changes in operating rules or drought restrictions. The flow chart in figure 1c shows the connection between the bootstrap runoff traces and a basin model.

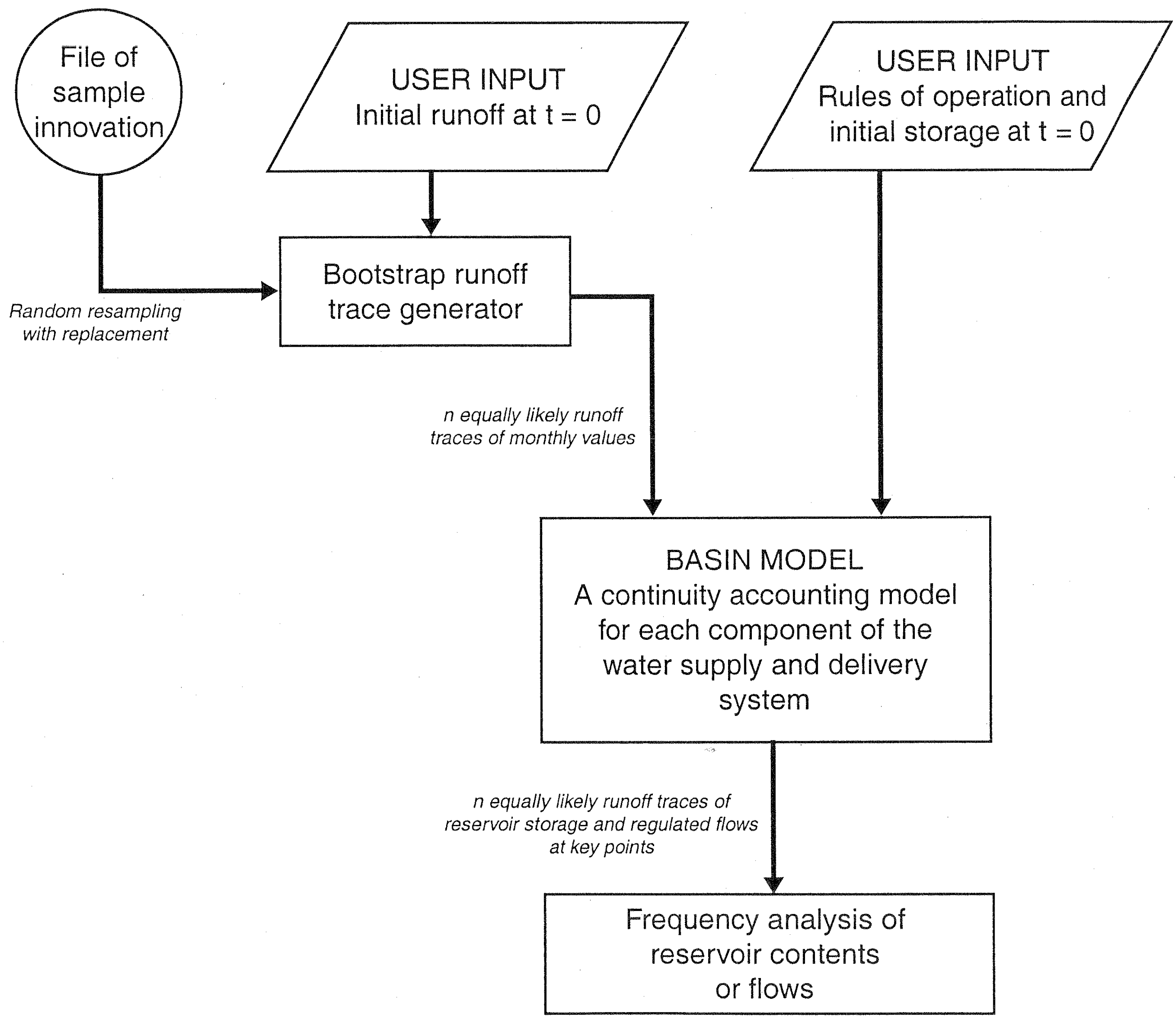


Figure 1c. Flow chart of bootstrap position analysis applied to a water-supply storage and delivery system used for the study in New Jersey.

Each month of a bootstrap sequence of random components is selected by randomly selecting a year with replacement and choosing the component for the month for that year. In this manner, many sequences can be generated. This generation is possible because the components are independent random observations. Thus, 300, 400, 500 or more 11-month bootstrap position analysis traces can be generated from the 68 years of observed data. Selecting the error components at random in position analysis has another advantage aside from producing more traces. The bootstrap allows one to include the effects of long-range (90 days or more) forecasts of weather. Suppose that a 90-day forecast estimates that it is 5 percent more likely that conditions will be drier than normal. Then the bootstrap selection process can be modified to make it 5 percent more likely to select a large negative error component that would make it more likely for a "dry" position analysis trace to be generated. The model allows the user to specify the probabilities of having a normal month, a wetter than normal month, and a drier than normal month.

Time Series

The reconstructed time series of monthly runoff for the Manasquan River at Allenwood was used to develop the model described above. Using the reconstructed runoffs of the basin and the model parameters, error components for the 68-year base period were computed using equation 3.

Starting values for Z and E are required in position analysis to generate a trace. For each trace, the starting value of Z is set equal to the value of the log-transformed standardized runoff for the present month. The starting value for E is computed recursively from equation 3 using observed values of Z for at least 12 months prior to the present month in order to overcome the effects of arbitrarily initiating the sequence with E = 0. Using the present observed value for Z and the computed value for E to start, a bootstrap trace is generated by sequentially computing Z's using a series of 12 residuals randomly drawn from the observed residuals for each month. A slight rescaling correction is needed to correct for sampling bias in the residuals. Thombs and Schucany (1990) show this correction for an ARMA (1,1) model to be $[(N_0-4)/(N_0-8)]^{0.5}$ where N_0 is the number of observations. In the PARMA (1,1) model, N_0 is the total number of observations divided by the number of months in a year. Each month of a bootstrap sequence of residuals is selected by randomly selecting a year with replacement and choosing the residual for the month for that year. This means that the selected residuals for each month in a sequence may be from a different year. By choosing residuals for specific months, estimation of parameters for a particular distribution of the observed residuals can be avoided.

Accounting for Parameter Uncertainty

The effects of parameter uncertainty on synthetic streamflow generation have been clearly established (Stedinger and Taylor, 1982). Cover and Unny (1986) use the bootstrap method to analyze the uncertainty in ARMA models. A similar approach is used here to account for the effects of parameter uncertainty on the PARMA model used herein. The effects of parameter uncertainty and long range weather forecasts are included by following the steps below:

1. From an 68-year record of reconstructed natural log-transformed runoff data, monthly means and standard deviations are calculated and the standardized runoffs computed (equation 1) for Allenwood. Parameters ϕ and θ_j are estimated; residuals calculated (equation 3) and rescaled to correct for bias.

2. A bootstrap N-year record is computed for each site by randomly drawing with replacement from the residuals in step one N+2 blocks of 12 consecutive sample innovations (contemporaneous across sites) and recursively calculating standardized runoffs for N+2 years. The first two years of calculated values are discarded to overcome the effects of arbitrary starting values. New monthly statistics and parameters for the N-year bootstrap record are calculated and saved. A new set of residuals is calculated from the bootstrap "record" and saved.

In addition, each residual is ranked by size. The residuals with ranks in the lowest third are classified as below normal. The residuals with ranks in the middle and upper thirds are classified as normal and above normal, respectively. Thus, each residual carries with it a classification (below normal, normal, or above normal). This classification scheme will be used in accounting for long-range weather forecasts. Step 2 is repeated 50 times. As a result, one has 50 sets of monthly means and standard deviations, 50 sets of parameters ϕ and θ_j, and 50 sets of monthly residuals 68 years in length from which to generate the position analysis runoff sequences.

3. To generate one 12-month runoff sequence for the position analysis model with beginning month k, one of the 50 sets of parameters and residuals is randomly chosen. Next, on the basis of the 90-day forecast of the U.S. Weather Service, the probability of precipitation being below-normal, normal, or above normal is set and one of the three classifications is randomly chosen. From among the 68 years of residuals, a 12-month sequence of residuals beginning with month k was randomly chosen from among all the months k with the chosen classification. Finally, a 12-month runoff sequence using specified starting values for runoff and residual, the chosen parameters and monthly statistics, and the selected sequence of residuals were computed recursively. Step 3 was repeated B_p times (B_p is the number of times to repeat step 3).

4. The basin model uses daily flows. The following procedure was used to forecast a reasonable distribution of daily flows to associate with each forecast monthly sequence. For a given month in a forecast sequence, the distribution of daily flows for that month was randomly selected by choosing an observed distribution of deviations from the mean from the observed reconstructed daily flows at Allenwood. The random selection process only looks at observed months within 1 calendar month of the forecast month. For example, if the distribution of daily flows for a forecast for April is needed, then the candidate observed distributions are limited to only those for the months of March, April, and May. This result gives 204 possible distributions from which to choose. From these 204 observed distributions, the number of candidates is limited further by only choosing the 25 distributions for which the observed monthly mean is closest in value to the forecast mean. In this manner, the chosen distribution of daily deviations from the mean must come from an observed month in the same part of a year with a similar monthly mean flow.

APPENDIX D. Manasquan River Model Help Manual

Model Installation

Using the model

General Risk Analysis Model (GRAM)
Position Analysis Model (POSA)

Entering and editing numbers

Outputs

Appending new flow data

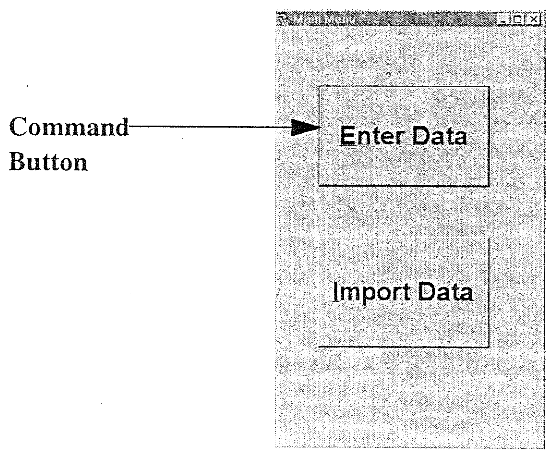
Model Installation

System Requirements: Microsoft® Windows 95® or later, or Microsoft® NT® 4.0 or later, Microsoft® Excel® 95 or later

1. Open the folder that contains the Manasquan River Model.
2. Double-click setup.exe.
3. Follow setup directions.

Using the model

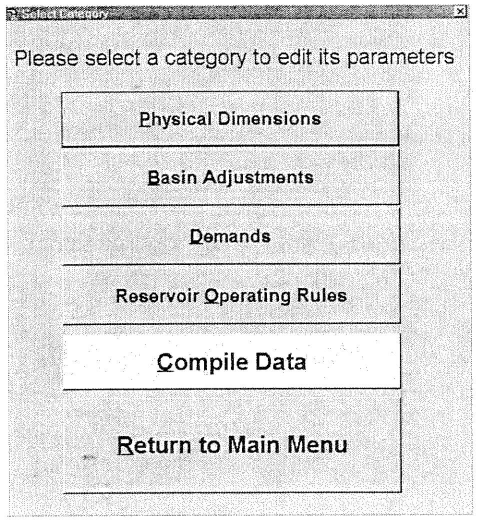
1. Locate and open the folder that contains the Manasquan River Model.
2. Double click on the **Manasquan River Model** to open the program.
3. The *Main Menu* dialog box will appear with two options, **Enter Data** or **Import Data**. Click on one of the command buttons to proceed.



- Enter Data - Loads default values, which can be edited.
- Import Data - Gives the user a choice of previously run input variables to load into the model. Values also can be edited.

> **Note:* To use keystroke commands to engage a command button, press **Alt** and the letter underlined on the command button. For example, to engage the **Import Data** command button, press **Alt** and **I** simultaneously.

4. After a data option has been chosen, the *Select Category* window will appear.



Select a category to edit its parameters, or if you chose to import data and **do not** want to edit the data, click **Compile Run** and continue to Step 5. The parameters in the categories are as follows:

a. Physical Dimensions

- *Total Reservoir capacity* – The maximum volume, in billion gallons (BG), in the reservoir.
- *Dead Storage* – The minimum volume, in BG, in the reservoir that is not available for use by the water supply.
- *River Intake Pump Maximum* – The maximum flow, in million gallons per day (MGD), that can be pumped from the Manasquan River.
- *River Intake Pump Minimum* – The minimum flow that can be pumped from the Manasquan River.
- *Reservoir Pump Maximum* – The maximum flow, in MGD, that can be pumped to the Reservoir.
- *Reservoir Pump Minimum* - The minimum flow, in MGD, that can be pumped to the Reservoir.
- *Intake Pumping Factor* – The rate, as a fraction, at which the River Intake Pump will operate. For example, a value of 0.5 indicates a 50-percent operation rate.
- *Reservoir Pumping Factor* – The rate, as a fraction, at which the reservoir pump will operate.

b. Basin Adjustments

- *Ground Water Shallow Withdrawals and Change in Leakage* – The term "Ground Water Shallow Withdrawals" refers to the amount of water withdrawn from the shallow aquifers, usually for industrial and agricultural use. The term "Change in Leakage" refers to the seepage from shallow aquifers to confined aquifers caused by the pumping of confined aquifers. These two terms are added together to create one ground-water withdrawal term, in MGD, for the Manasquan River model.
- *Surface Water Shallow Withdrawals* – The amount of flow from surface-water withdrawals within the Manasquan River Basin.
- *Point Source Flows to Basin* – The amount of flow from point-source discharges in the basin.

- *Evaporation and Seepage Losses* – Losses, in inches, resulting from evaporation and seepage from the reservoir. Data are obtained from the National Oceanic and Atmospheric Administration and Metcalf and Eddy (1985).
- *Manasquan River Regional Sewage Authority (MRRSA) Flows* – The average yearly flow, in MGD, at MRRSA. These data are used to calculate the inflow and infiltration (I/I).
- *Percentage of Total MRRSA Flow from Contributing Municipalities* – The total wastewater flow, in MGD, from municipalities located in the contributing watershed area of the Manasquan River Basin. These data are used to calculate the I/I.

c. Demands

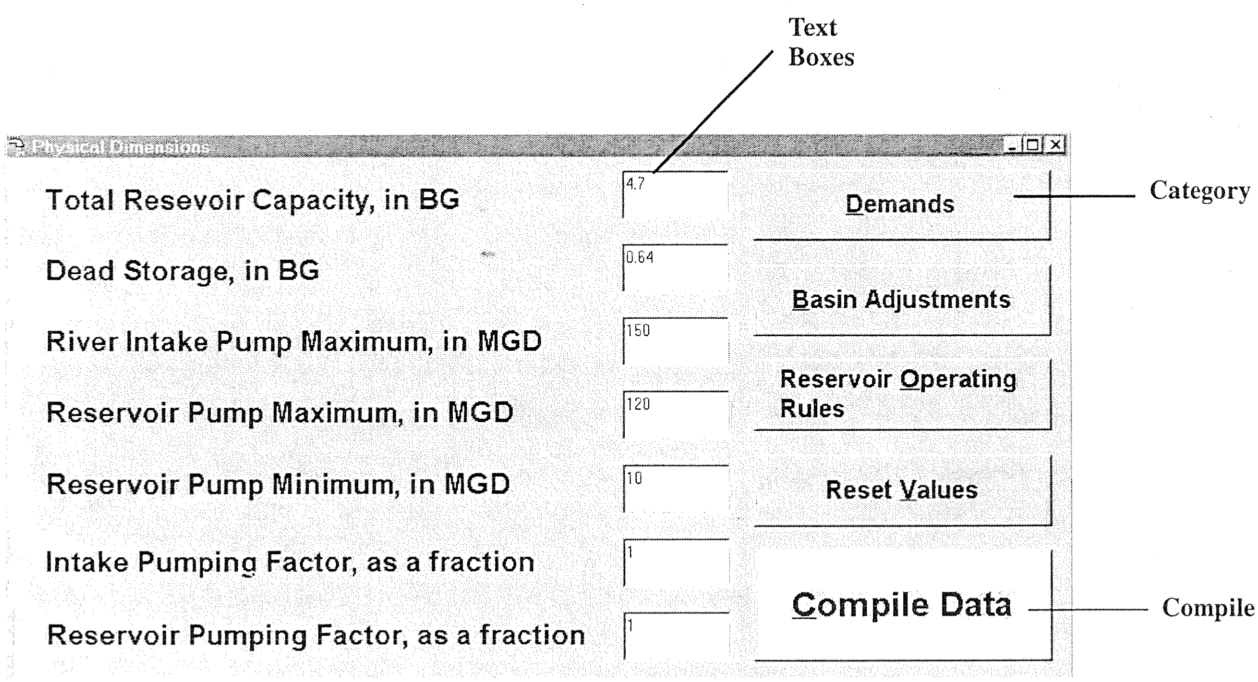
- *Hospital Road Distribution Chamber* – The demand, in MGD, at the distribution chamber located on Hospital Road in Allenwood, Wall Township, Monmouth County.
- *Manasquan Reservoir Pipeline* – The demand, in MGD, from the Manasquan Reservoir pipeline located at the NJ-AWC Oak Glen Treatment Plant in Howell Township, Monmouth County.
- *Manasquan Reservoir* – The demand, in MGD, directly from the Manasquan Reservoir.
- *Phase I Drought (Drought Warning)* – The demand, as a fraction of normal, during a Phase I drought condition. During a drought warning, voluntary restriction on water use can reduce demand on the system. Phase I condition determined by the New Jersey Water Supply Authority.
- *Phase II Drought (Drought Emergency)* – The demand, as a fraction of normal, during a Phase II drought condition. During a drought emergency, restrictions on water use can reduce the demand on the system. Phase II condition determined by the New Jersey Water Supply Authority.
- *Passing Flow at Allenwood streamflow gage* – The required passing flow of the Manasquan River at Allenwood streamflow gaging station.

d. Reservoir Operating Rules

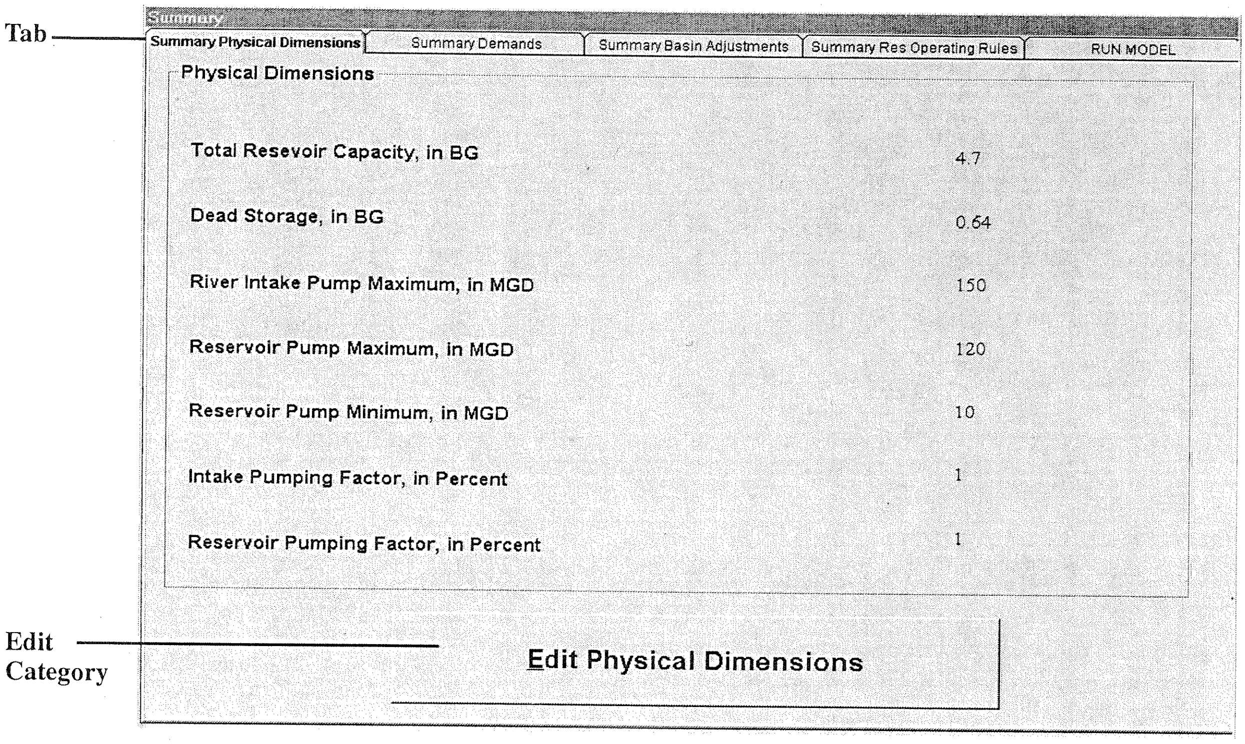
- *Timber Swamp Brook Release* – The monthly releases to Timber Swamp Brook, in MGD.
- *Normal Reservoir Level* – The normal level of the reservoir, as a fraction of full.
- *Pumping Target Level* – The level of the reservoir at which pumping to the reservoir will cease, as a fraction of full.
- *Pumping Trigger Level* – The level of the reservoir at which pumping to the reservoir will begin, as a fraction of full.
- *Drought Watch Level* – The level of the reservoir at which a drought watch will occur, as a fraction of full.
- *Phase I and II Drought* – The level of the reservoir at which a Phase I or II drought will occur, as a fraction of full.

5. After a category has been selected, the parameters can be edited. When editing of the text boxes is completed, you can select another category to edit, or select **Compile Data** to begin compiling the data. The *Summary* window will appear upon completion of the compilation.

**Note:* The values shown in the text boxes are the values that will be compiled.



6. In the *Summary* window, the parameters that will be used to compile the run can be reviewed. The various categories can be viewed by clicking on the tabs along the top of the Summary window. If additional changes are required, click the **Edit** button at the bottom of the window.

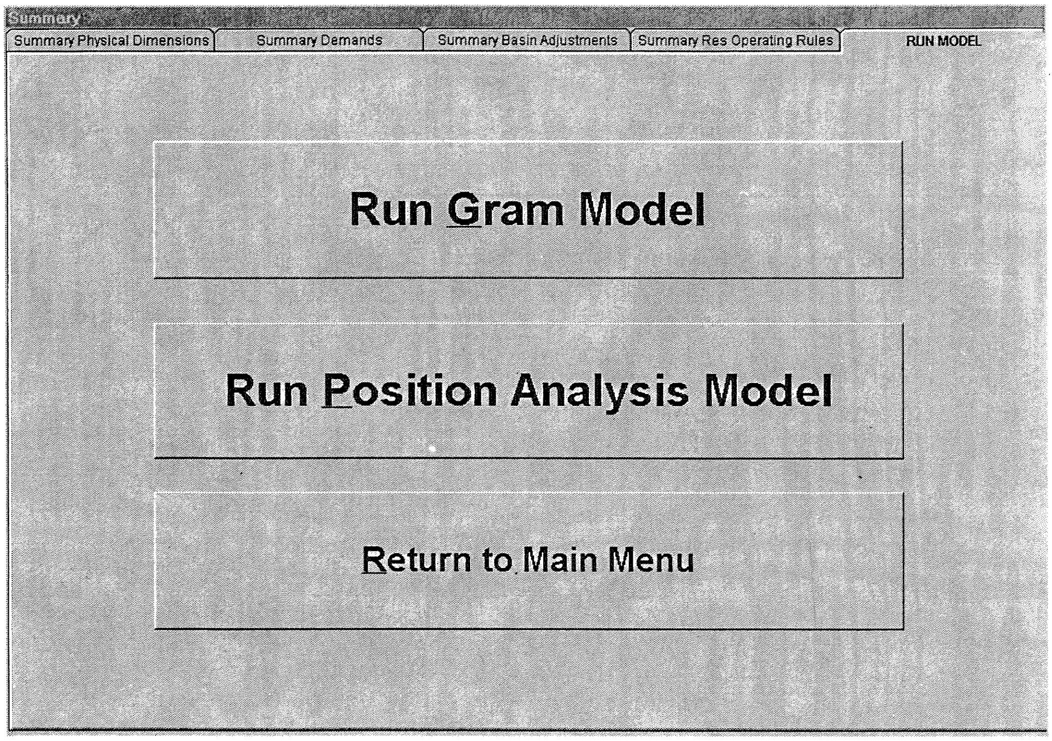


7. Click the **Run Model** tab to proceed.

8. From the **Run Model** tab, click on the corresponding button to run the General Risk Analysis Model or Position Analysis Model.

   A. General Risk Analysis Model (GRAM) – The model is based on reconstructed historical flows for a period of 68 years. It will determine reservoir levels with a given set of operating rules and withdrawal rates for the period of record.

   B. Position Analysis Model (POSA) – The model forecasts the likelihood of specified outcomes that would result from a specific operating plan for the basin over a period of a 6 or more months for different precipitation conditions.



General Risk Analysis Model (GRAM)

1. Enter a beginning and ending date and the beginning reservoir storage capacity. Click on the **Finished!** button to continue to Step 2.

2. Enter a name to save your input file. Click **OK** to continue to Step 3.

3. Enter a name to save the output file. Click **OK** when finished.

4. *Compile another run* dialog box will appear. If you would like to compile another run, click **Yes**. The screen will return you to the *Main Menu* dialog box. Follow the directions from Using the Model, Step 3 of the Help Manual to compile a new run.

> **Note*: When choosing the **Yes** option to compile another run, the values in the text boxes will be the data from the previous run and NOT the default or imported data. To view the current data, you must go to the selected category page and click **Reset Values**. This action will reset the values ONLY for that selected category. If you would like to reset the values for all the categories, you must select **Reset Values** for all the categories or exit the model completely and begin again.

5. If **No** in the *Compile another run* dialog box is selected, the *Exit* dialog box will appear. To exit, click **Yes**. Click **No**, to return to the *Main Menu*.

Position Analysis Model (POSA)

1. Enter the month you would like to begin the forecast for the model.

2. Enter the 12 most recent flows in cubic feet per second (ft^3/s) for Manasquan River at Squankum, N.J., ending with the first month of forecast.

3. Enter the probability that the next month will be drier than normal.

4. Enter the probability that the next month will be normal.

5. Enter the probability that the next month will be wetter than normal.

> **Note*: The three precipitation probabilities must add up to 100 percent.

6. Choose for the model to pick a random seed (a generated randomly chosen number) or for the user to enter a random seed. The entered random seed must be NEGATIVE.

> **Note*: Entering the same number for the random seed for successive runs will yield identical random seed conditions for the calculations for those runs.

7. Enter a name to save the input file. Click **OK** when finished to continue to Step 3.

8. Enter a name to save the output file. Click **OK** when finished.

9. *Compile another run* dialog box will appear. If you would like to compile another run, click **Yes**. The screen will return to the *Main Menu* dialog box.

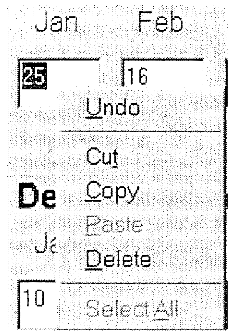
> **Note*: When choosing the **Yes** option to compile another run, the data entries that you view will be the same as the previous data, NOT the default or imported data. To view the new data go to the selected category page and click **Reset Values**. This action will reset the values ONLY for that selected category. If you would like to reset the values for all the categories, you must select **Reset Values** for all the categories or exit the model completely and begin again.

10. If **No** is selected in the *Compile another run* dialog box, the *Exit* dialog box will appear. To exit, click **Yes**. Click **No** to return to the *Main Menu*.

Entering and Editing Numbers

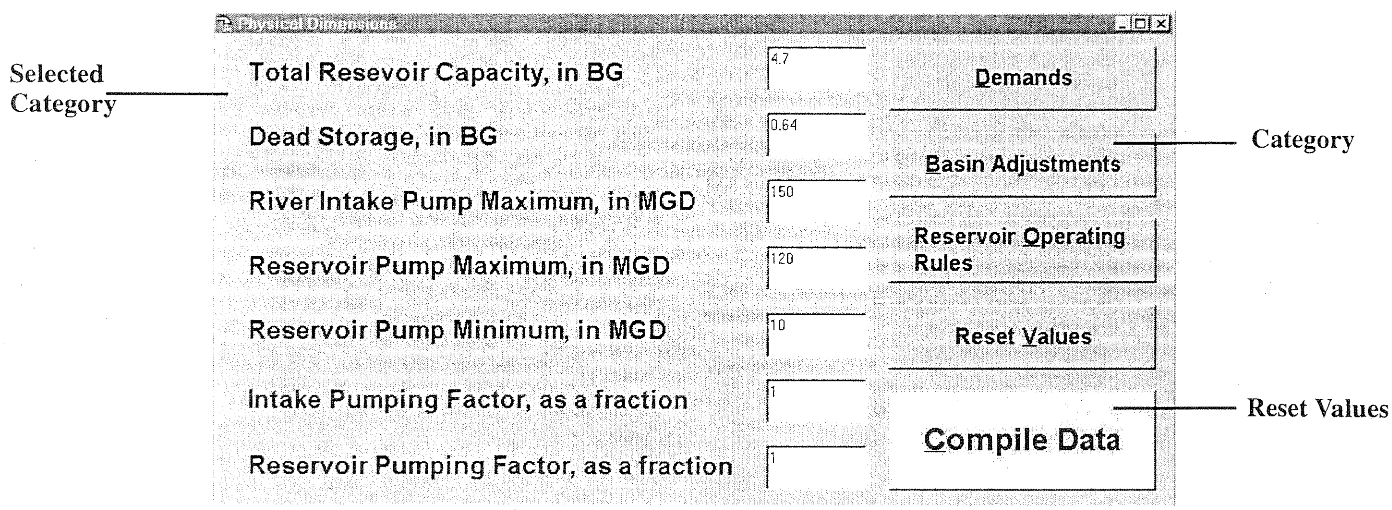
1. Numbers can be edited within the text box by left-clicking in the box and typing in the preferred text.

2. Right-click in the text box for options to undo, cut, copy, paste, and delete.



Note:* If you would like to repeat a number in multiple text boxes, type the number into a text box, double-click in the text box to select all the text, right-click in that same text box and select **Copy. Then to paste this new number in the remaining text boxes, right-click in the new text box and select **Paste**. If you click **Undo**, the text will return to the previous entry.

3. To return to the data of the current run for all entries of a selected category, click the **Reset Values** button. This option changes only the entries for the currently selected category, NOT all categories. To change the entries to the data of the current run for ALL categories, select each category separately, and click the **Reset Values** button.



Outputs

GRAM Model

The GRAM model output will produce three Excel sheets: Output results, Storage, and Flow.

1. Output results

The output results contain all the input data used for the run, as well as the results from the run.

CURRENT SETUP		
Input file name		input90.csv
TOTAL RESERVOIR CAPACITY IN BG		4.7
DEAD STORAGE IN BG		0.64
RIVER INTAKE PUMP MAX IN MGD		150
RESERVOIR PUMP MAX IN MGD		120
RESERVOIR PUMP MIN IN MGD		10
Intake Pumping FACTOR		1
Reservoir Pumping FACTOR		1
MRRSA FLOW IN MGD		6.5
Percent MRRSA flow		66
Percent contributing		50
NAME OF COLUMNS BELOW		
A	Demand - Hospital Rd Distribution Chamber in MGD	
B	Demand from reservoir pipe (Howell) in MGD	
C	Demand directly from reservoir in MGD	
D	Fraction of demand during Phase I drought condition	
E	Fraction of demand during Phase II drought condition	
F	Passing flow required at Hospital Rd in MGD	
G	GW shallow withdrawls + leakage in MGD	
H	SW shallow withdrawls in MGD	
I	Point source flows to basin in MGD	
J	Releases to Timber Swamp Brook in MGD	
K	Normal reservoir level as fraction of full	
L	Pumping target volume as fraction of full	
M	Pumping trigger volume as fraction of full	
N	Drought WATCH volume as fraction of full	
O	Phase I drought volume as fraction of full	
P	Phase II drought volume as fraction of full	
Q	Evaporation + seepage losses from reservoir in inches	

MONTH	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1	16.25	10	0	0.95	0.75	8	1.11	0.02	0	0.2	0.9	1	0.8	0.7	0.6	0.5	0.8
2	16.25	10	0	0.95	0.75	8	1.05	0.02	0.01	0.2	0.91	1	0.81	0.75	0.65	0.55	1.68
3	16.25	10	0	0.95	0.75	8	1.17	0	0.02	0.2	0.94	1	0.84	0.8	0.7	0.6	2.32
4	16.25	10	0	0.95	0.75	8	1.13	0.08	0.02	0.2	0.96	1	0.86	0.8	0.7	0.6	3.86
5	16.25	10	0	0.95	0.75	8	1.15	0.11	0.01	0.2	1	1	0.9	0.8	0.7	0.6	4.27
6	16.25	10	0	0.95	0.75	8	1.15	0.2	0.01	0.2	0.94	1	0.84	0.8	0.7	0.6	4.98
7	16.25	10	0	0.95	0.75	8	2.02	0.36	0.01	0.2	0.91	1	0.81	0.75	0.65	0.55	5.66
8	16.25	10	0	0.95	0.75	8	2.54	0.28	0.01	0.2	0.91	1	0.81	0.67	0.57	0.47	4.86
9	16.25	10	0	0.95	0.75	8	2.42	0.19	0.01	0.2	0.86	1	0.76	0.58	0.48	0.38	3.08
10	16.25	10	0	0.95	0.75	8	2.39	0.09	0.01	0.2	0.86	1	0.76	0.58	0.48	0.38	2.07
11	16.25	10	0	0.95	0.75	8	2.46	0.01	0.01	0.2	0.85	1	0.75	0.58	0.48	0.38	1.99
12	16.25	10	0	0.95	0.75	8	2.39	0	0.01	0.2	0.88	1	0.78	0.65	0.55	0.45	1.08

GENERAL RISK ANALYSIS MODEL

MON/YEAR	STORAGE	RELEASE	TO RES PUMPING	FR RIV PUMPING	PASSING FLOW	CONDITIC	NORMAL	WATCH	WARN	DROUGHT	DEAD STORAGE

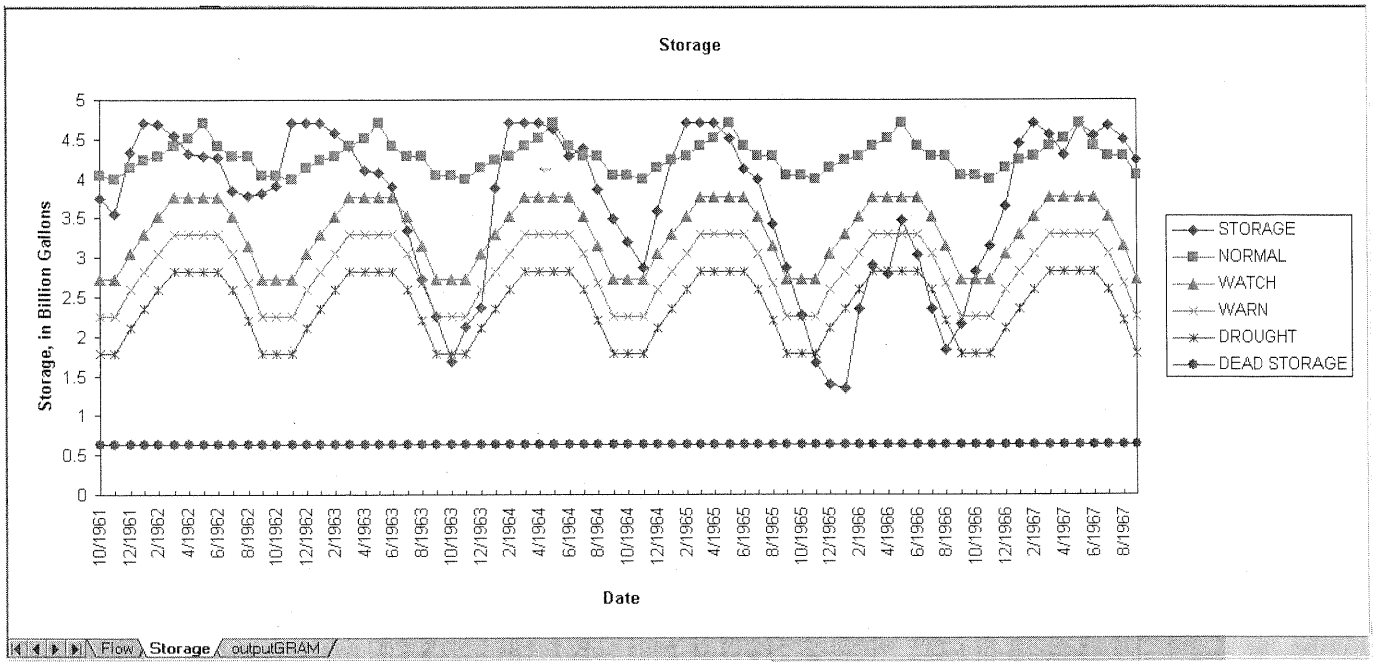
Flow / Storage / outputGRAM

- Mon/Year – Month/Year
- Storage – Reservoir volume, in billion gallons (BG)
- Release – Releases from the reservoir, in million gallons per day (MGD)
- To Res Pumping – Amount of flow being pumped to the reservoir, in MGD
- Fr Riv Pumping – Amount of flow being pumped from the river to the settling basins, in MGD
- Passing flow – Amount of flow remaining in the river
- Condition – Indicates the status of the reservoir. There are four levels: Normal, Watch, Warning, and Drought
- Normal – Reservoir volume during normal conditions, in BG
- Watch – Reservoir volume during watch conditions, in BG
- Warning – Reservoir volume during warning conditions, in BG

- Drought – Reservoir volume during drought conditions, in BG
- Dead Storage – Minimum reservoir volume, in BG
- In Drought – Storage is less than the drought watch level, true or false
- Months of drought – The number of months the period of record is in drought conditions

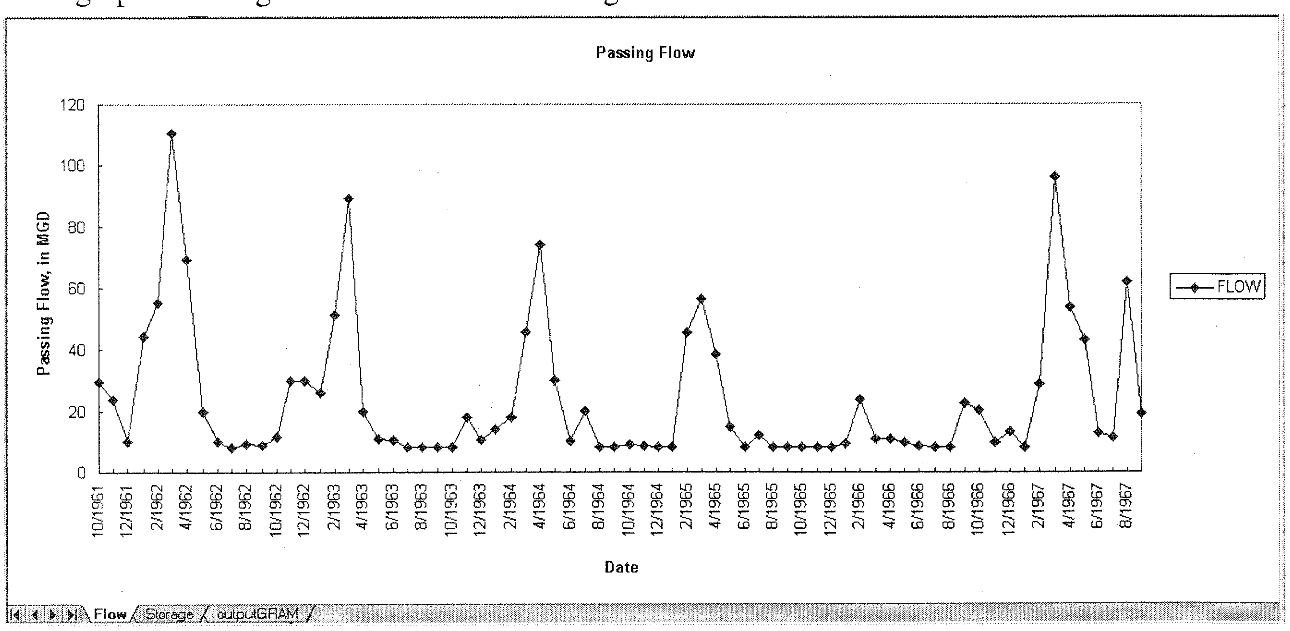
2. Storage

A graph of storage in relation to the date is generated from the results of the run.



3. Flow

A graph of storage in relation to the date is generated from the results of the run.



POSA Model

The POSA model output will produce two Excel sheets: Output results and a graph of non-exceedance probabilities.

1. Output results

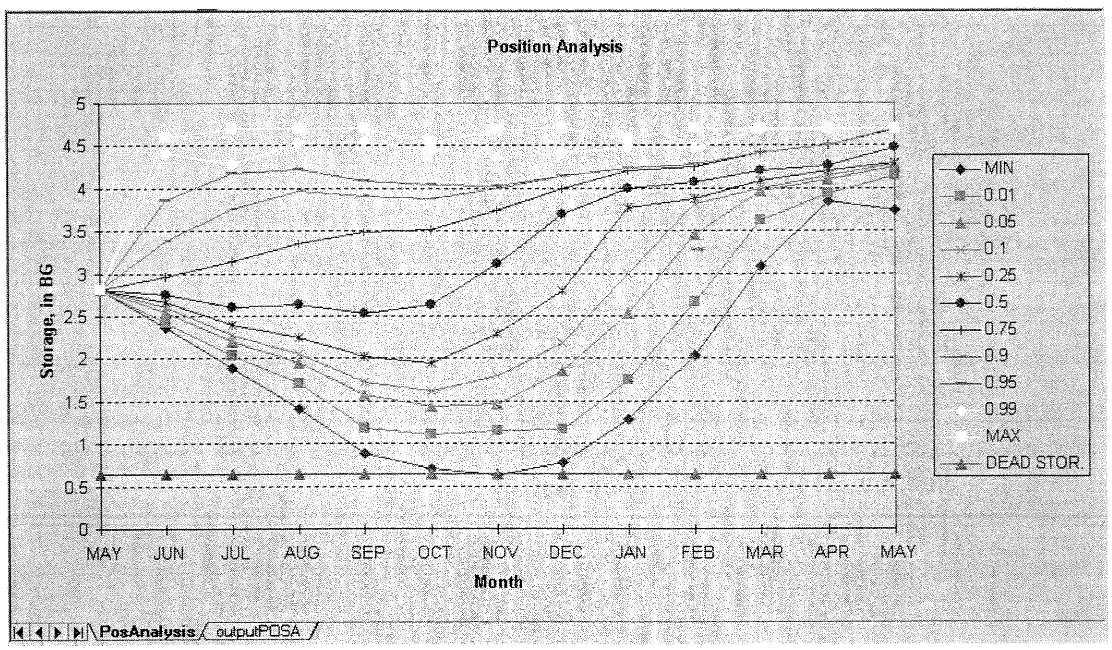
The output results contain all the input data used for the run, as well as the results from the run.

	A	B	C	D	E	F	G	H	I	J	K	L	M
50	NON- EXCEEDENCE PROBABILITY												
51	MONTH	MIN	0.01	0.05	0.1	0.25	0.5	0.75	0.9	0.95	0.99	MAX	DEAD STOR.
52	MAY	2.82	2.82	2.82	2.82	2.82	2.82	2.82	2.82	2.82	2.82	2.82	0.64
53	JUN	2.36	2.43	2.55	2.6	2.66	2.76	2.97	3.39	3.86	4.42	4.59	0.64
54	JUL	1.89	2.03	2.2	2.28	2.4	2.61	3.14	3.76	4.17	4.28	4.7	0.64
55	AUG	1.41	1.71	1.94	2.05	2.25	2.63	3.35	3.97	4.22	4.54	4.7	0.64
56	SEP	0.89	1.19	1.57	1.72	2.02	2.53	3.49	3.91	4.08	4.55	4.7	0.64
57	OCT	0.71	1.11	1.44	1.62	1.95	2.63	3.52	3.88	4.04	4.44	4.53	0.64
58	NOV	0.63	1.15	1.47	1.8	2.29	3.11	3.74	4	4.03	4.36	4.68	0.64
59	DEC	0.78	1.17	1.85	2.19	2.8	3.7	3.99	4.14	4.15	4.41	4.7	0.64
60	JAN	1.28	1.75	2.53	3	3.77	3.99	4.21	4.23	4.24	4.47	4.58	0.64
61	FEB	2.04	2.67	3.46	3.81	3.88	4.07	4.25	4.28	4.28	4.48	4.7	0.64
62	MAR	3.08	3.62	3.96	3.99	4.09	4.21	4.42	4.42	4.42	4.68	4.7	0.64
63	APR	3.84	3.93	4.1	4.15	4.21	4.27	4.51	4.51	4.51	4.69	4.7	0.64
64	MAY	3.74	4.14	4.25	4.28	4.3	4.47	4.69	4.7	4.7	4.7	4.7	0.64
65													

PosAnalysis | outputPOSA

2. POSA graph

The graph shows non-exceedance probabilities generated from the results of the run.



Appending New Flow Data

1. The flow of Manasquan River at Allenwood must first be reconstructed using the following formula (in million gallons per day, MGD):

$$Q_{rA} = Q_{oA} - S_d + S_w + Gw_s + \Delta L + I/I - M_r \ ,$$

where

Q_{rA}	=	Reconstructed flow at Manasquan River at Allenwood, N.J.,
Q_{oA}	=	Observed flow at Manasquan River at Allenwood, N.J., plus intake pumpage (This does not include runoff from Timber Swamp Brook upstream from the reservoir.),
S_d	=	Point source discharges,
S_w	=	Surface-water withdrawals,
Gw_s	=	Shallow (surficial) ground-water withdrawals,
ΔL	=	Change in leakage due to withdrawals from confined aquifers,
I/I	=	Infiltration/Inflow, and
M_r	=	Manasquan Reservoir release to Timber Swamp Brook (M_r = zero on overflow days).

2. Open *alldat.txt.* This file should be located in the folder where the model is running. Append the new data to the existing data in the alldat.txt file in the format (Year, Month, Day, Flow in MGD/d (Q_r)) below:

   Each entry must consist of 20 characters. For example, an entry of 1,234,567.8 MGD for November 11, 2001, and 1 MGD for September 1, 1999, would be entered as follows:

	Year				Blank space	Month		Blank space	Day		Blank Space	Streamflow							Fixed decimal	Streamflow
Column number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Example 1	2	0	0	1		1	1		2	5		1	2	3	4	5	6	7	.	8
Example 2	1	9	9	9		0	9		0	1								1	.	0

> **Note*: The new data must line up in the exact number of character positions as the old data. In addition, flow data must not exceed the tenth decimal place.

3. Save and close *alldat.txt.*

Chang, Ming, Tasker, Gary, and Nieswand, Steven.—MODEL SIMULATION OF THE MANASQUAN WATER-SUPPLY SYSTEM IN MONMOUTH COUNTY, NEW JERSEY,—
U.S. Geological Survey Water-Resources Investigations Report 01-4172