Raritan Basin Water Supply System Safe Yield Evaluation and Operation Model

New Jersey Water Supply Authority
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EXECUTIVE SUMMARY

The New Jersey Water Supply Authority operates Raritan Basin water supply facilities for the State of New Jersey and its residents. These facilities include Spruce Run Reservoir, Round Valley Reservoir, and the Delaware and Raritan Canal. More than 1.5 million residents in central and northern New Jersey get their drinking water in part or wholly from water purveyors, which purchase water under contract from the Authority. Water is also purchased from the Authority for irrigation, recreational and industrial uses.

To enhance knowledge about the system, the Authority developed a new model of the Raritan Basin System to assess the safe yield, operational protocols, and future water supply alternatives. In particular, the model was developed to affirm the safe yield and evaluate the operations of a new water supply project (the Confluence Pumping Station). The model was developed using RiverWare, a software program designed specifically for the evaluation of river and reservoir system operations. The University of Colorado developed and maintains RiverWare for the United States Bureau of Reclamation and the Tennessee Valley Authority.

Data required for model development and calibration included the system status time series (elevations, releases, pumped volumes), hydrology, physical dimensions, limitations of the system components (pumping and release capacity, storage volumes), and operational scenarios. The Authority maintains a database of system statistics, which include reservoir pool elevations (storage)[1], release volumes, pumped volumes, and Canal inflows. The United States Geological Survey monitors streamflow data at 16 locations in the Raritan Basin System and one location on the Delaware and Raritan Canal. Precipitation and evaporation data were available from the Office of the State Climatologist and Rutgers Cooperative Extension, respectively.

System operations include releases from both reservoirs and the Canal and pumping to Round Valley Reservoir. The Authority manages these actions within the Raritan Basin system to achieve the following goals:

- Maintain minimum passing flows at three streamflow monitoring locations
    - Stanton (on the South Branch of the Raritan River),
    - Manville (on the Raritan River above the Millstone River Confluence), and
    - Bound Brook (on the Raritan River below all river purveyor intakes);
- Provide adequate flow for use by water purveyors;
- Maintain Spruce Run Reservoir's elevation to facilitate summer recreation; and
- Operate the system cost-effectively.

The safe yield is the amount of water that a reservoir system can supply without fail during the drought of record[2]. Previous estimates of the system safe yield were 225 mgd (160 mgd

[1] Since reservoir storage cannot be directly measured, the pool elevation is used to determine the storage based on the elevation-volume relationship for the reservoir. This relationship is determined in a similar manner as cut and fill calculations.
[2] N.J.S.A. 58:1A-3.

from the river and 65 mgd from the Canal). Allocation permits[3] for water users are based upon the safe yield. Currently, 218 of the 225 mgd established safe yield is allocated, but only 184[4] mgd is contracted for sale.

The RiverWare model of the system indicates that the safe yield from the Raritan Basin is 241 mgd (176 mgd from the river and 65 mgd from the Canal). The increase in the river safe yield of 16 mgd is attributed to differences in streamflow estimation techniques, increases in return flows and the approach to simulating precipitation and evaporation.

The RiverWare model also was used to assess the safe yield of the system with the addition of the Confluence Pumping Station Project. The project entails the installation of a pumping station at the confluence of the North and South Branches of the Raritan River. The pumping station will be able to pump water from 490 square miles of drainage area into Round Valley Reservoir, allowing the system to store flows from the North Branch of the Raritan River and the lower South Branch of the Raritan River. The Confluence Pumping Station project adds 46 mgd to the system safe yield for a total of 287 mgd. Previously, the Confluence Pumping Station was predicted to add an additional 53 mgd to the safe yield. The reduction is likely due to the increase in safe yield in the existing system. More water is stored from the existing system, so less storage is available for water from the Confluence Pumping Station Project.

The model may be used in the future to assess operations, additional water supply alternatives, the effects of increasing depletive ground water use on safe yield, and other scenarios. Although the Raritan Basin System passing flows required at Stanton, Manville, and Bound Brook are statutory, the effects to the system from implementing ecological flow goals also may be evaluated.

[3] Issued by the New Jersey Department of Environmental Protection's Bureau of Water Allocation.
[4] The Authority has purchase contracts for 181 mgd, but is obligated to supply 184 mgd. The Elizabethtown Water Company has a "grandfathered" use of 2.91 mgd from the Somerville Water Company, which predates the Authority. (see NJDEP Water Allocation Permit 5033, dated March 23, 2003).

1.0 INTRODUCTION

1.1 Background

The Raritan River Basin system provides drinking water for more than 1.5 million residents in central New Jersey. The New Jersey Water Supply Authority manages the water resources of the Raritan Basin for the residents of the State. The Authority operates the major components of the water supply system, which are Spruce Run Reservoir, Round Valley Reservoir, and the Delaware and Raritan (D&R) Canal. Water purveyors purchase the water under contract from the Authority and then treat and distribute the water to their customers. The Authority also sells water under contract to customers for agricultural and other business purposes. Revenue from the sale of the water is used to operate and maintain the system components.

The Authority is charged with operating and maintaining water supply facilities for the State, specifically "the Delaware and Raritan Canal Transmission Complex and the Spruce Run-Round Valley Reservoir Complex."[5] The revenue from these facilities is pledged to the Authority to "…design, initiate, acquire, construct, maintain, repair and operate [water supply] projects." To do so, the Authority needs to know how much water can be reliably delivered from the Raritan Basin System and how these systems can be managed to ensure the availability of that water. Therefore, a model was developed to better understand the dynamics of the water supply system and determine the consistent dependable amount of water available for use by society and the environment.

1.2 Safe Yield

Safe yield is the amount of water that can continually be supplied from a reservoir system without fail based on the drought of record. The safe yield of the Raritan Basin and Delaware and Raritan Canal system was previously determined to be 160 mgd from the river and 65 mgd[6] from the Canal or 225 mgd total. The drought of record in the Raritan Basin was the 1960's drought (1963-1966), during which precipitation was less than about two-thirds of the annual average of 46 inches based on rainfall data recorded between 1895 and 2002.

To estimate the safe yield, a continuity-accounting model is used to hypothetically subject the system to historic streamflows and specified operating rules. Different operating rules may produce different safe yields. Estimates of the reliability[7], resilience[8], and vulnerability[9] of reservoir systems can be determined with safe yield/operations models by using synthetic streamflow records combined with statistical evaluation techniques. Stochastic features add the ability to evaluate probable outcomes, such as the probability of a

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[5] Per N.J.S.A. 58:1B-5.

[6] 65 mgd is the maximum amount of flow that can be diverted to the Canal under Delaware Basin Drought Conditions per the Delaware River Compact, an agreement among New York City, New York State, Pennsylvania, New Jersey and Delaware.

[7] Portion of time a reservoir or water supply system is able to meet consumer demand

[8] The probability of recovery from failure to a defined acceptable state within a specified time period (also, the rate of recovery from failure)

[9] A measure of the likely magnitude or significance of failure (severity of failure)

reservoir falling below drought warning level given a starting condition and a set of operational rules. For the purposes of this report, only model development and the system's safe yield was examined. A more detailed explanation of how the safe yield is determined can be found in Appendix A.

1.3 Previous Modeling Efforts

The Raritan Basin System has been modeled previously for various purposes. Mr. Harvey Sarven, PE, a consultant for the NJDEP Division of Water Resources, developed the first known model[10] of the Raritan Basin Reservoir system between 1966 and 1968. Neither the source code nor the executable version of this model could be located. His study essentially determined the safe yield of the river system and then used those values to develop a "purchase factor," which weights the value of the water by the effect the withdrawal location has on the safe yield. Based on the streamflow data from 1930s drought, the safe yield of the system was 190 mgd. Later simulations by Sarven with streamflows from the more severe drought of the 1960s indicated that the safe yield of the system is 160 mgd. The Delaware and Raritan Canal has a safe yield of 65 mgd, which is based on the maximum diversion to the Canal during a drought emergency in the Delaware River Basin defined by criteria[11] established by the Delaware River Basin Commission.

1.4 Previous NJWSA Models

Since its inception in 1981, the Authority developed two basin models to assess the Raritan Basin and Canal water supply system operations. The first model, developed by New Jersey Institute of Technology (NJIT) in 1985, evaluated specific economic and hydrologic system performance (330 scenarios) on a daily basis using the historic streamflow record. The second, developed by United States Geological Survey (USGS), is an interactive operations analysis model that evaluates system operations on a monthly basis to forecast the effects of current operations for drought preparedness. The Authority has relied on this model in past years. Both of these models are continuity accounting models that also can be used to evaluate system safe yield in addition to evaluating limited system operations.

1.4.1 NJIT Model

The NJIT model was developed in FORTRAN[12] and was used to evaluate the Raritan Basin System under different operational conditions and scenarios. The model is a typical "safe yield" model in that historic streamflow data are used to evaluate system performance through a mass-balance accounting model. Daily streamflow data were used for the simulations. The primary purpose of the 1985 study (and the model) was to evaluate operational scenarios that maintained safe yield while minimizing pumping costs. Some of the operational scenarios considered included:

- Supply augmentation to the Raritan River with D&R Canal water;
- Uniform and variable (by month) water supply demand at Bound Brook;

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[10] Sarven, Harvey W., 1967.
[11] Delaware Compact
[12] A computer programming language, used extensively by engineers in the latter half of the 20th century, which is no longer supported by the computer programming industry.

- Number of pumps used at the South Branch Pumping Station; and
- Allowable reservoir storage levels.

The model was used to assess 330 combinations of water demand, Canal supply, and pumps utilized were simulated to develop system operations rules for the Authority. The study concluded that:

- Using fewer pumps at the South Branch pumping station was the most cost effective operations policy with the only drawback being that slightly less water would be in storage for a drought (since the pump rate controls the volume of water transferred to the reservoir).
- The droughts of the 1930s and 1960s resulted from successive years of reduced precipitation.[13]
- Lower reservoir storages result when variable demands, rather than uniform demands, are used for the simulations.[14]
- Given energy costs, augmenting supply with Canal water is preferable to releasing from Round Valley Reservoir.

The utility of the NJIT model was that 330 simulations of different reservoir operations were simulated and then evaluated. The model is not interactive in that the only operations modifications that can be evaluated are demand, water transfers from the Canal, and the number of pumps used. This model was developed to answer specific questions about how to economically optimize pumping operations (economically) and the system's hydrologic performance.

1.4.2 USGS Model

The USGS Model also was developed in FORTRAN in 1996 for evaluating the water supply status from system operations during drought conditions using monthly streamflow data. The model assesses how the system would have performed in the past under user specified operational rules. The model can forecast operations for a year into the future based on the previous year's monthly streamflow record. The USGS developed the model as a tool for the Authority to evaluate various operations scenarios.

The model has two modes: General Risk Analysis Model (GRAM) and Positional Analysis Model (PAM). The GRAM mode is used to estimate the probability of events (duration of storage depletion, for example) given historic streamflows, proposed operating rules and estimated withdrawal rates. The PAM mode provides a means to forecast system performance, based on the previous 12 months of monthly streamflow data. Through the PAM[15] mode, the model can evaluate the likelihood of events such as reservoir drawdown or release requirements to meet minimum passing flows.

[13] A short duration, rapid onset droughts
[14] This implies that the use of a uniform demand for calculations will overestimate the safe yield.
[15] The PAM mode uses stochastic methods to generate a large number of future potential flow traces. Many flow traces are used to simulate the system so that the likelihood of possible outcomes can be evaluated statistically.

Although withdrawals to meet minimum passing flows are determined on a daily basis, the model uses monthly streamflow data to simulate the Raritan Basin System. To account for the daily variations in streamflows and withdrawals, the USGS adjusted both (passing streamflows and withdrawals) upward[16] using an empirical formula developed by the New York State Department of Environmental Conservation.

The model's flexibility lies with the options to enter values for various operational conditions. The values that can be altered are:

- Monthly drought declaration levels for combined New York City Delaware River Reservoirs (affects amount that can be diverted to the Canal);
- Allowable withdrawals from Delaware River by drought condition (affects amount that can be diverted to the Canal);
- NYC Reservoirs – reservoir capacity, minimum release, augmented release; target storage;
- Starting Reservoir Levels (NYC, SR, RV);
- Spruce Run Reservoir – minimum release, reservoir capacity;
- Round Valley Reservoir– capacity, monthly target storage;
- South Branch pumping station capacity;
- Use of South Branch or Confluence Pumping Station;
- Pumping curves – for combined reservoir operation;
- Minimum Passing Flows (Stanton, Manville, Bound Brook);
- Current monthly flows at input and minimum passing flow gauges;
- Depletive use rates (net demand), by drought condition; and
- Sewage return rates (related to depletive use rates).

The model only reflects new operational protocols if the proposed scenarios involve altering one or more of the above values (bulleted). In addition, the results are based on monthly streamflows, which will tend to produce larger safe yields than daily streamflows.

1.5 Justification for New Model

The droughts of 1998-1999 and 2001-2002 increased concerns about the vulnerability of New Jersey's water supply. While the Raritan Basin is, to some extent, water rich, other regions of the State are not. Previously, interconnections with the Raritan Basin System and North Jersey have been discussed and interconnections do exist between the two. Through the development of a new safe yield/operations model, the Authority will be able to evaluate the impact of increasing demand and exporting water from the Raritan Basin to other areas.

The Raritan Basin system is not fully contracted, which allows current operations of the reservoir system to be less structured. Currently, contracted water sales are about 82 percent of the safe yield; thus, the system has been operated for economic rather than hydrologic efficiency. As the water uses in the region approach the safe yield of the system, more hydrologically efficient operations of the system may be needed to ensure the system can

[16] This is conservative.

provide the safe yield. The model will be able to determine how operations affect the safe yield of the system and if the system can be operated more efficiently to increase the safe yield.

1.6 Model Selection

The Authority investigated several models and modeling options for re-evaluating the safe yield, including modification of prior models. The NJIT and USGS models were written in FORTRAN. Source code was available for both models. Although FORTRAN compilers[17] are still available, FORTRAN is used less and less as computer programming technology advances. Therefore, the Authority decided to pursue the use of state-of-the-art technology. After research on several major and minor models for reservoir operations, the Authority chose RiverWare. RiverWare is software that contains the algorithms necessary for operations modeling. The model developer inputs the specifics of the system being studied and RiverWare processes the information to obtain a solution (an analogous software package is USEPA's SWMM). RiverWare was developed by the University of Colorado Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) for the United States Department of the Interior, Bureau of Reclamation and the Tennessee Valley Authority, and thus is likely to be supported well into the future. One advantage of this type of software package is that the model developer does not need to write code and future users of the model will not need to modify code, which can be difficult if the code is not well documented. With RiverWare, system components and operations policies easily can be added or removed from the simulation.

[17] Compilers translate the source code into an executable (functioning) program.

2.0 DATA REQUIREMENTS

Safe yield is a mass-balance analysis of the water resources available in a drainage basin. Data needed to determine the safe yield of the system include hydrologic information, physical dimensions and limitations of system components, and operational scenarios. Hydrologic data required may include precipitation, evaporation, streamflows, and surface and ground water interactions. Physical information about system components include reservoir dimensions (elevation-volume and elevation-surface area relationships), release structure capacities, pumping capacities and spillway dimensions. Operational scenarios include pumping, releases, and interbasin transfers.[18]

Normally, safe yield models are developed to evaluate how much water might be available from a drainage area where a reservoir or reservoirs could be built. In those cases, the models are theoretical and are not calibrated (since the reservoir system does not exist). For this model, data are known about the system and can be used to gain a better understanding of generally unquantifiable phenomenon such as evaporation, seepage, bank storage, and flow routing. As such, the Raritan Basin system model was calibrated with observed data: gauged inflows, precipitation, reservoir pool elevations (storage), releases, and spills. The observed information allowed the Authority to develop a better understanding of how the system operates and what hydrologic processes affect the availability of water. In addition, the model developed simulates operations and will be used to evaluate proposed operational and water supply alternatives.

2.1 System Configuration

The Raritan Basin is a surface water supply system consisting of an in-line reservoir, an off-line reservoir, and a water supply Canal that conveys water into the basin from the Delaware River. Figure 1 presents the geography of the Raritan Basin System, while Figure 2 presents a schematic view of the water supply system. This water supply system is unusual because raw water for treatment is withdrawn directly from the river and the Canal and not from a reservoir. No direct connection exists between the reservoirs and the water treatment facilities. Spruce Run Reservoir is the in-line reservoir, which collects drainage from about 42 square miles. Releases and spills from Spruce Run Reservoir enter Spruce Run and join the South Branch of the Raritan River just upstream of the Town of Clinton. Round Valley Reservoir is an off-line storage reservoir with about 5.6 square miles of natural drainage area (of which up to 3.5 square miles are covered with the reservoir surface area). Water is pumped from the South Branch of the Raritan River upstream of Stanton through the South Branch Pumping Station[19] into the Reservoir. The drainage area from which the flow can be pumped is about 142 square miles. Water can be released from Round Valley through the main release to the South Branch Rockaway Creek in Whitehouse or to the South Branch of the Raritan River through the Alternate Release at the South Branch Pumping Station. The Millstone River joins the Raritan River 8.5 miles downstream of the confluence of the North and South Branches of the Raritan River. Intakes for two drinking water treatment plants are

[18] An interbasin transfer occurs when water is diverted from one watershed to another. Delaware Basin water is transferred to the Raritan Basin via the Delaware and Raritan Canal. Water can be released directly to the river or is withdrawn from the Canal for treatment and distribution from the water purveyors.
[19] Also known as the Hamden Pumping Station.

Figure 1. Geography of the Raritan Basin

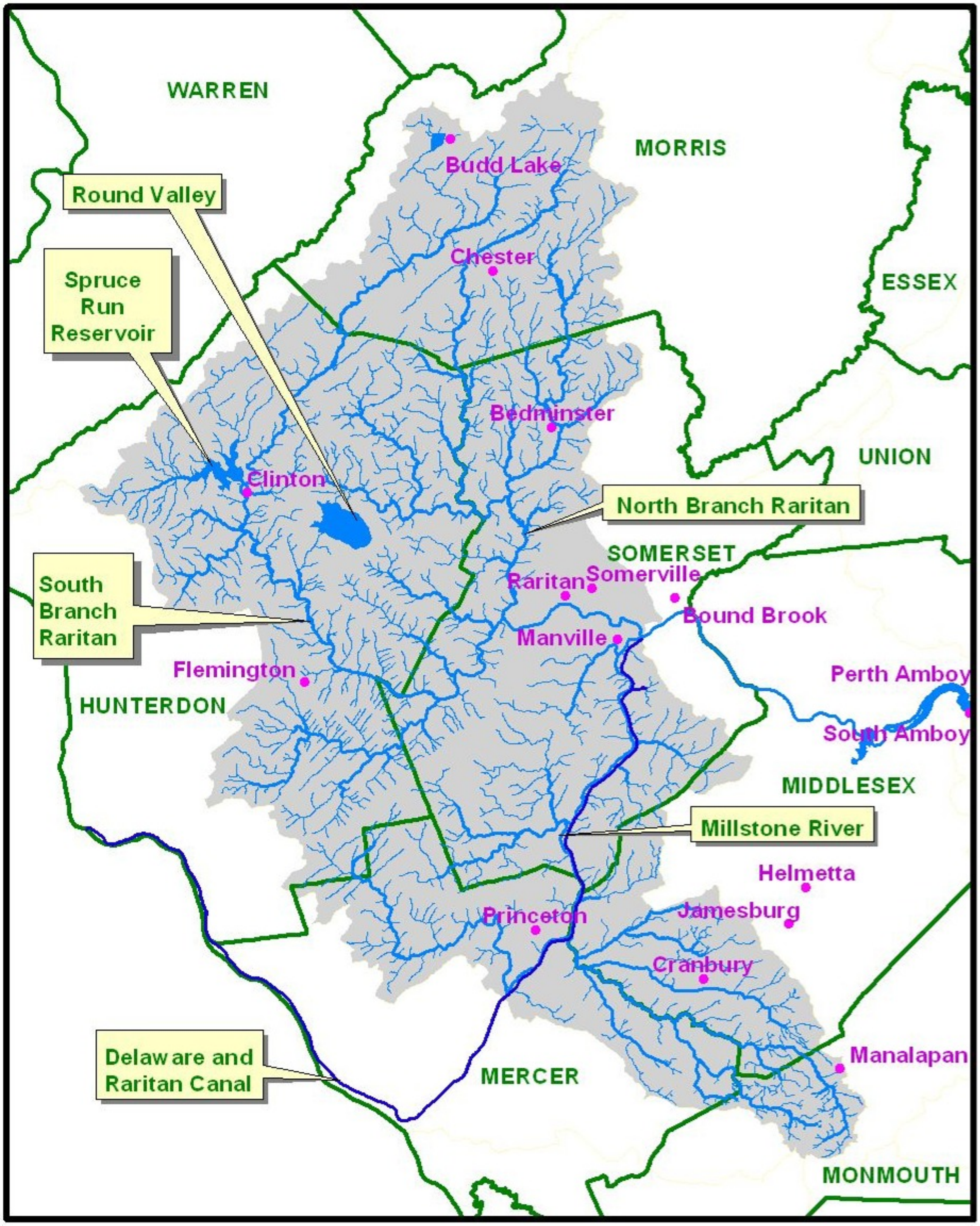
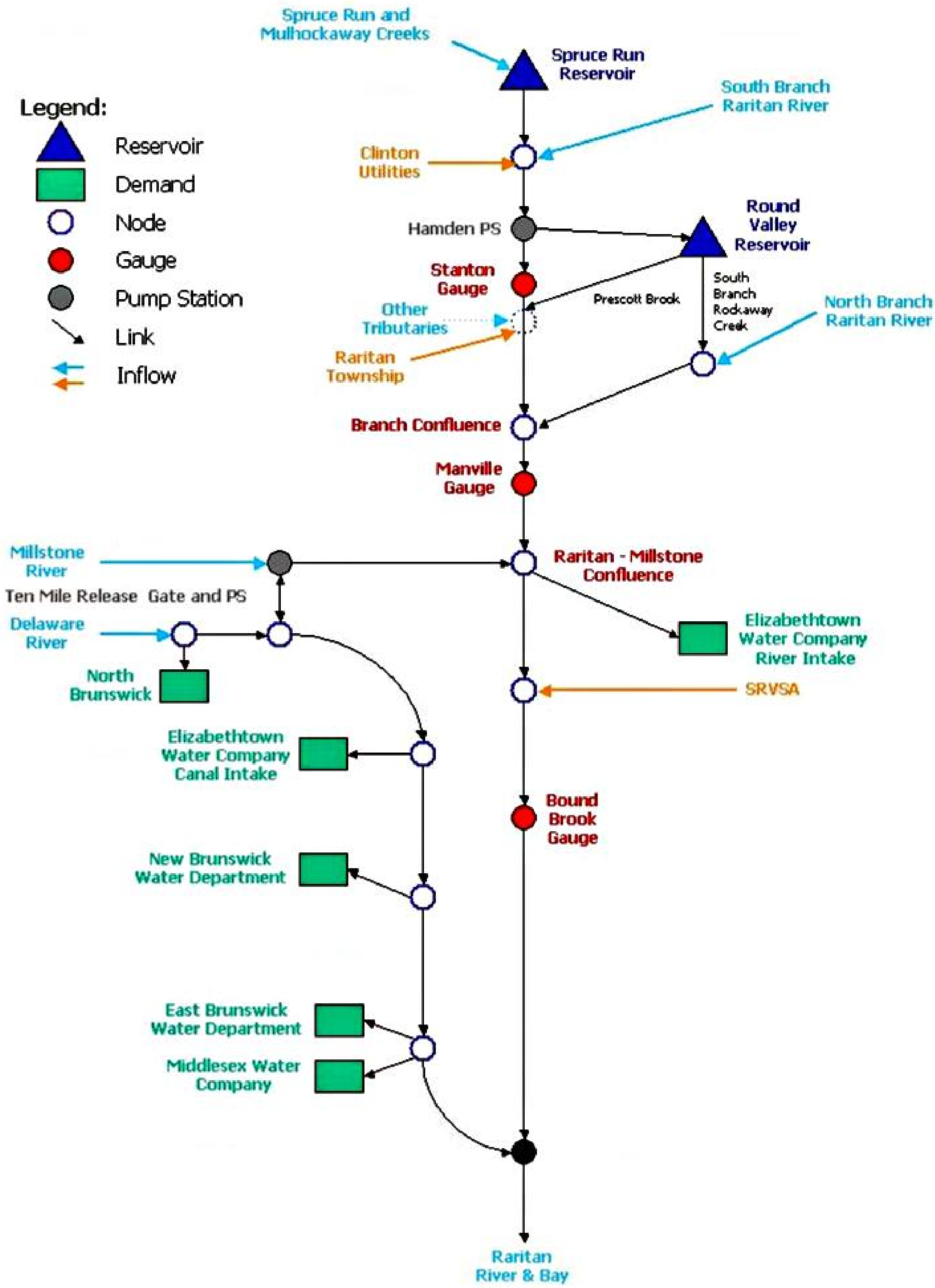


Figure 2. Raritan Basin Water Supply System Schematic



located at the confluence of the Raritan and Millstone Rivers. The total drainage area[20] of these river systems is 780 square miles.

The Delaware and Raritan Canal is an inter-basin transfer of up to 100 mgd from the Delaware River. Water is diverted from the Delaware into the Canal at Bull's Island, near Stockton, New Jersey, and travels 60 miles to New Brunswick where the water is discharged to the Raritan River. Water purveyors withdraw water from the Canal at several locations along the route. Water not withdrawn by water purveyors is either discharged to the Millstone River at the Ten Mile Lock release gate[21] or to the Raritan River at the downstream terminus at the Route 18 spillway. A pump station located at Ten Mile Lock can transfer water from the Raritan-Millstone River Confluence into the Canal. Releases from the Canal are not required at any location.

Minimum passing flows must be met at three locations: Stanton (downstream of South Branch Pumping Station), Manville (below the confluence of the North and South Branches of the Raritan River) and Bound Brook (below the river water purveyor intakes). Passing flows at the three locations were determined using three different methodologies. Flow at Stanton was based on a study by Vermeule (early 1900s), which specified a flow of 0.25 mgd per square mile of drainage area, for streams below water supply reservoirs (a similar value was determined for Wanaque Reservoir in Passaic County, NJ). Manville passing flows were based on the 7Q10[22] flow as determined by the New Jersey Geological Survey (NJGS) in the late 1800s. Killam Associates determined the passing flows at Bound Brook for a study in the 1950s for the Somerset Raritan Valley Sewerage Authority (SRVSA) Pollution Discharge Elimination System Permit.[23] All three minimum passing flows were included in the statute authorizing construction of the two reservoirs in the 1960s.

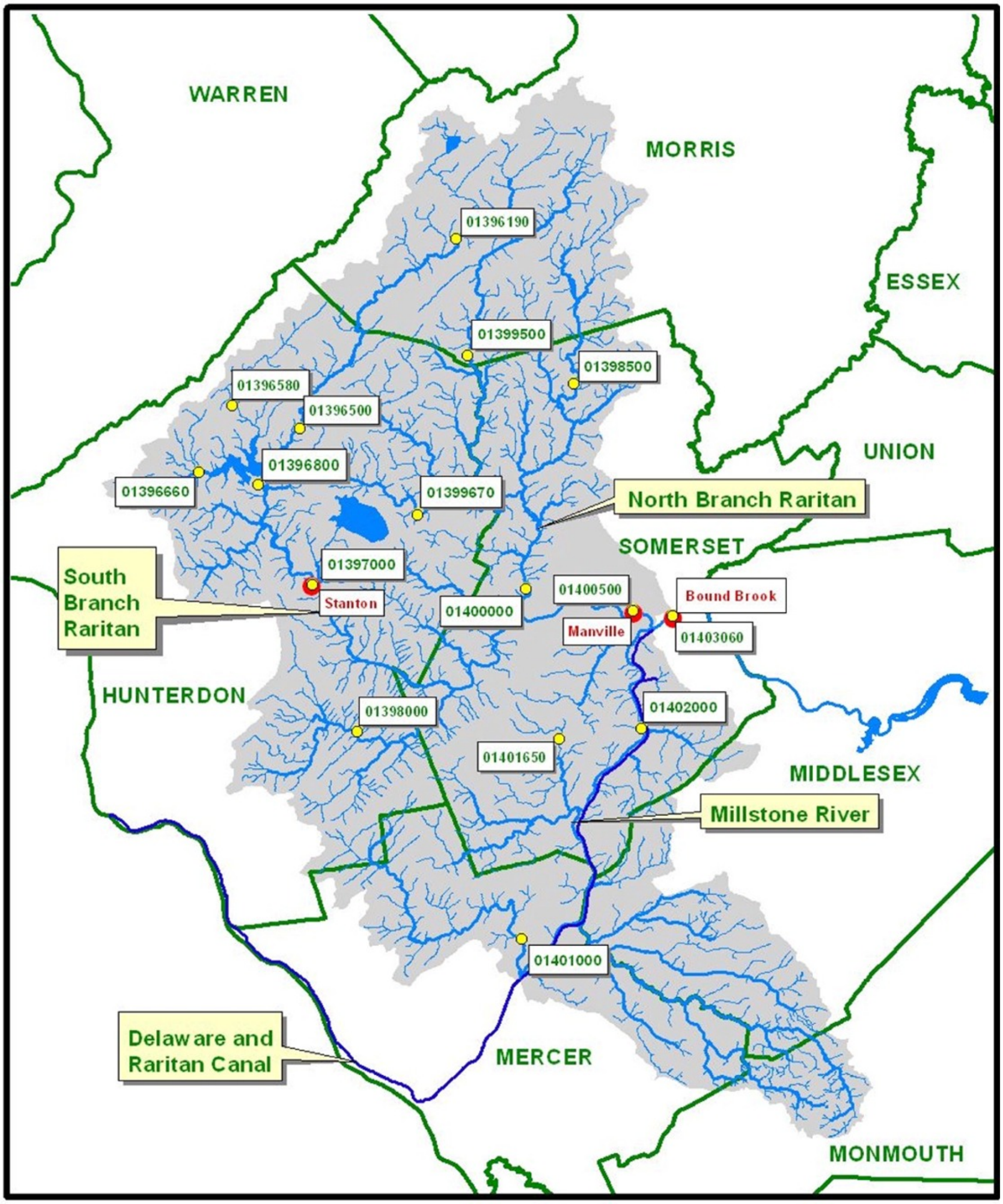
2.2 Streamflows

Streamflows are the driving data requirement for the estimation of safe yield, as they are the mass that is balanced to determine the safe yield. The United States Geological Survey (USGS) monitors streamflows at 16 locations in the 780 square mile drainage area above the purveyor intakes on the river. Table 1 presents the gauges in the Raritan Basin and the length of their flow records. Figure 3 presents the locations of the USGS streamflow gauging stations.

Observed streamflow data are used for both model input and calibration. Data from unregulated[24] gauges are used to estimate the flows into the system. For streams and areas for which no data exist, flows are estimated by weighting the flow from a nearby streamflow gauge by the ratio of the drainage areas (ungauged flow = gauged flow * ungauged area/gauged area). For instance, the flows from the Mulhockaway Creek gauge are used to estimate the flows from the Black Brook into Spruce Run; flows from the South Branch at High Bridge are used to estimate flows from Cakepoulin Creek. Data from the regulated

[20] Above the purveyor intakes on the Raritan River
[21] Previously, this release was called the "waste gate."
[22] The lowest consecutive 7 day flow in a 10-year period, a common low flow design standard.
[23] Personal communication between Jeff Hoffman (NJGS) and Don Kroeck in May 2004.
[24] "Unregulated" means that the flow is not affected (significantly) by the interference of humankind.

Figure 3. Locations of Streamflow Gauging Stations in the Raritan Basin



gauges are used to assess the model's predictive ability or calibration. Since flows at the Stanton, Manville, and Bound Brook gauges are affected by actions at Spruce Run Reservoir (impoundment and releases) and Round Valley Reservoir (pumping and releases), flows at these gauges are regulated and used for model calibration.

Inspection of Table 1 indicates that data are not available at some locations for the drought of record, the 1960s. In those instances, the MOVE.1[25] technique is used to "back cast" the missing data using observed data from another site with data during that time period. This technique preserves the mean and variance of the existing streamflows in the extended or "back cast" record. The MOVE.1 technique also is used to "fill" periods of missing data due to gauge malfunction or discontinuation. A detailed explanation of what gauges were used to estimate flows at other locations and other time periods is found in Appendix B.

Per the Delaware River Compact,[26] flow from the Delaware River is diverted to the Raritan Basin via the Delaware and Raritan Canal. The Canal, originally built in the 1800s for the conveyance of goods between New York and Philadelphia, is currently maintained for water supply and recreational purposes. During "normal" operations, 100 mgd may be diverted into the Canal from the Delaware with not more than 120 mgd to be diverted on any single day. During drought warning, 70 mgd may be diverted and during drought emergency 65 mgd may be diverted. Drought is defined by Delaware River Basin conditions and not by Raritan Basin conditions. The Authority monitors Canal flows through gates, skimmers and weirs and major points along the Canal, including Port Mercer (upstream of all the Canal purveyor intakes) and through the river interconnection (waste gate) at Ten Mile. The USGS also monitors flows at Port Mercer and has only rated their data as "fair" with poor records at low flow[27]. To the extent possible, these data were used, but suspect periods in the record were modified to better reflect other observed conditions.

[25] The MOVE.1 technique is regularly used by the USGS to fill gaps in the data record or extend the existing data record.
[26] Delaware River Basin Commission. Delaware River Basin Water Code. April 2001.
[27] USGS, "Water Resources Data: New Jersey: Water Year 2002: Volume 1. Surface-Water Data." Water Data Report NJ-02-1.

Table 1. Streamflow Gauges in the Raritan Basin

USGS ID	Name	Description	Period of Record	Drainage Area Sq. mi.	Minimum Daily Flow (mgd) date	Maximum Daily Flow (mgd) date
01396190	South Branch Raritan River at Four Bridges	On right bank, just downstream of bridge on Elizabeth Avenue, 0.3 mi SW of Four Bridges, 0.6 mi downstream of Drake's Brook, 0.7 mi northwest of Naughright, and 2.7 mi northwest of Chester.	Jan-1999 to present	31	1.5 8/19/2002	988 9/16/1999
01396500	South Branch Raritan River near High Bridge, NJ	On left bank 1 mile NE of High Bridge and 4.4 mi upstream of Spruce Run	Oct-1918 to present	65.3	8.4 8/11/1966	2,158 1/25/1979
01396580	Spruce Run at Glen Gardner, NJ	On right downstream of wingwall of bridge on Sanatorium Road in Glen Gardner, 0.8 mi downstream from Alpaugh Brook and 2 mi upstream from Spruce Run Reservoir	Mar-1978 to Sep-1988, Dec-1991 to Aug-2005	11.3	0.7 9/4/1999	420 9/16/1999
01396660	Mulhockaway Creek at Van Syckel, NJ	On left bank downstream side of bridge on Jutland Road, 0.2 mi south of Van Syckel, 0.8 mi north of Perryville, and 0.3 mi upstream from Spruce Run Reservoir	Jul-1977 to present	11.8	0.7 8/2/1999	593 9/16/1999
01396800	Spruce Run at Clinton, NJ	1,800 ft downstream from dam at Spruce Run Reservoir, 0.2 mi north of Clinton, 0.3 mi upstream from mouth, and 2.2 mi southwest of High Bridge	May-1959 to present	41.3	0.0 see below	1,330 7/7/1984
01397000	South Branch Raritan River at Stanton, NJ	On right bank at downstream side of bridge on Stanton Road at Stanton Station, 0.4 mi upstream from Prescott Brook, and 1.4 mi west of Stanton.	Jul-1919 to present	147	7.8 10/18/1963	5,210 8/19/1955
01398000	Neshanic River at Reaville, NJ	On left bank 50 ft downstream from bridge and Everitts Road, 0.6 mi southwest of Reaville, 1.5 mi downstream from Third Neshanic River and 2.2 mi upstream from Black Brook	Jun-1930 to present	25.7	0.0 7/29/1965	4,550 9/16/1999
01398500	North Branch Raritan River near Far Hills, NJ	On left bank 75 ft upstream from Ravine Lake Dam, 1.3 mi southeast of Peapack, 1.6 mi north of Far Hills, and 2.3 mi upstream from Peapack Brook.	Oct-1921 to Sep-1975 and Oct-1977 to present	26.2	0.1 10/22/1953	1,140 10/19/1996
01399500	Lamington (Black) River near Pottersville, NJ	On right bank, 1.1 miles upstream from bridge on 512, 1.2 miles NW Pottersville, and 5.5 mi upstream from Cold Brook	Oct-1921 to present	32.8	1.0 10/4/1930	585 1/25/1979
01399670	South Branch Rockaway Creek at Whitehouse Station	On right bank 1,700 ft upstream from bridge on US Route 22, 0.4 mi NE of Whitehouse Station and 0.8 mile upstream from mouth.	Oct-1986 to present. Stage data back to 1977	12.3	0.05 11/12/1994	572 9/16/1999

USGS ID	Name	Description	Period of Record	Drainage Area Sq. mi.	Minimum Daily Flow (mgd) date	Maximum Daily Flow (mgd) date
01400000	North Branch Raritan River near Raritan, NJ	On right bank, 400 ft upstream from US Highway 202, 1.4 mi upstream from confluence with South Branch and 2.7 mi west of Raritan.	Jun-1923 to present	190	4.9 9/26/1964	9,880 7/7/1984
01400500	Raritan River at Manville, NJ	On left bank at downstream side of bridge on North Main Street (Finderne Avenue) at Manville, and 1.4 mi upstream from Millstone River.	Aug-1921 to present	490	11 9/19/1964	19,800 9/17/1999
01401000	Stony Brook at Princeton, NJ	On right bank 10 ft downstream of bridge on U.S. Highway 206, 1.6 mi southwest of Princeton and 4.0 mi upstream from Carnegie Lake	Oct-1953 to present	44.5	0.0 8/5/1966	2,410 9/16/1999
01401650	Pike Run at Belle Mead, NJ	On right bank 20 feet upstream from bridge on Township Line Road, 0.7 mi east of Belle Mead, 0.8 mi upstream from Cruser Brook, and 1.0 mi downstream from bridge on U.S. Route 206.	Jul-1980 to present	5.36	0.0 8/20/1980	1,030 9/16/1999
01402000	Millstone River at Blackwells Mills	On left bank 30 ft downstream from highway bridge at Blackwells Mills and 0.3 mi downstream from Six Mile Run	Aug-1921 to present	258	3.2 9/16/1923	14,200 9/17/1999
01403060	Raritan River below Calco Dam at Bound Brook, NJ	On right bank 1,000 ft downstream from Calco Dam and Cuckhold Brook, 1,400 ft upstream from bridge on Interstate 287, and 1.2 mi downstream from Millstone River, and 1.2 mi southwest of Bound Brook.	Oct-1944 to present	785	24 9/6/1964	39,400 9/17/1999

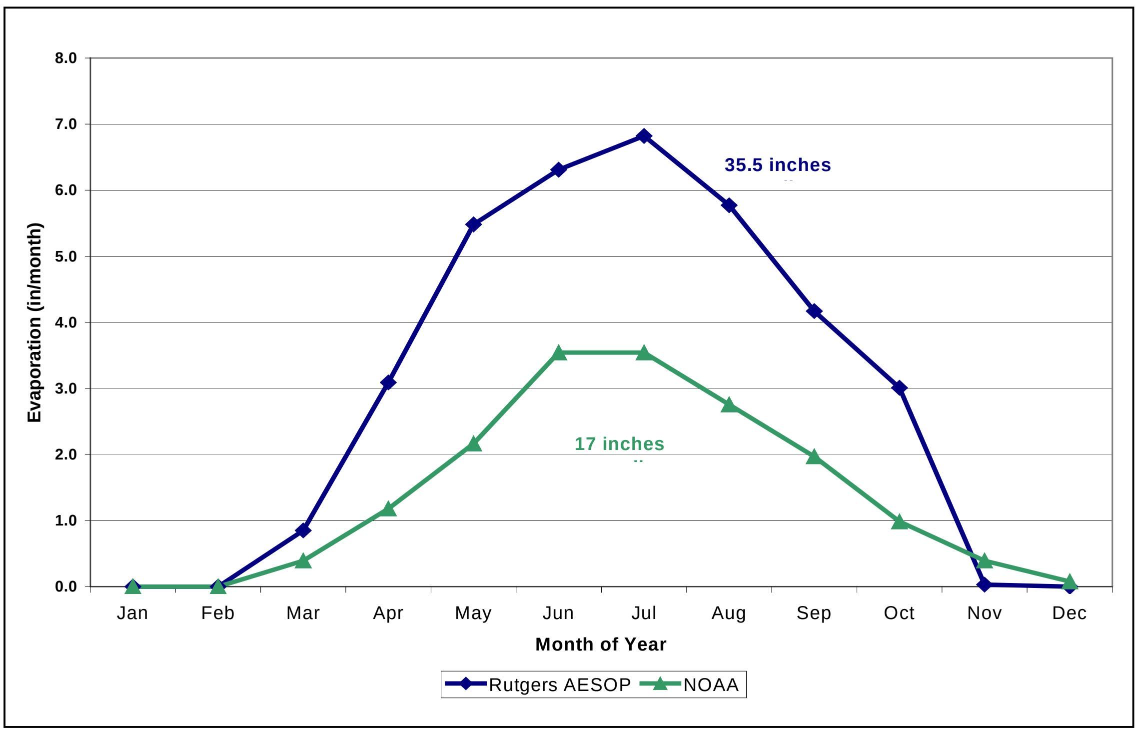
Minimum and maximum flows are based on the daily average flow. Instantaneous peak flows are larger.
Only gauges that record discharge are included.
The Spruce Run at Glen Gardner Gauge 01396580 was moved downstream on September 1, 2005 and renamed 01396582. The minimum flow at 01396580 of 0 mgd was recorded during the period between 8/22/1963 through 3/12/1964, during which period Spruce Run Reservoir was being filled.

2.3 Precipitation and Evaporation

Precipitation and evaporation data are used for balancing volumes in the reservoirs, not for rainfall-runoff calculations. Since good quality streamflow data are available for the basin, rainfall-runoff calculations are not required and would unnecessarily complicate the model. Precipitation averages about 46 inches per year in the Raritan Basin area, based on the full period of record (1895-2002)[28] and about 49 inches per year based on the last 30 years (1971-2002). The State Climatologist maintains a database of precipitation data for many rainfall gauges throughout the State. The nearest station[29] with a continuous and good quality precipitation record was the Flemington station, located in the central western portion of the Basin. Data from the Flemington rainfall gauge were used to estimate the direct contribution of rainfall to the reservoirs. The rainfall contribution to reservoir volume can be significant and counteracts evaporation. For instance, 0.5 inches of rain over the reservoirs adds 18 million gallons of water to Spruce Run Reservoir and 32 million gallons of water to Round Valley Reservoir.

Evaporation causes loss of water from the reservoir surface. Evaporation data for New Jersey were available from two sources: National Oceanic and Atmospheric Administration (NOAA) and Rutgers Cooperative Extension. The NOAA data indicated that evaporation was 17 inches/year. The Rutgers data predicted evaporation of 35.5 inches/year. Figure 4 shows the monthly variation in evaporation for the two data sources.

Figure 4. Monthly Variation in Evaporation



[28] Office of the New Jersey State Climatologist (http://climate.rutgers.edu/stateclim/)
[29] John Parlagreco, Office of the State Climatologist

2.4 Allocations and Demands

An allocation[30] is the amount of water a utility or other entity has reserved "the right" to withdraw from a water source based on NJDEP Water Allocation Permits. A demand is the actual amount of water that is withdrawn by the purveyor or water user. The Authority agrees to provide an amount of water to the water user or purveyor through a contract by releasing water from the reservoirs to maintain streamflow and delivering water via the inter-basin transfer facilitated by the Canal. The contract reflects the average annual amount of water treated and supplied by the water purveyors and is not always equivalent to their water allocation. The purveyors can use more than their contracted amount, but must pay a surcharge on that water. Portions of the safe yield are allocated to different water users to manage the water supply system. Currently, 218 mgd of the estimated 225 mgd of Raritan Basin System safe yield is allocated; however, the contracted amount of water for water treatment, irrigation, and recreational uses is only 184 mgd (82 percent of the established safe yield).

2.4.1 Surface Water Demands

The Raritan Basin System has 5 major surface water purveyors, listed in Table 2. These water purveyors have allocations for 97 percent of the estimated 225 mgd safe yield of the system and represent 98 percent of the water contracted by the Authority. In addition to the five water purveyors, the New Jersey Department of Environmental Protection and the Authority have allocated and contracted an additional 10.5 mgd of the Raritan Basin safe yield for agriculture and irrigation. The largest water purveyor, Elizabethtown Water Company[31], is the only purveyor that uses water from the river system. Elizabethtown Water Company has two water treatment plants, both of which can draw water from either the Canal or the river. The river intakes for both plants are located at the confluence of the Raritan and Millstone Rivers. The other water purveyors, North Brunswick, New Brunswick, East Brunswick, and Middlesex Water Company, withdraw their water from the Canal.

[30] The New Jersey Department of Environmental Protection (NJDEP) assigns water allocations for the rivers. The New Jersey Water Supply Authority holds the allocation permit for the Canal and manages Canal withdrawals for the NJDEP.

[31] The Elizabethtown Water Company, as of December 2005, is in the process of merging with New Jersey American Water Company. For the purposes of this report, the Elizabethtown Water Company will be referred to as such.

Table 2. Water Purveyor Allocations and Demands				
Purveyor	**Allocation (mgd)**	**Contract (mgd)**	**Average Annual Use (mgd)**	**Peak Monthly Use (mgd)**
Elizabethtown Water Company	162 * of which up to 32 can be obtained from the Canal	124	123	182 (Jul-1999)
North Brunswick	8	8	5.7	7.1 (Aug-2001)
New Brunswick	10.5	10.5	9.9	11.7 (Jan –2001)
East Brunswick	8	8	6.8	11.2 (Jul -2003)
Middlesex Water Company	27	27	25.2	36.2 (Jul-1999)
Average Annual and Peak Monthly use based on monthly data from fiscal years 1998-2003 reported to the Authority by the water purveyors (WATREP.xls). *This allocation includes a grandfathered diversion privilege of 2.91 mgd for which Elizabethtown Water Company is not billed (Water Allocation Permit No. 5033, dated March 25, 2003).				

Actual water use data were available for the purveyors for fiscal years 1998 through 2003. Monthly data were available for North Brunswick, New Brunswick, East Brunswick, and Middlesex Water Company. Monthly data from 1980 to the present were available for Elizabethtown Water Company. Daily data also were available for Elizabethtown Water Company for the same period (1997-2003), differentiated by water source (Canal or River).

2.4.2 Variability

Demand for water varies depending on the time of day, the season, the weather, treatment plant operations and even public perception. The NJIT study of the system for hydrologic and economic efficiency investigated the effect of variable demand on system storage and safe yield. The study found that less water was available in storage when variable demand was considered. Since the monthly demand for water is greatest during the period when water is less available (the summer), this result is reasonable and thus appropriate for inclusion in the model.

For the determination of safe yield, water demand is varied monthly, based upon “peaking factors” derived from the available monthly demand data. Although daily data are available for one purveyor, daily data tend to be noisy and dependent upon factors for which data are unlikely to be available. Table 3 presents the monthly demand profiles for each of the five major water purveyors (the Elizabethtown Water Company water treatment plants only withdraw water sporadically from the Canal) to reflect both Canal and river withdrawals. Data used to develop the profiles are contained in Appendix C.

Table 3. Peaking Factors for Demand Estimation in Safe Yield Simulation						
	Sarven /NJIT	Elizabethtown Water Co.	Middlesex Water Co.	East Brunswick	North Brunswick	New Brunswick
January	0.95	0.98	0.92	0.87	0.99	0.84
February	0.89	0.99	0.82	0.79	0.85	0.97
March	0.96	0.98	0.92	0.84	0.89	0.86
April	0.94	0.99	0.89	0.87	0.89	1.03
May	1.05	1.04	1.09	1.04	0.96	1.01
June	1.06	1.08	1.21	1.14	1.02	1.02
July	1.11	1.10	1.29	1.40	1.16	1.07
August	1.08	1.08	1.07	1.19	1.12	1.10
September	1.04	1.00	1.00	1.06	1.06	1.06
October	1.04	0.94	0.97	1.00	1.04	1.06
November	0.94	0.94	0.92	0.89	1.03	0.92
December	0.94	0.95	0.89	0.90	0.98	1.07

Elizabethtown Water Company demand is all allocated to the River (except for periods in the calibration simulations for which Canal water use data were available). Withdrawals from the Canal are discretionary, so no pattern exists for that demand. Based on monthly data from fiscal years 1998-2003 reported to the Authority by the water purveyors.

2.4.3 Ground Water

The movement of ground water into the stream system, known as base flow, affects the safe yield of the Raritan System. Reductions in base flow reduce the safe yield of the system, because the Authority must compensate by releasing additional water from the reservoirs during dry periods. Water allocation permits from the Raritan Basin are based on the system's safe yield, which was calculated using historic base flows. Therefore, NJDEP requires that anyone seeking a water allocation permit that increases their consumptive or depletive withdrawal of ground water must contract with the Authority for that loss of Raritan System stream flows.

Studies by the USGS of well fields in the Drakes Brook portion of the South Branch-Raritan River watershed and the upper Lamington River watershed indicated that 1 mgd of water pumped from these well fields and removed from the watershed causes a 1 mgd reduction in base flow to the river systems. A similar study by USGS in another New Jersey aquifer, the coastal plain system underlying the Toms and Metedeconk Rivers, indicated that increases in the volume of water pumped from the upper aquifer directly reduced the rivers' baseflow by a similar amount, dependent on the proximity of the well field to the streams. Other national studies of shallow aquifer systems indicate a similar impact of depletive and consumptive ground water withdrawals on stream base flow. Therefore, NJDEP uses this relationship as the basis for the requirement that new and increased water allocations within the Raritan System watershed result in contracts with the Authority.

2.5 Return Flows

Wastewater return flows provide flow to the system in addition to streamflows. In the Raritan Basin, only three major wastewater treatment plants discharge downstream[32] of gauges used

[32] Flow from dischargers upstream of monitoring gauges is recorded as part of the monitored flow. Therefore, flows from these plants are not simulated to avoid duplicating that flow volume in the model.

to estimate flows in the system. These plants and their associated flows are presented in Table 4 below. While flows from Clinton Utilities and the Raritan Township MUA have an insignificant effect on the safe yield, the Somerset Raritan Valley Sewerage Authority (SRVSA) discharge is useful in reducing the amount of water that the Authority needs to provide to meet the 90 mgd passing flow at Bound Brook.

Table 4. Wastewater Return Flows	
Wastewater Treatment Plant	**Average Flow (mgd)**
Clinton Utilities	2.03
Raritan Township	2.62
Somerset Raritan Valley Sewage Authority (SRVSA)	14.2
Values taken from NJDPES Permits. Note: SRVSA is permitted to 21.3 mgd and has applied for an increase to 24.3 mgd, but the average monthly flow is only 14.2 mgd (as reported in their NJDPES permit).	

2.6 Operational Rules

The reservoirs are primarily operated to augment flow in the river at the drinking water treatment plant intakes and at the three passing flow gauges (Stanton, Manville, and Bound Brook). The following guidelines summarize the operational protocol currently followed by the Authority.

- Water is released preferentially from Spruce Run Reservoir.
- A minimum reservoir pool elevation of 265 feet (less than 8 feet below the spillway or the full elevation of 273 feet) must be maintained in Spruce Run Reservoir from June 1 through August 31 for recreation purposes.[33]
- When Spruce Run Reservoir cannot meet the required augmentation flow due to recreation or reserve storage constraints, releases are made from Round Valley Reservoir.
- If the passing flow at Stanton cannot be met with releases from Spruce Run Reservoir (when storage is being reserved), releases are made from Round Valley Reservoir through the alternate release. When the alternate release can no longer be used, Spruce Run Reservoir releases flows only to maintain Stanton.
- Water is pumped into Round Valley only when no releases are being made from either reservoir and when there is sufficient volume in Round Valley to store the water.
- When Round Valley fills to above design capacity (target storage), resulting from precipitation contributions, releases are made until reservoir is slightly less than the design capacity (target drawdown storage).
- Drought is defined by a required combined storage of the reservoirs that varies by month.
- Excess Canal flows up to 30 mgd are released to the river through Ten Mile Release Gate.
- Water from the Raritan River can be pumped into the Canal to meet demands.

Since the safe yield of the system is not fully contracted, these protocols are based on a contract base of 184 mgd and reflect the most economically efficient operations rather than those that might maximize the safe yield.

[33] N.J.S.A. 58:22-8c.

2.7 Failure Indices

The safe yield is exceeded when the demand from the system can no longer be met. This occurs when the reservoir storage is below the non-usable storage (also know as “dead pool”) in the reservoir. For the purposes of this study, the “dead pool” for each reservoir was defined at 10 percent full. When the storage is depleted, the non-natural systems can no longer augment the streamflows to meet the demand. Therefore, depletion of the reservoirs to 10 percent full was used as the indicator of the failure to meet demand. This indicator of failure also was used for previous modeling efforts.

3.0 MODEL DEVELOPMENT

Data for model development and calibration were available for water years 1994 through 2003 (October 1, 1993 through September 30, 2003). While the system has been operated for almost forty years, only the most recent (1990 – present) observed information for the reservoirs is in digital format. For this period, staff has recorded reservoir elevations and release amounts in addition to Canal flows. The period (water years 1994-2003) is representative of typical operations and includes both wet and dry years. The record contains four periods of significant drawdown for Spruce Run and two for Round Valley. Both reservoirs have a multi-year drawdown event.

3.1 Spruce Run Reservoir

The Spruce Run and Mulhockaway Creek drain about 40 square miles and feed Spruce Run Reservoir. All water from this drainage area must pass through the reservoir, which holds 11 billion gallons (BG) of water and has a full surface area of about 1,350 acres. Figure 5 presents the elevation-volume and elevation-surface area relationships for Spruce Run Reservoir. Since elevation is readily observed, these relationships are used to determine the volume (storage) and surface area, which are not readily measured. Spruce Run Reservoir has a mandated minimum release of 5 mgd and a maximum release of 180 mgd. The reservoir can release the full 180 mgd at 10 percent full (1.1 billion gallons, elevation 230.6 feet). Releases are made to the Spruce Run. The reservoir has an overflow spillway, 550 feet long, with its crest at elevation 273 feet.

Figure 5. Elevation-Volume and Elevation-Surface Area Relationships for Spruce Run Reservoir

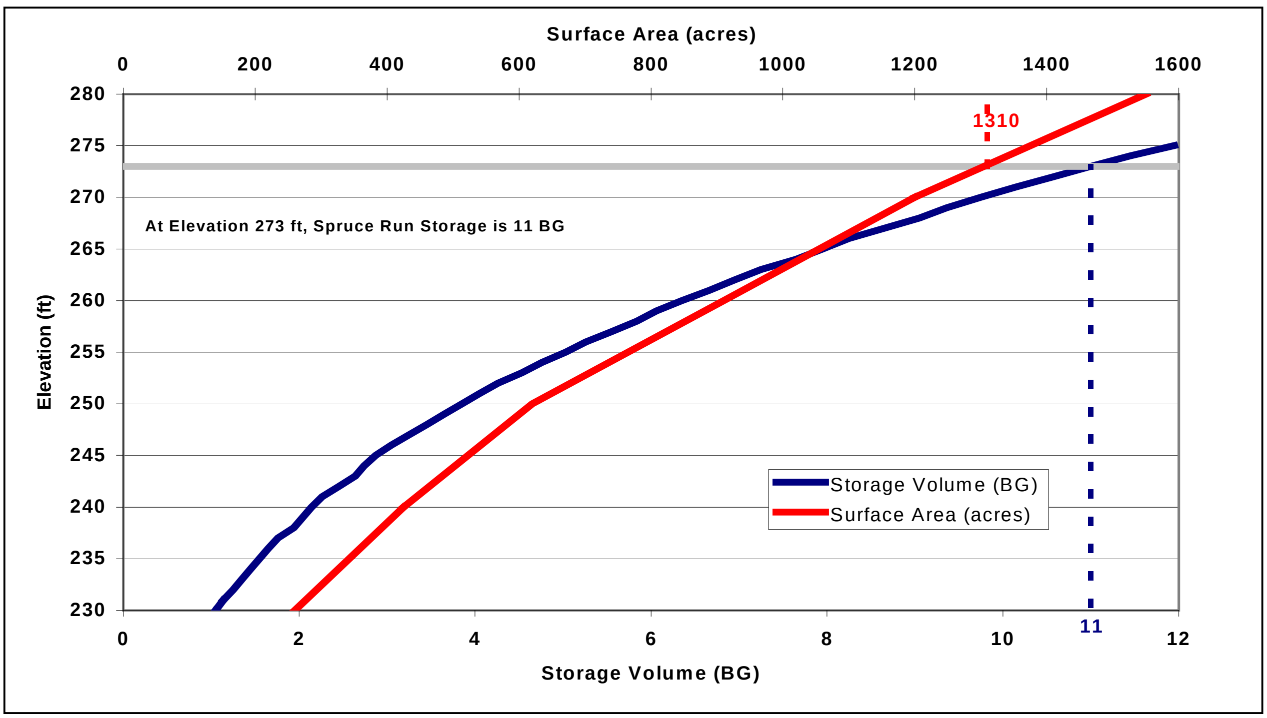
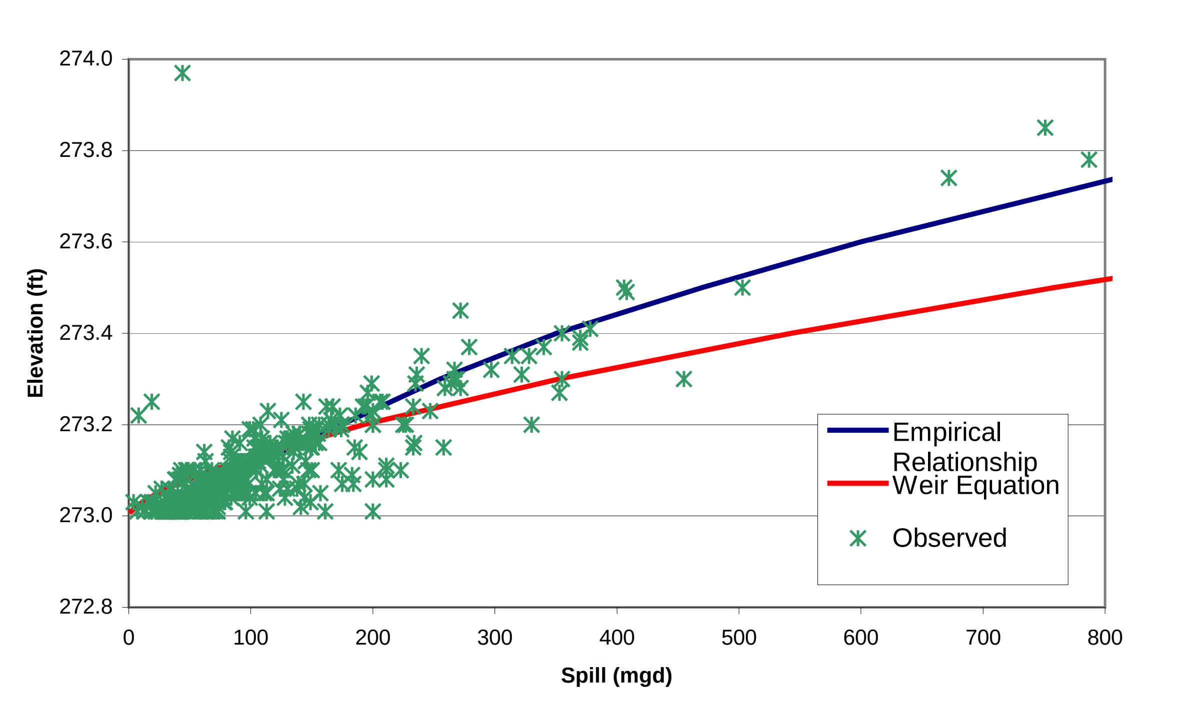


Figure 6 presents the equation used to estimate flow over the spillway. This equation is based on an empirical relationship derived from observed data and is not consistent with the weir equation. This difference is likely due to the wind effects that push additional water over the spillway. Spill from the reservoir joins Spruce Run just upstream of the USGS gauge on the Spruce Run in Clinton. Water is preferentially released from Spruce Run Reservoir, rather than from Round Valley Reservoir, to augment flow at any of the passing flow gauges. In the summer, unless there is a drought, the reservoir must be maintained at a specific elevation/volume to facilitate recreation as mandated by N.J.S.A. 58:22-8. Of note, the reservoir can release about 30 mgd daily over the summer (if full on June 1) and still maintain recreation, based on ideal drawdown. Occasionally, water is released from Spruce Run to inhibit ice jams in the river. The water is released to maintain higher flows in the river and raise the water surface elevation. The additional water released to the river prevents ice from blocking the flow by raising the water surface elevation.

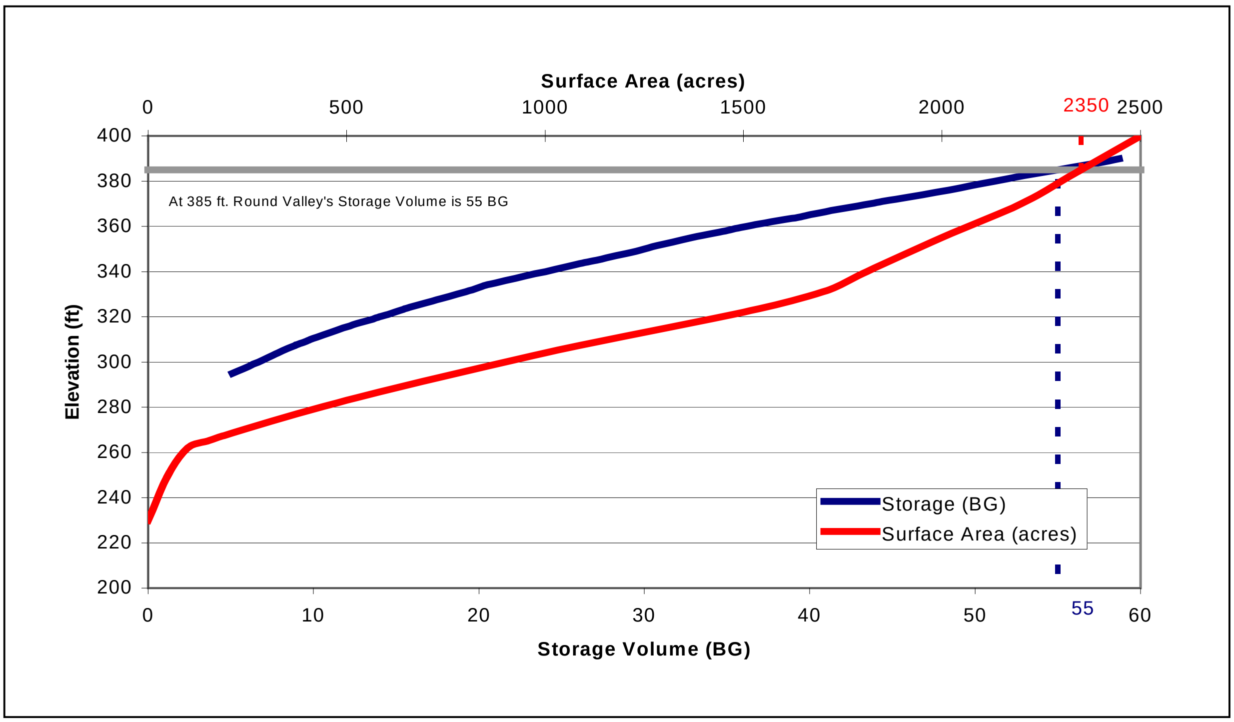
Figure 6. Relationship for Estimating Flow over Spruce Run Reservoir Spillway



3.2 Round Valley Reservoir

Unlike Spruce Run Reservoir, Round Valley Reservoir is an off-line pumped storage reservoir. The reservoir can store 55 BG of water with a maximum surface area of 2,350 acres. Figure 7 presents the elevation volume and elevation surface area relationships for Round Valley. Except for runoff from its small natural drainage area (approximately 5.6 square miles, 2.1 square miles land surface and 3.5 square miles reservoir surface), the reservoir only receives water through the South Branch Pumping Station from the South Branch of the Raritan River. The reservoir has two mandatory releases of 0.83 mgd to the Prescott Brook and 0.17 mgd to the South Branch Rockaway Creek. Seepage is collected from the base of the reservoir for these releases. Major releases are made from the North Tower to the South Branch of the Rockaway Creek in Whitehouse, NJ. The reservoir can release the full 350 mgd at 10 percent full (5.5 billion gallons, elevation 296 feet). If the elevation of the Reservoir is above 340 feet, releases of up to 120 mgd also can be made from the South Tower through the force main from South Branch Pumping Station. The reservoir has no spillway, since the contributing drainage area is small. Infrequently, releases are made to drawdown the reservoir when excess rainfall adds water to an already full or near-full reservoir.

Figure 7. Elevation-Volume and Elevation Surface Area Relationships for Round Valley Reservoir



3.3 Delaware and Raritan Canal

The Delaware and Raritan Canal diverts water from the Delaware River at Raven Rock to the Raritan Basin. The Canal consists of a Feeder Canal and the main Canal and is approximately 60 miles in length. The Canal can transfer 100 mgd, 70 mgd, and 65 mgd, during normal operations, drought warning and drought emergency status, respectively. This flow is measured at Port Mercer, approximately 29 miles from the Delaware River diversion. Travel times through the Canal range from 8 days at 65 mgd to 5 days at 100 mgd. Between Port Mercer and its terminus, the Canal is approximately 80 feet wide by 8 feet deep. Storage in the Canal between Port Mercer and its terminus is roughly 0.56 BG.

Purveyor intakes are located at accumulated miles from the Delaware River as follows: North Brunswick 42.9, Elizabethtown Water Company 49.2, New Brunswick 58.5, and Middlesex Water Company and East Brunswick 58.5. Average demands from the Canal based on current water use data are about 48 mgd, peaking at about 66 mgd. Under normal operations (100 mgd), about 30 mgd is discharged to the Raritan River through the release gate at Ten Mile Lock, rather than through the Canal terminus in New Brunswick. Releasing flow to the river at this location rather than the Canal terminus reduces the augmentation flow requirements from the reservoirs to meet both Elizabethtown Water Company demands and minimum passing flows at Bound Brook. Up to 60 mgd can be pumped from the River into the Canal through the pumping station, also located at Ten Mile Lock.

For the calibration period (1993-2003), the Authority has observed flow data at Port Mercer and through the Ten Mile waste gate. The pumping station was not used during this period. Data collected at Port Mercer by both the Authority and the USGS are only rated "fair." To the extent possible the recorded data were used, but for instances when the data did not agree with other observed information, the record was adjusted to better match observed conditions. For the safe yield simulations, the Delaware River Basin Commission provided Delaware River System Drought Status from their operations model.

3.4 Rivers

The travel time effects and losses (infiltration) or gains (exfiltration) between the reservoirs and minimum passing flow gauges were somewhat exhibited in the flow record. To evaluate this, the use of flow routing and gain/loss methods were investigated at the South Branch Raritan River above Stanton and the South Branch Raritan River above the confluence with the North Branch Raritan River (below the South Branch confluence with the Neshanic River). Table 5 presents the travel times estimated for the system and used to time releases based on the amounts of water usually released for flow. However, modeling travel time did not improve the results, so storage routing was not used.

Table 5. Observed Travel Times in the System for Usual Augmentation Releases			
From:	**To:**	**Time (hours)**	**Distance (miles)**
Spruce Run	Stanton Gauge	6	8
Spruce Run	Bound Brook Gauge	24	34
Round Valley – Whitehouse Release	Bound Brook (via the South Branch Rockaway Creek	18	23
Round Valley – Alternate Release	Bound Brook (via the South Branch Raritan)	20	26
Round Valley – Alternate Release	Stanton Gauge	2	4

Losses were simulated using an empirical, seasonal, flow-dependent methodology. The methodology is configured so that losses increase from August through October, as generally observed in the flow data. Gains were not simulated because they did not significantly improve the simulation.

3.5 Demands

Water demands and allocations were previously discussed in Section 2.3. For the Canal purveyors (North Brunswick, East Brunswick, New Brunswick and Middlesex Water Company), monthly water use data were available for fiscal years 1998 – present and used to represent the demand in the model. Prior to that, the demand for Canal purveyors was calculated as the monthly demand pattern times contract amount for each water purveyor. For Elizabethtown Water Company, monthly water use data were available from 1980 – 2003. Daily data were available beginning in 1997. For periods prior to 1997, actual monthly data were used to represent the demand. Daily data were used for the remainder of the calibration period. For the safe yield analysis, monthly demand pattern data (Table 3) were used for all purveyor demands.

3.6 Minimum Passing Flows

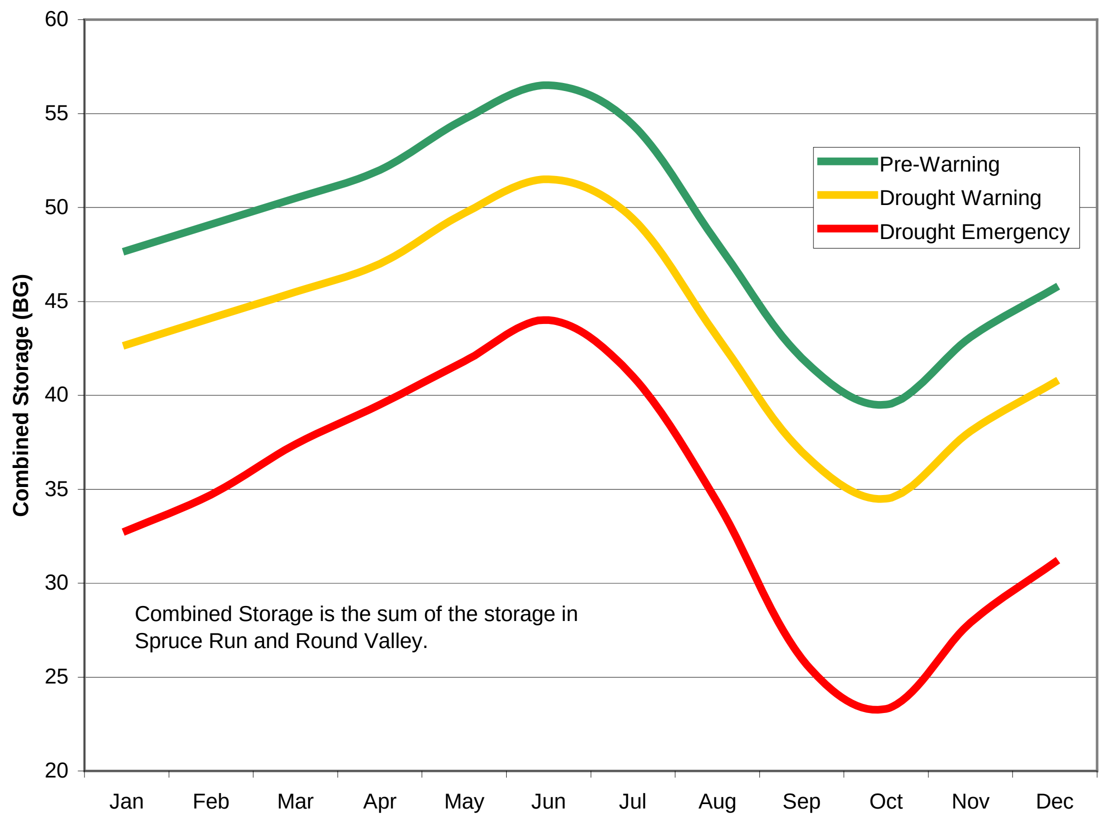
In addition to meeting purveyor demands, the Authority is required, by statute (N.J.S.A 58:22-8), to release flow from the reservoirs to meet minimum passing flows at three locations: Stanton (40 mgd), Manville (70 mgd), and Bound Brook (90 mgd). To meet the passing flow at Bound Brook, the Authority must consider the Elizabethtown Water Company withdrawals and return flows from the Somerset Raritan Valley Sewerage Authority (SRVSA) above the Bound Brook gauge. During the drought of 2001, the NJDEP reduced the minimum passing flows to 30 mgd at Stanton and 70 mgd at Bound Brook, which was modeled in the calibration simulations. Future reductions during drought declarations are not guaranteed and were not simulated for the safe yield analysis.

3.7 Drought Declarations

Based on a position analysis study by the Authority, the Raritan Basin has a combined storage curve to define drought conditions in the Raritan Basin. Figure 8 presents this curve.

For the purposes of the simulation, drought management measures are initiated at drought warning, not at full drought.

Figure 8. Combined Storage Levels that Define the Drought Status of the Raritan Basin Reservoir System



3.8 Operational Rules

The reservoirs are primarily operated to augment flow in the river at the drinking water treatment plant intakes and the three passing flow gauges (Stanton, Manville, and Bound Brook). Actions (or operations) of the system include the following:

- Release from Spruce Run Reservoir;
- Release from Round Valley Reservoir to the South Branch Rockaway Creek via Whitehouse;
- Release from Round Valley Reservoir through the Alternate Release through the South Branch Pump Station upstream of Stanton;
- Pump to Round Valley Reservoir through the South Branch Pumping Station;
- Release from the Canal through the release gate at Ten Mile Lock; and
- Pump to the Canal through Ten Mile Pump Station (rare).

These actions occur when certain system conditions are met. Such conditions include:

- Ice jam formation on the rivers;
- Streamflow less than:
    - 40 mgd at Stanton
    - 70 mgd at Manville
    - 90 mgd at Bound Brook;
- Demand at river intakes greater than streamflow;
- Demand at Canal intakes greater than Canal inflows;
- Demand from Canal intakes less than Canal inflows;
- Water available for pumping when Round Valley Reservoir has available storage; and
- Round Valley fills to greater than design capacity.

The following guidelines, repeated from Section 2.6, summarize the operational protocol currently followed by the Authority.

- Water is released preferentially from Spruce Run Reservoir.
- A minimum reservoir pool elevation of 265 feet (less than 8 feet below the spillway or the full elevation of 273 feet) must be maintained in Spruce Run Reservoir from June 1 through August 31 for recreation purposes.[34]
- When Spruce Run Reservoir cannot meet the required augmentation flow due to recreation or reserve storage constraints, releases are made from Round Valley Reservoir.
- If the passing flow at Stanton cannot be met with releases from Spruce Run Reservoir (when storage is being reserved), releases are made from Round Valley Reservoir through the alternate release. When the alternate release can no longer be used, Spruce Run Reservoir releases flows only to maintain Stanton.
- Water is pumped into Round Valley only when no releases are being made from either reservoir and when there is sufficient volume in Round Valley to store the water.
- When Round Valley fills to above design capacity (target storage), resulting from precipitation contributions, releases are made until reservoir is slightly less than the design capacity (target drawdown storage).
- Drought is defined by a required combined storage of the reservoirs that varies by month.
- Excess Canal flows up to 30 mgd are released to the river through Ten Mile Release Gate.

Water from the Raritan River can be pumped into the Canal to meet demands.
Since the safe yield of the system is not fully contracted, these protocols reflect the most cost-effective operations rather than those that would maximize the safe yield. Additional operational protocols that were needed for evaluation of the safe yield included the following:

[34] N.J.S.A. 58:22-8c.

- When Round Valley Reservoir storage is less than 24 BG (Spruce Run Reservoir storage will usually be around or below 3.75 BG[35]), release from Spruce Run Reservoir to meet Stanton ONLY, since the alternate release from Round Valley Reservoir cannot be used (release amounts are governed by head and friction losses).
- When Round Valley Reservoir storage is less than 8.15 BG (Spruce Run Reservoir storage will usually be around or below 3.75 BG, so both contain about 2.65 BG above "dead pool"), release half of the required augmentation flow from each reservoir. (When both reservoirs are low, this effects tandem drawdown so both reservoirs "fail" simultaneously. For example, Round Valley will not contain 7 BG when Spruce Run Reservoir fails at 1.1 BG).
- When a drought watch is declared for the Raritan Basin and the reservoirs are not releasing, pump all available flow into Round Valley Reservoir. (Available flow is flow greater than the required minimum passing flows and demands from water purveyors).

These protocols were needed to represent operation of the system, not observed during the calibration period (operations when reservoirs are close to failure). Figure 9 presents a flow diagram that outlines the process for the determination of releases from the reservoirs.
In RiverWare, operational policy is implemented based upon a priority assigned to a rule by the model developer. The rules are then ordered by importance or value to system operations. The model "implements" actions, based on their priority in the rule set, similar to how any operator would manage the system. Conditions can be included in an individual rule that nullifies the intended action. The model executes the rule set such that if one action changes the conditions used by a lower priority rule to initiate another action, rules of lower priority may be re-evaluated. A detailed explanation of RiverWare's rule-based simulation logic is outside the scope of this report. For more detailed information, refer to http://cadswes.colorado.edu/riverware/.

[35] Reserve Storage

4.0 MODEL CALIBRATION

Model calibration is the process of estimating the unknown or unmeasurable phenomena of the system and then assessing how well those estimates, along with known system measurements, simulate observed events. Such phenomena include, but are not limited to: precipitation and evaporation (spatial variability, limited data), seepage, bank storage, and channel storage. Observed data are needed to form the foundation of the model.

Both determinate and indeterminate versions of the model were developed to assess how well estimated data and RiverWare simulate the Raritan Basin System. A determinate model is used to assess how well estimated data predict observed system status. The indeterminate model assesses how well the rules can predict actual operations.

4.1 Determinate Model

For model calibration, a determinate model was developed. In a determinate model, most information about the system is known. For water years 1993-2003, the majority of data about the system were known. Specifically available were:

- System Inputs (sources):
  - Precipitation data at a local gauge (Flemington);
  - Streamflows (at regulated and unregulated gauges);
  - Pumped Flow (from the South Branch Raritan into Round Valley Reservoir);
- System Outputs (demands/losses):
  - Releases (Spruce Run Reservoir, Round Valley Reservoir Main and Alternate Releases);
  - Evaporation (estimated from Rutgers data);
  - Round Valley Reservoir Seepage (measured);
  - Purveyor Demands (monthly and daily);
- System Status:
  - Streamflows at minimum passing flow gauges;
  - Reservoir Pool Elevations (storage).

By evaluating and adjusting assumptions and estimated information (predictors of unmeasureable phenomena) such that the model best simulates observed conditions, the developer calibrates the model. For instance, two estimates of evaporation data were collected for this study. Data from Rutgers were found to produce the best results during model calibration. For the determinate model, reservoir pool elevations (storage) were assumed unknown. Then, the developer compared the observed and simulated storage and streamflows to assess the calibration.

Figure 10 presents the comparison of observed vs. simulated storage for the determinate model simulation. The model reasonably predicts the storage of both reservoirs and the flows at the minimum passing flow gauges. Comparison of observed versus simulated indicates that the model slightly under predicts flow at the gauges, which signifies that the model is conservative. Through the calibration process, the following were determined:

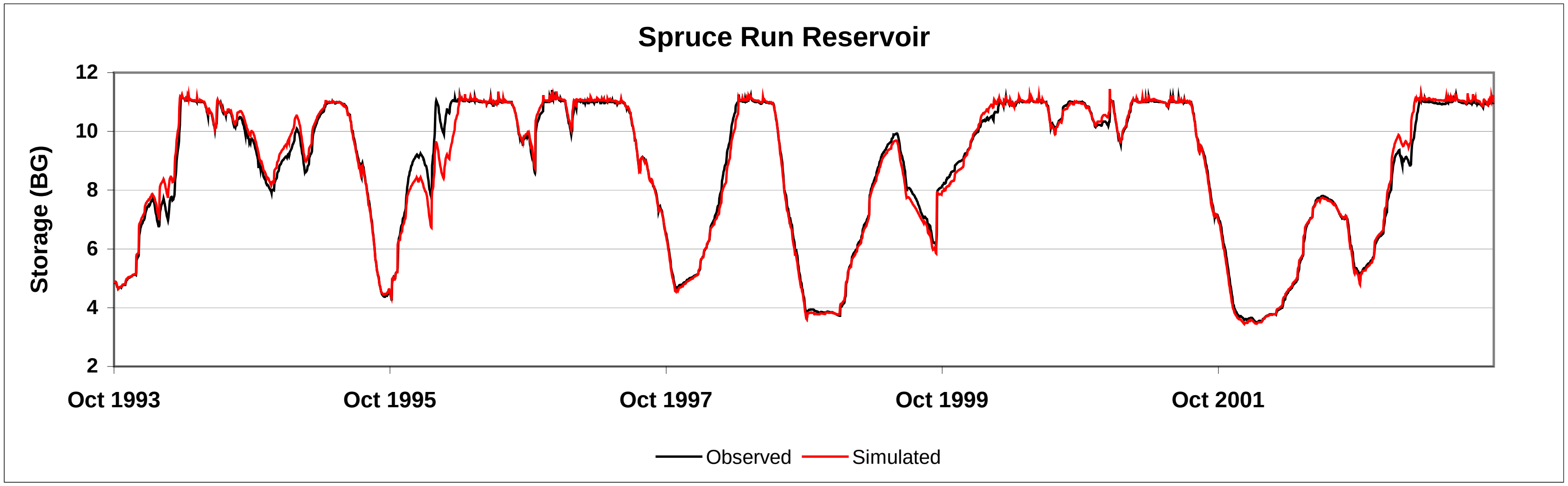
- Using drainage area weighting to obtain flows for ungauged drainage areas and using the MOVE.1 technique to fill missing data periods was effective at capturing the essence of flows within the basin.
- Evaporation data (35.5 inches per year) from Rutgers's Cooperative Extension adequately mimic evaporation on both reservoirs.
- The Flemington rainfall gauge adequately represented the over-reservoir precipitation.
- Spruce Run Reservoir noticeably benefits from bank storage return flows during periods of low pool elevation (storage), whereas Round Valley Reservoir does not.
- Variable lag time in the rivers was not simulated.
- Losses in the River system due to channel storage, evaporation, and other phenomena were simulated as seasonal, flow-dependent losses for the months of August through October. Losses were estimated during the calibration process based on evaluation of streamflow data.

Figures 11-14 present a comparison of simulated versus observed flows at the minimum passing flow gauges. Although the data are scattered about the 1:1 line, the plots (Figures 12-14) indicate strong relationships between observed and simulated values. The flows are generally within the uncertainty associated with flow monitoring data, which is generally estimated as +/-10 percent[36] and greater for low flows[37]. Although significant differences do exist, they are likely the result of spatial differences in rainfall and travel time.

[36] An examination of residuals in the low flow regime (less than 100 mgd at Stanton and 150 mgd at Bound Brook), more than 85% of the residuals were within 25% of the observed value. At Bound Brook, about 72% of the residuals were within 25% of the observed value. Since the error tolerance in flow monitoring tends to be greater for low flows, these residuals were deemed reasonable.

[37] At the Bound Brook Gauge at 90 mgd, a change in stage of 0.01 ft can result in a change in flow of roughly 4 mgd.

Figure 10. Determinate Model: Observed vs. Simulated Reservoir Storage



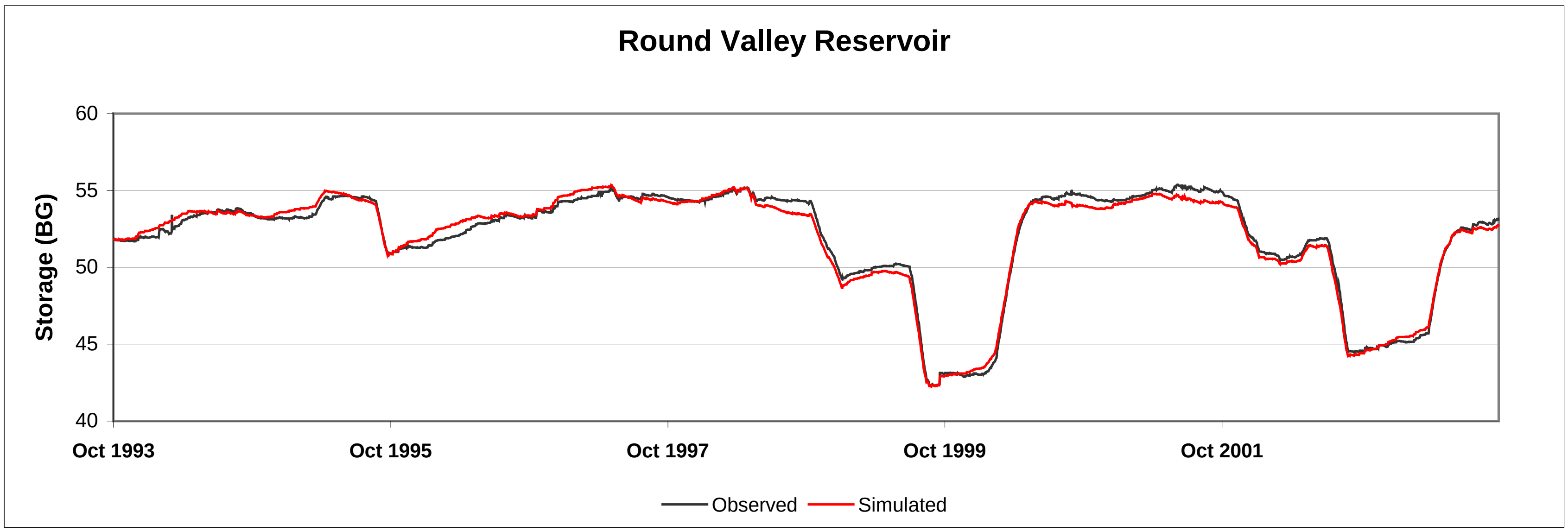


Figure 11. Determinate Model: Example Time Series at Minimum Passing Flow Gauges

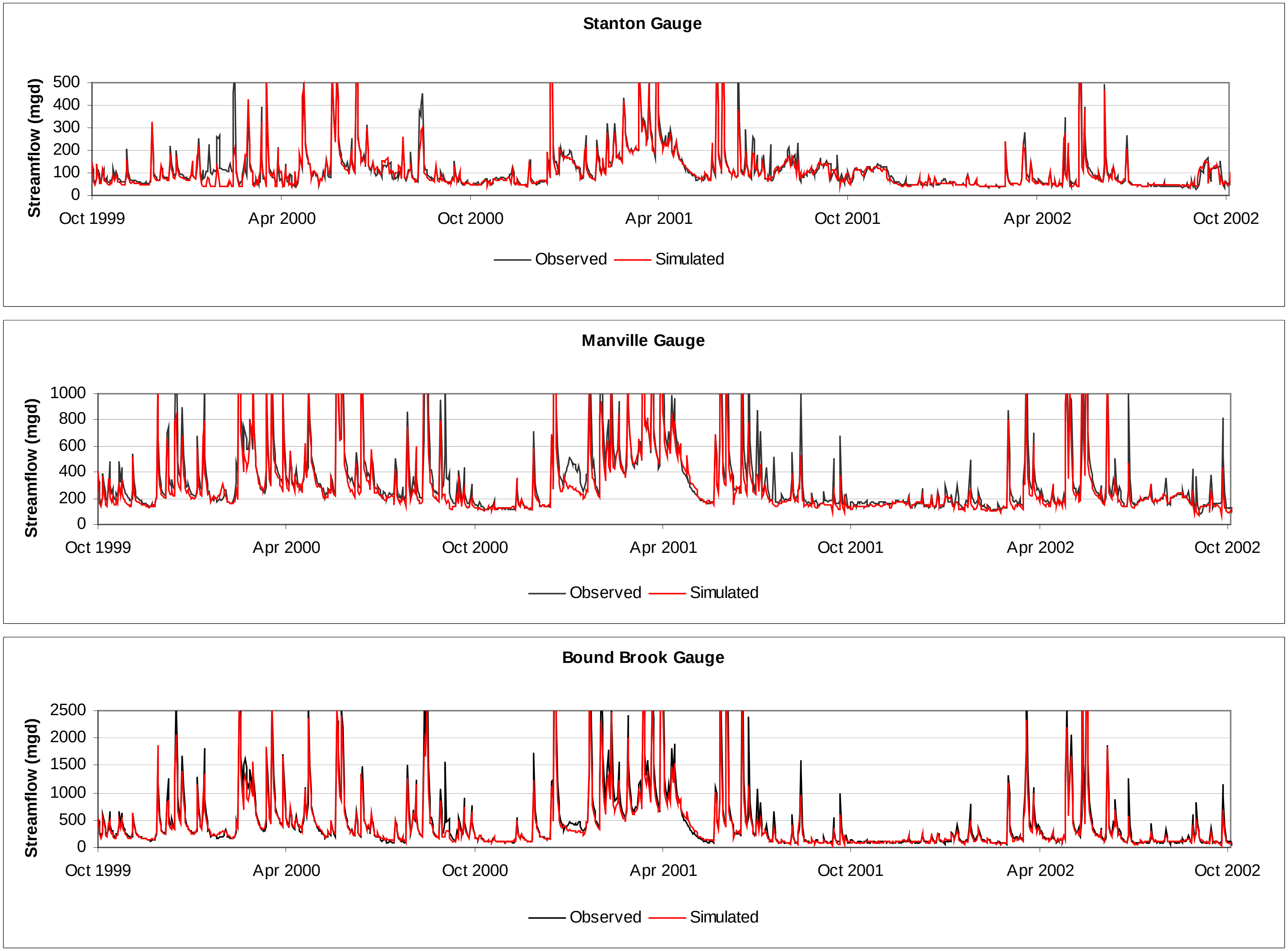


Figure 12. Determinate Model: Observed vs. Simulated Flow at the Stanton Gauge (USGS 0137000)

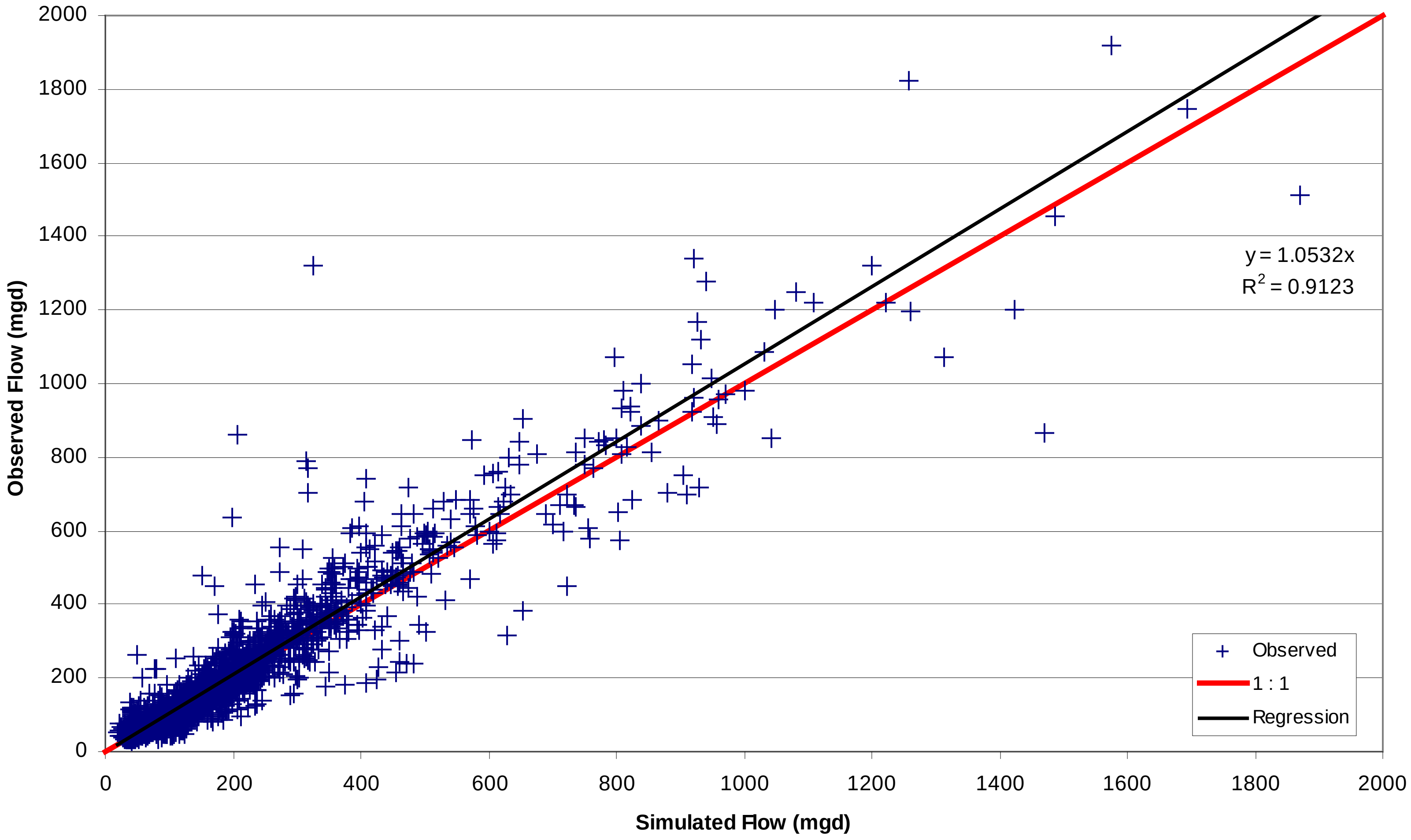


Figure 13. Determinate Model: Observed vs. Simulated at the Manville Gauge (USGS 01400500)

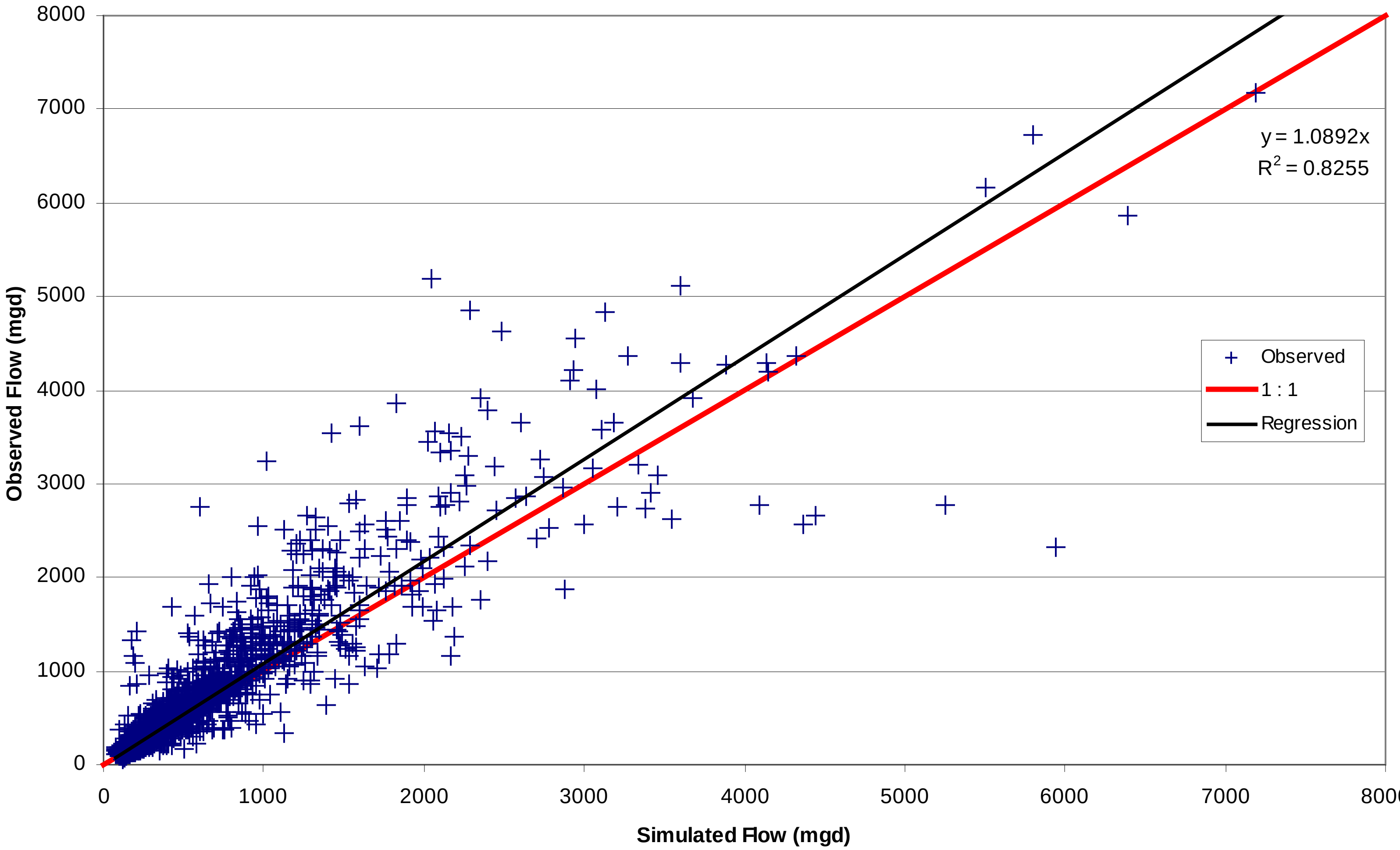
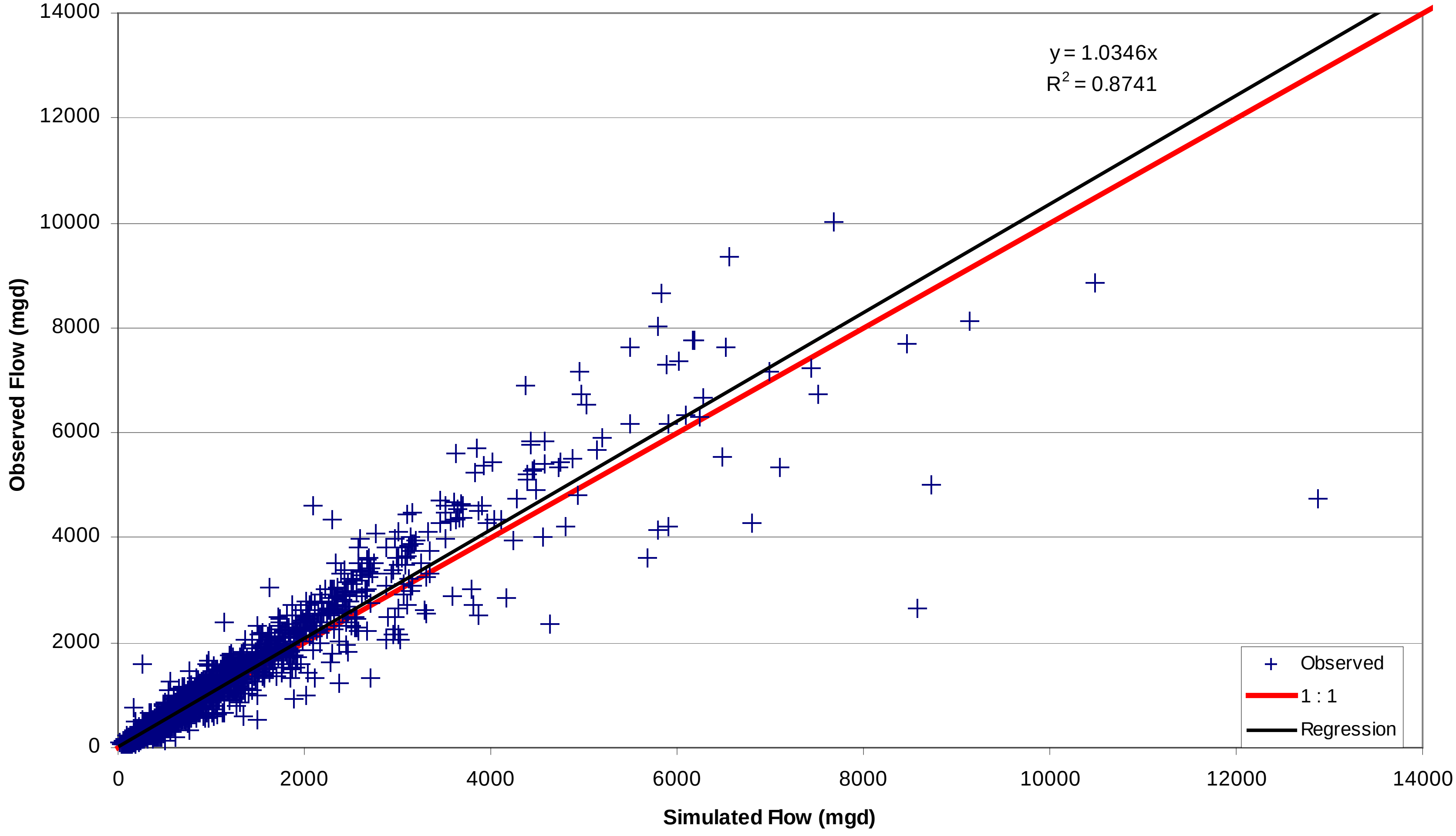


Figure 14. Determinate Model: Observed vs. Simulated Flow at Bound Brook Gauge (USGS 01403060)



4.2 Indeterminate Model

An indeterminate model was developed to assess how well the rules reflect operations policy. Policies (operations protocols) are used to determine the system actions, specifically, the releases from and pumping to the reservoirs. The operations policy of the Raritan Basin System was presented previously as a decision flow chart in Figure 9. This policy represents the operations discussed in Sections 2.4 and 3.7. There are some caveats to the operations policy, which reflect operator discretion, equipment testing and regular and non-regular maintenance, which cannot readily be incorporated into the model.

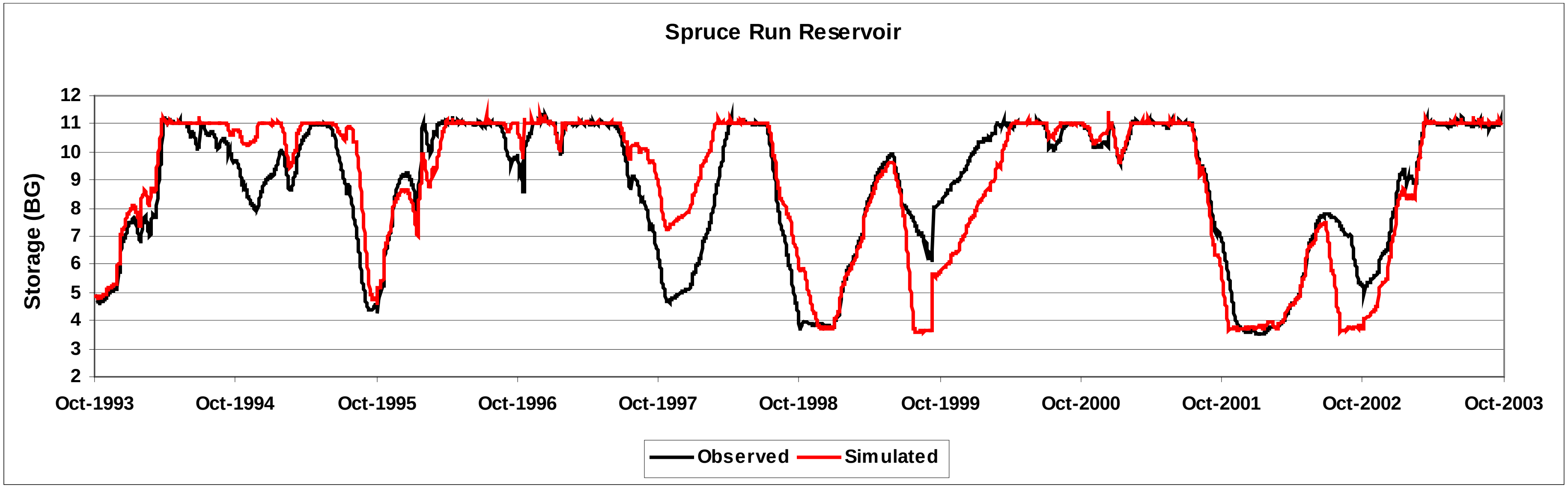
Figure 15 presents the simulation of the system from 1993-2003 under standard operations policy. As the figure indicates, operations of the system during this period of time deviated from that of policy. This is to be expected since the Authority strives for current operations to be economically efficient rather than hydrologically efficient. Since the system is not fully contracted, the Authority operates the system to minimize costs and protect other uses (recreation) rather than maximize the hydrologic benefits of the system. However, the operational rules do mimic observed conditions in that the reservoirs' behaviors are similar (drawdown/refill cycles).

Representative operating rules were created to better simulate the operations during 1993 – 2003. Representative rules reflect operations to protect the force main in 1999 and 2002 and changes in the minimum passing flows during the declared drought (combined storage did not indicate drought, but passing flows were reduced). In 1999, an inspection of the force main indicated that a section of pipe needed replacement. For protection of the force main, releases from Spruce Run Reservoir were reduced to augment Stanton only. Round Valley Reservoir provided the remainder of the augmentation. Storage was maintained in Spruce Run Reservoir in the event that water could not be pumped to Round Valley Reservoir during repairs. The pipe section was repaired in the winter of 2003.

Figures 16-20 present the indeterminate model simulation with the representative operating rules. The model reasonably predicts the storage of both reservoirs (Figure 16) and the flows at the minimum passing flow gauges (Figure 17). Comparison of observed versus simulated indicates that the model slightly under predicts flow at the gauges, which signifies that the model is conservative. Through the calibration process of the indeterminate model, the following additional conclusions were determined:

Rules operate as expected but do not replicate observed conditions due to operator discretion and system maintenance. Additional rules that reflected discretionary or temporary operations can be used to adequately simulate the observed conditions.

Figure 15. Indeterminate Model with Standard Operating Rules: Observed vs. Simulated Reservoir Storage



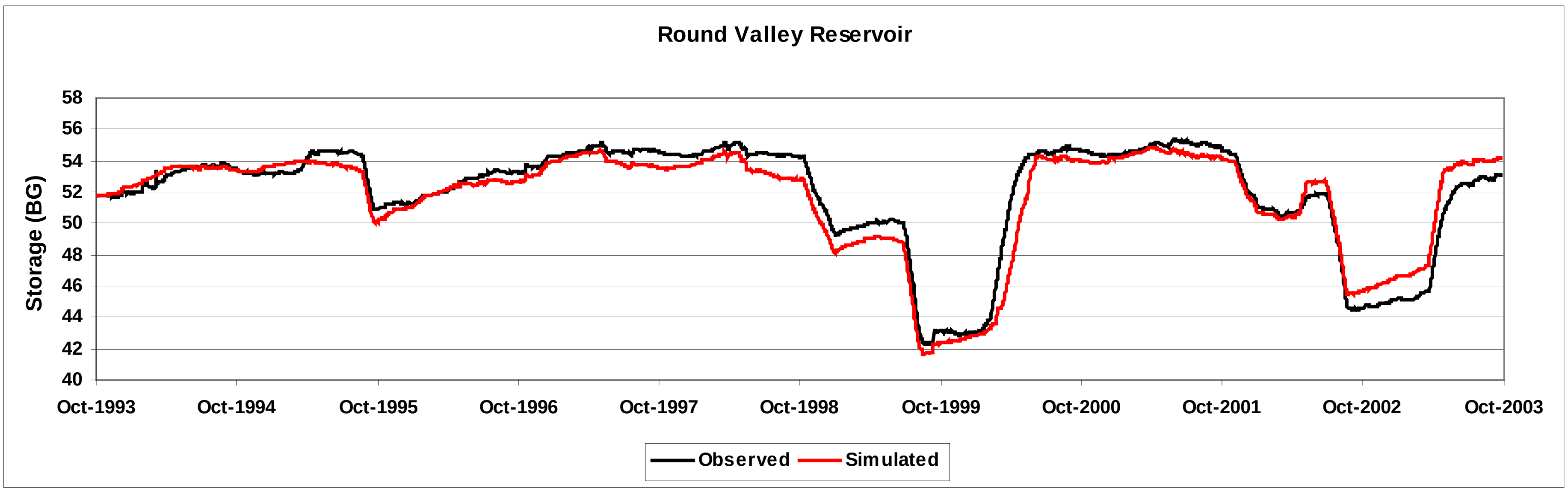
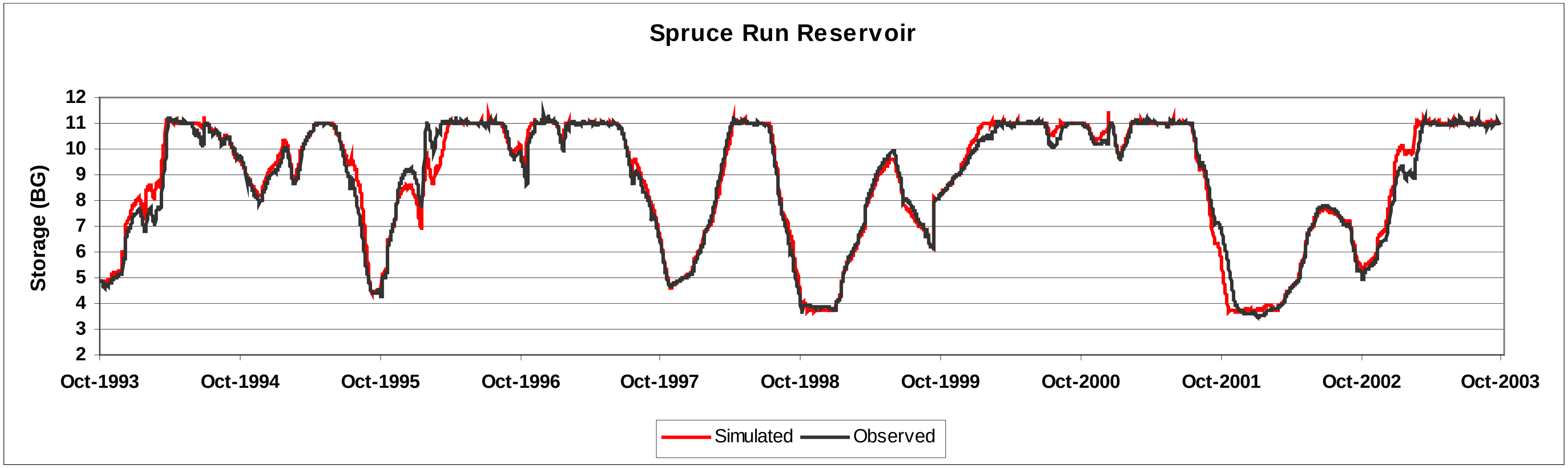


Figure 16. Indeterminate Model with Representative Operating Rules: Observed vs. Simulated Storage



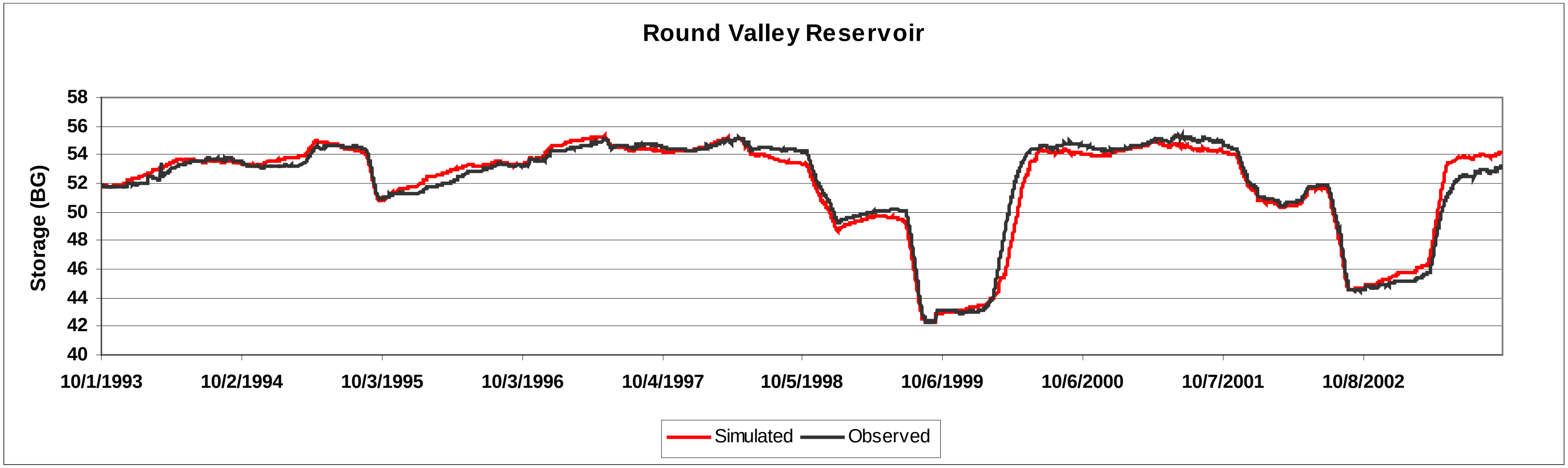
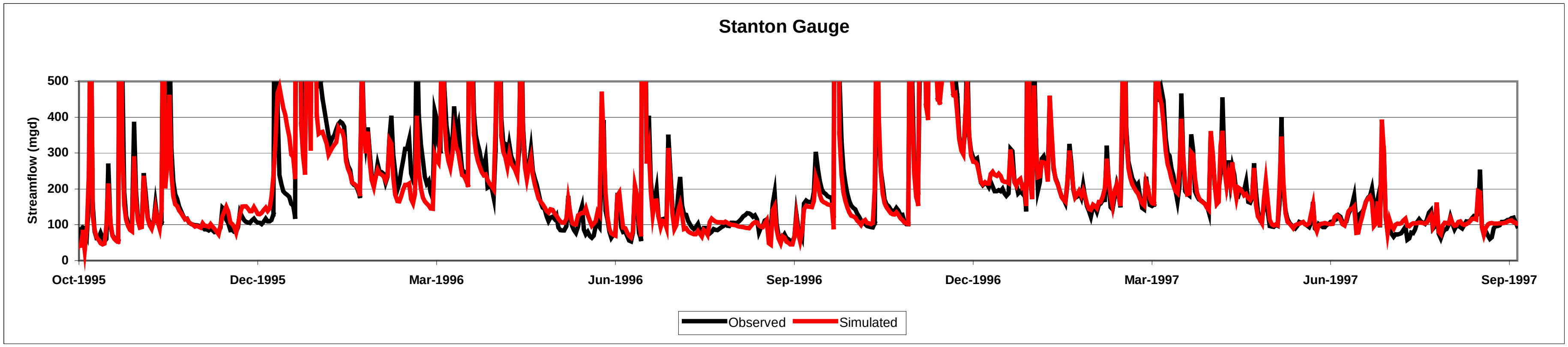
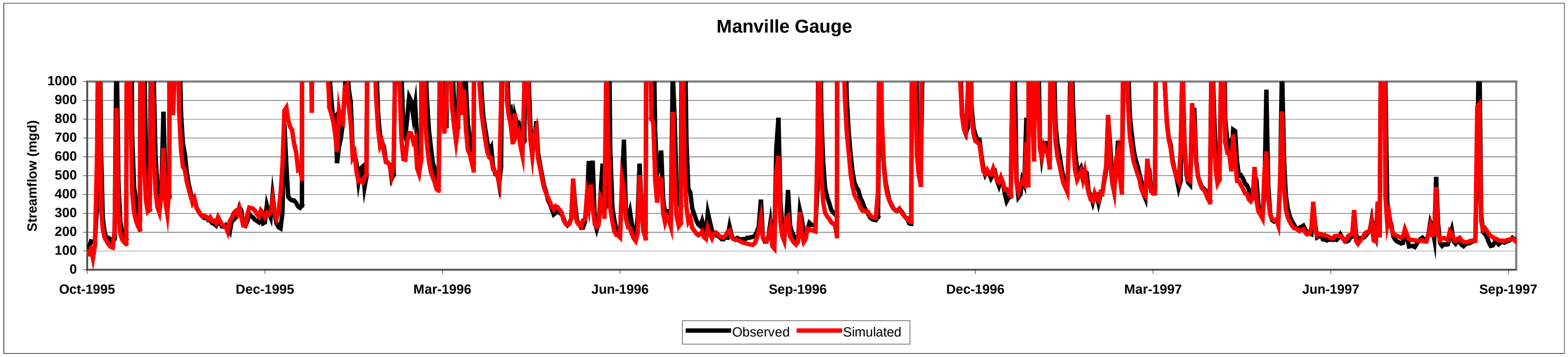


Figure 17. Indeterminate Model with Representative Operating Rules: Example Time Series at Minimum Passing Flow Gauges





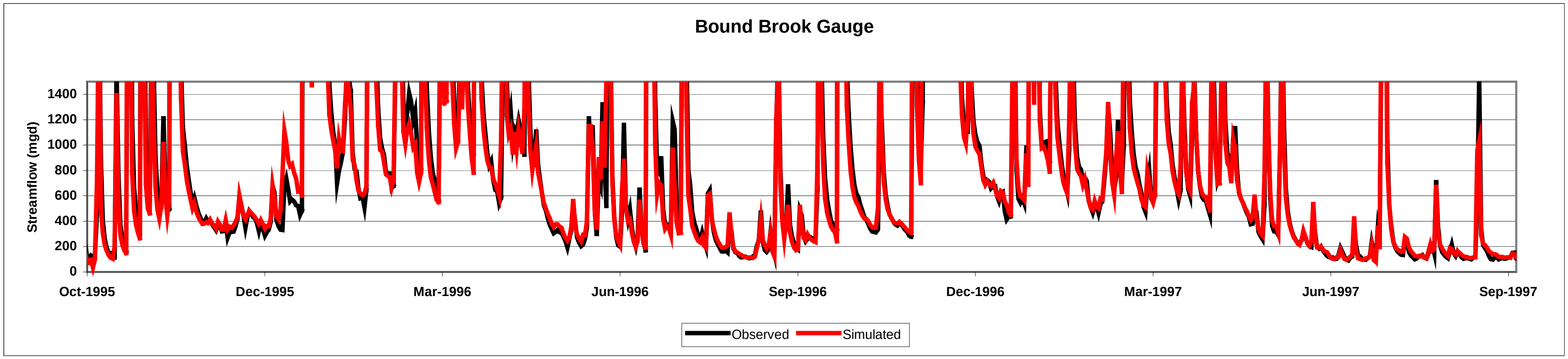


Figure 18. Indeterminate Model with Representative Operations: Observed vs. Simulated at the Stanton Gauge

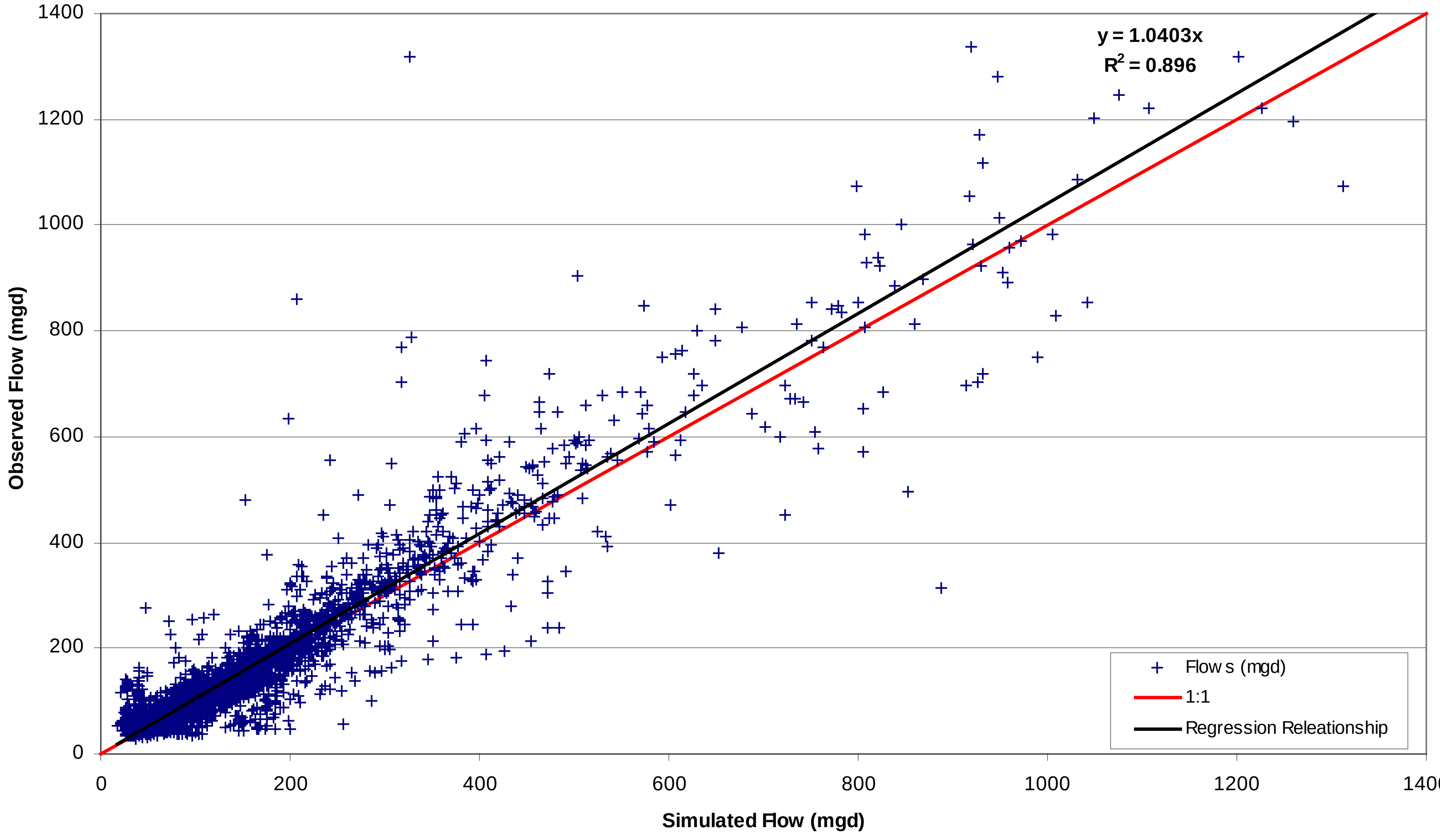


Figure 19. Indeterminate Model with Representative Operations: Observed vs. Simulated Flows at the Manville Gauge

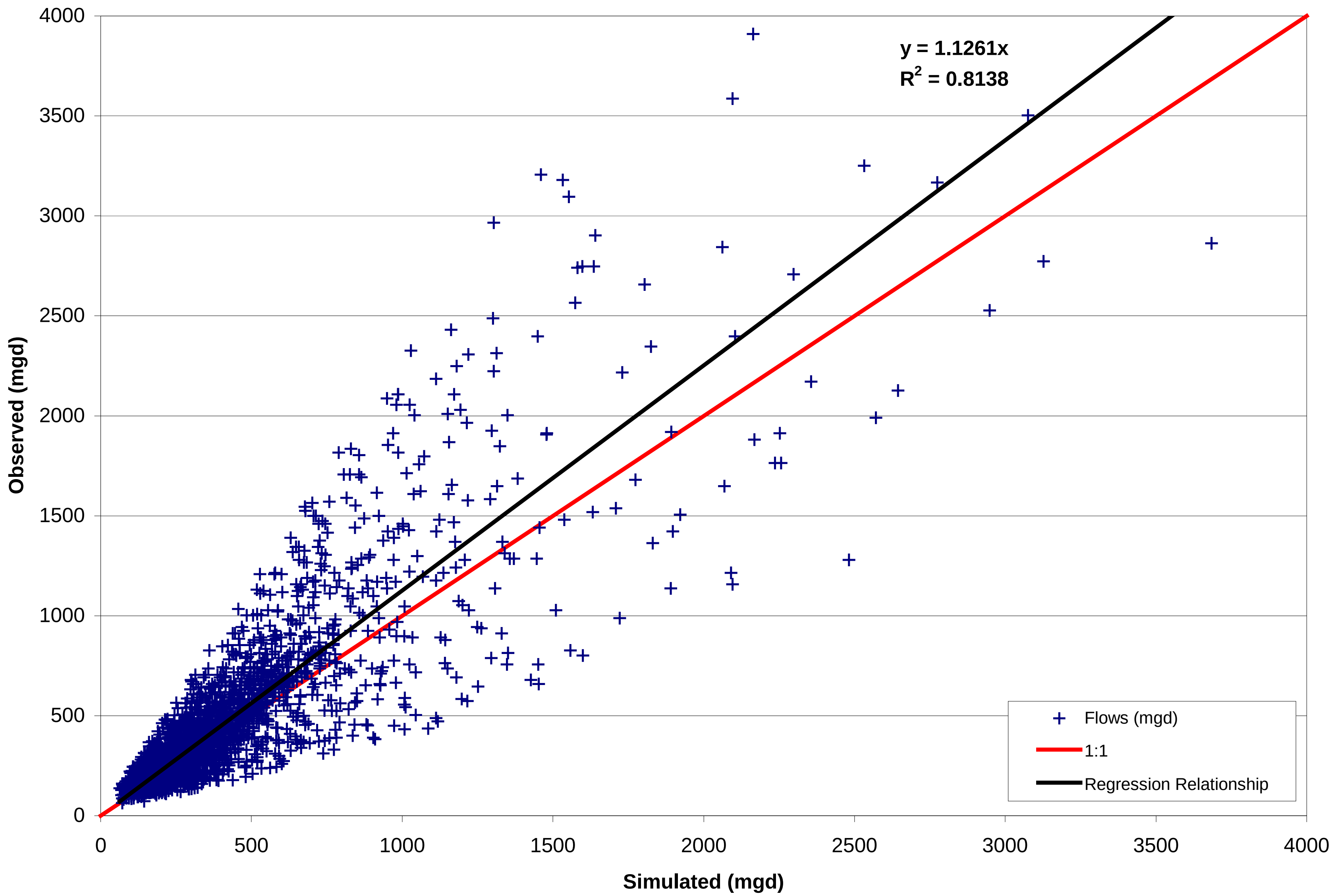
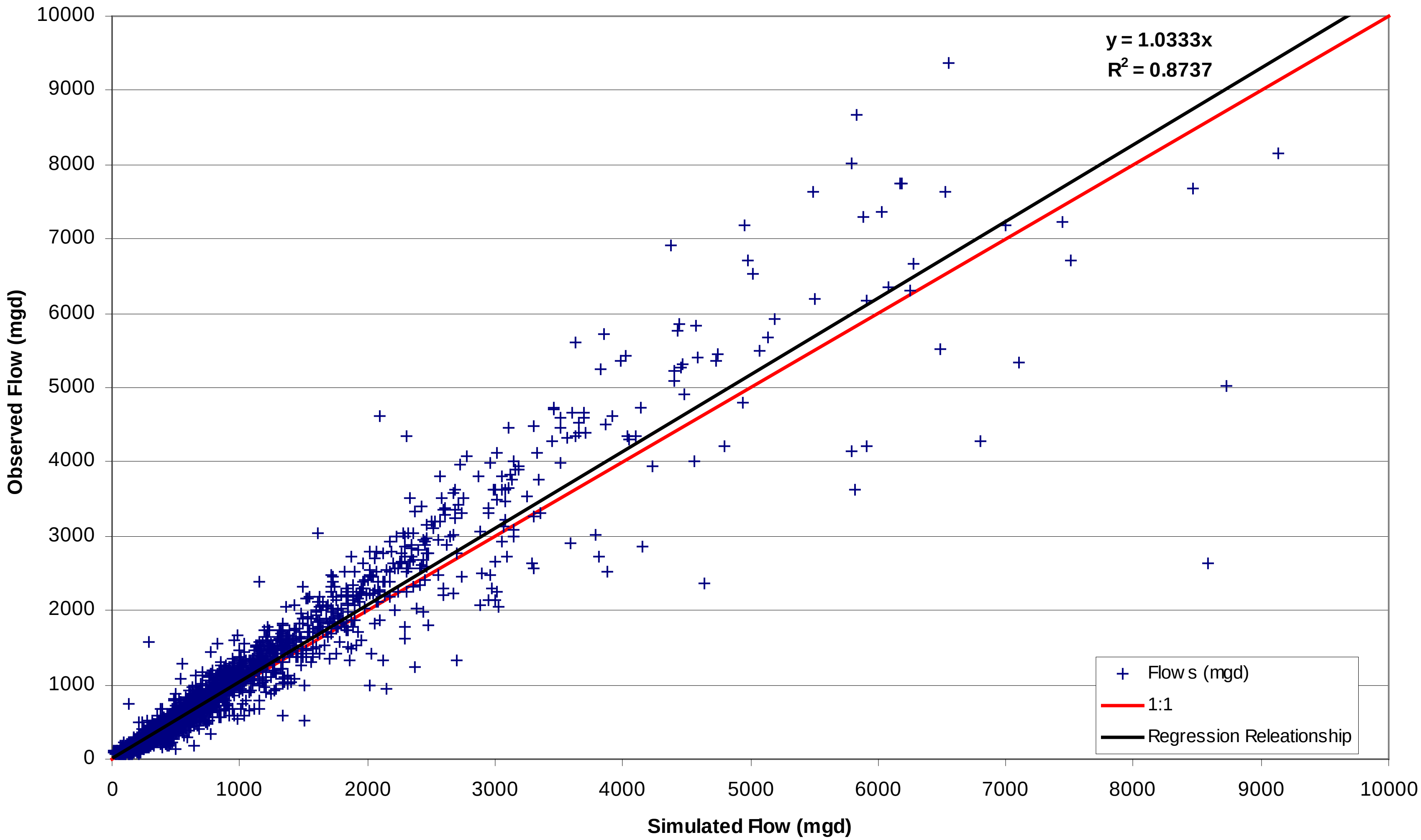


Figure 20. Indeterminate Model with Representative Operations: Observed vs. Simulated at the Bound Brook Gauge



5.0 SIMULATIONS AND RESULTS

The purpose of developing the model was to allow the Authority to predict how the system might operate under conditions not yet observed or operations not yet tried. In addition, the model could be used to evaluate the addition or removal of system components, such as a reservoir. The Authority used the model to re-evaluate the safe yield of the system and to assess the gain in the safe yield of the system with the addition of a pumping station (the Confluence Pumping Station).

5.1 Reassessment of the Safe Yield

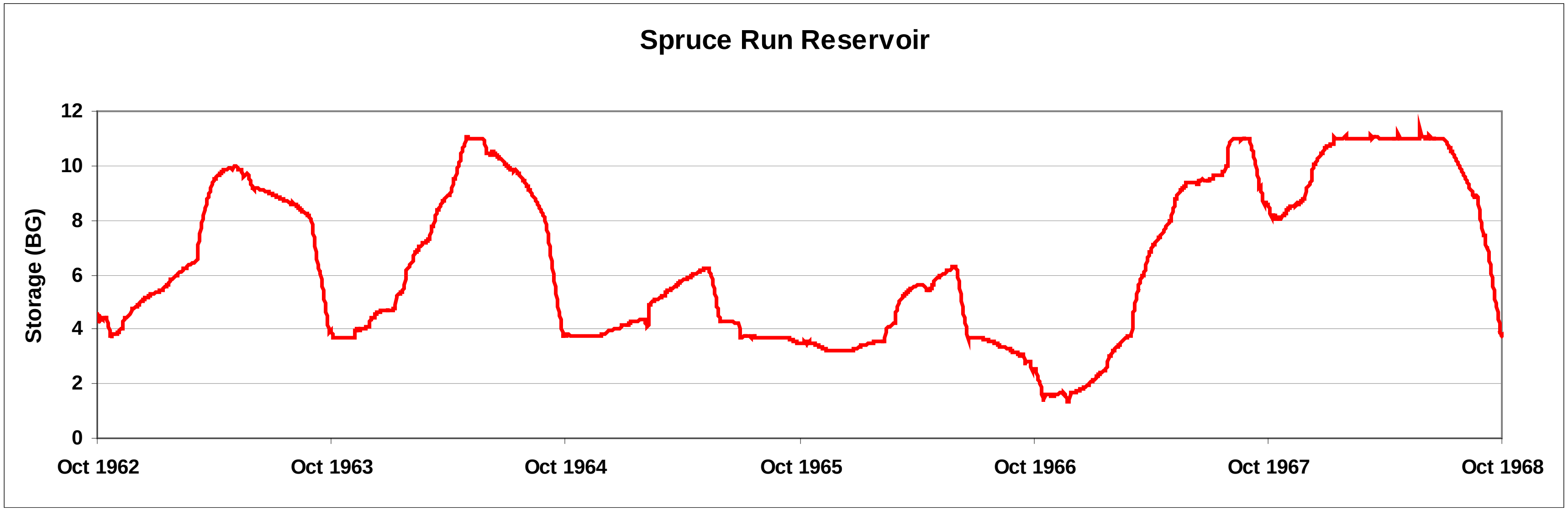
As previously stated, the safe yield is the amount of water that a system can provide without failure during a repeat of the drought of record. This is the legal definition[38] of the safe yield and determines the amount of water that the NJDEP will allow to be allocated to various water users. In wet years, more water could be used, but the wetness of a year cannot be predicted; thus, the safe yield is considered a conservative value. Previous simulations of the safe yield have pumped all available water into Round Valley Reservoir and did not limit the pumping to specific times of year; therefore, that operation also was used for this simulation although less conservative. Flows from the Delaware and Raritan Canal through the release gate at Ten Mile Lock were not included so the river system could be evaluated without augmentation from the Canal. Since the Canal flows are dependent upon the Delaware River Basin Drought status and not the Raritan Basin Drought Status, this is appropriate and conservative. Figure 21 presents the storage volume in each reservoir throughout the simulation to determine the safe yield.

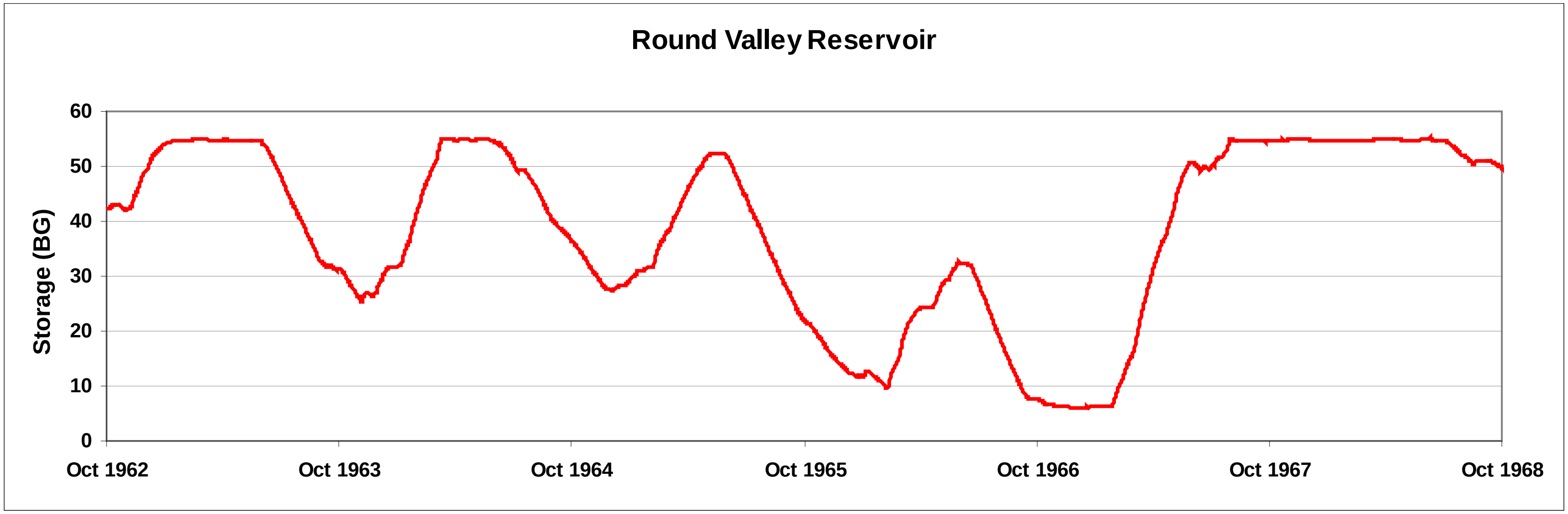
Using the RiverWare model of the Raritan Basin System, the safe yield is 241 mgd (176 mgd from the River and 65 from the Canal). Not pumping during the period from June 15 through September 15[39] had minimal effect on the safe yield since excess water for pumping is generally not available during the summer months. Addition of excess Canal water into the model indicated that the safe yield could be increased by another 10 mgd. However, since the drought severity may differ between the Raritan and Delaware River basins as in 1999 and 2001, this water may not always be available, so this simulation was discounted.

The additional 16 mgd (from 225 mgd to 241 mgd) is due to improved streamflow estimation techniques, the increase in return wastewater flows, and the inclusion of over-reservoir precipitation and evaporation. In the original Sarven model and the NJIT model, a linear regression analysis was used to determine the flows into Spruce Run Reservoir based on flows at the High Bridge Gauge. In this model, the MOVE.1 technique is used to "back cast" the data based on flow at High Bridge and then weighted by drainage area. Either method is appropriate, but the MOVE.1 technique is standard practice today. Also in the original Sarven and NJIT models, precipitation and evaporation are not modeled. The assumption is that evaporation from the reservoir equals the precipitation over the reservoir. While this is a conservative assumption, an analysis of the net contribution of precipitation less evaporation

[38] N.J.S.A. 58:1A-3h.
[39] As modeled by Sarven.

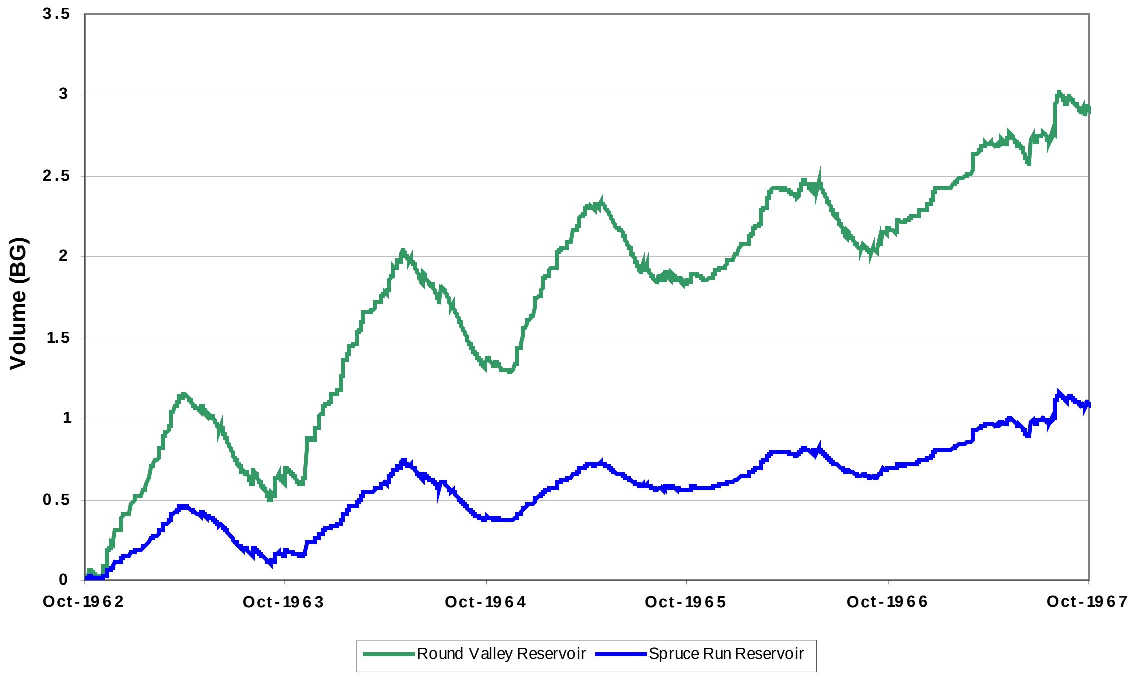
Figure 21. Safe Yield Simulation: Simulated Reservoir Storage





for water years 1963 through 1966 (the extent of the 1960s drought) is 2.5 BG for Round Valley and about 1.0 BG for Spruce Run. Figure 22 presents the cumulative net contribution of precipitation and evaporation for the years of the drought (beginning with full reservoirs).

Figure 22. Net Cummulative Contribution of Precipitation and Evaporation to the Reservoirs during the 1960s Drought (Precipitation – Evaporation)



5.2 The Confluence Pumping Station

The Confluence Pumping Station[40] is a proposed new water supply development project, which has been discussed in various state water supply planning projects since the 1980s. Currently, the combined reservoirs can only store water originated in about 147 square miles of the South Branch Raritan River watershed (including the Spruce Run Reservoir watershed). The Confluence Pumping Station project would allow water to be pumped from below the confluence of the North and South Branches of the Raritan River to Round Valley Reservoir, increasing the drainage area to approximately 490 square miles. The lower South Branch Raritan and the entire North Branch Raritan drainage areas capture additional streamflow that can be pumped to Round Valley Reservoir. The project includes construction of the pump station (capacity 200 mgd), the force main (and rehabilitation of the main (Whitehouse) release pipeline), and a conservation pool (from which water is pumped).

Simulations with previous models indicated that an additional 53 mgd in safe yield could be achieved with the addition of the Confluence Pumping Station. The RiverWare model of the system indicates that an additional 46 mgd in safe yield can be achieved for a total safe yield of 287 mgd (222 mgd from the River and 65 mgd from the Canal). The difference of 7 mgd

[40] A detailed discussion of the Confluence Pumping Station Project is beyond the scope and intent of this report. For more information, refer to the Eastern Raritan Basin Water Supply Feasibility Study, NJDEP, 1992.

is likely due to the additional safe yield gained in the existing system and the status of storage in the reservoirs. The gain in safe yield in the existing system means that more water is being pumped/stored in the reservoirs than in previous simulations (from either additional pumping or net precipitation). Thus, less volume is available to store water that can be pumped by the Confluence Pumping Station.Simulations with previous models indicated that an additional 53 mgd in safe yield could be achieved with the addition of the Confluence Pumping Station. The RiverWare model of the system indicates that an additional 46 mgd in safe yield can be achieved for a total safe yield of 287 mgd (222 mgd from the River and 65 mgd from the Canal). The difference of 7 mgd is likely due to the additional safe yield gained in the existing system and the status of storage in the reservoirs. The gain in safe yield in the existing system means that more water is being pumped/stored in the reservoirs than in previous simulations (from either additional pumping or net precipitation). Thus, less volume is available to store water that can be pumped by the Confluence Pumping Station.

6.0 SUMMARY

New modeling work by the Authority has determined that the safe yield of the Raritan Basin System is 241 mgd versus the previously estimated 225 mgd. The increase is due to differences in the estimation of streamflows, the methodology used for over-reservoir precipitation and evaporation, and the increase in wastewater return flows. The safe yield from the River is 176 mgd and from the Canal is 65 mgd.

The Confluence Pumping Station Project will increase the safe yield by 46 mgd for a total system safe yield of 287 mgd. Previous modeling efforts have indicated that the increase in yield from the Confluence Pumping Station would be 53 mgd. The reduction in the increase is likely an offset of the increase in the existing system safe yield. Since more water from the South Branch Pumping Station is stored, less room is available for water pumped from the confluence area.

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APPENDIX A

Safe Yield Determination

APPENDIX A: Safe Yield

Safe yield is determined using a mass balance equation continually applied over a specific time period for the reservoir and river system:

$$S_t = S_{t-1} + I_t - O_t - m_t D$$

Where:

S_t	=	Storage at the end of timestep t
S_{t-1}	=	Storage at the end of timestep t-1
I_t	=	Inflows to the system during timestep t (including precipitation, hydrologic inflows/streamflow, ground water contributions, pumped flows)
O_t	=	Outflows to the system during timestep t (including evaporation, seepage, channel losses, reservoir releases, canal releases)
m_t	=	Fraction of average annual demand based on month of timestep t
D	=	Average annual demand or Safe Yield

For the Raritan System, a set of these equations are evaluated, one for each component of the system that stores water (Spruce Run Reservoir, Round Valley Reservoir, Delaware and Raritan Canal) in addition to equations that route flows through a mathematical representation of the river network. A summary of the methodology used to determine the safe yield follows (steps 1-5):

1. Select a demand (D) for the system
2. Select a time series of streamflow and precipitation values.
3. Calculate values for all unknows in the system (storage, inflows, outflows). Iterate a-d for each timestep in the time series.
   a. Route natural streamflows through system and determine the status of all reservoirs (after precipitation, evaporation, hydrologic inflow, seepage, gains/losses, releases to reduce storage volume in a reservoir (create freeboard), etc.) and flows at gages with passing flow requirements.
   b. Determine the amount of water to release based on the amount of water needed to achieve the passing flow requirement or to fulfill the demands of water purveyors.
   c. Use operations rules to identify the appropriate source of stored water to release (which reservoir and/or canal) to fullfil the release requirement.
   d. Re-calculate new streamflows, purveyor shortages (if they occur), and storage in the reservoirs and canal given inflows and outflows.
   e. Calculate the volume that can be pumped if both passing flows and all purveyor demands are met.
4. Determine if the system was able to meet passing flows and purveyor demands without the storage in the reservoirs dropping below the minimum desired volume during the time series.

5. Iterate 1-4 to determine the largest demand for which the system can meet passing flows, supply purveyor demand, and maintain reservoir storage above the minimum desired volume.

Different values for the safe yield can be achieved based on the minimum passing flow requirements and the time series chosen to “drive” the model. In New Jersey, the statutory definition of the safe yield requires the use the time series from the drought of record (the 1960s). This statutory safe yield is what is used for water supply planning decisions. Monte Carlo simulations with different time series can be used to estimate the confidence interval around this statute derived value. However, many of the assumptions used to determine the safe yield are conservative, specifically, that minimum passing flows and demands are not reduced based on drought status.

APPENDIX B

Use of Streamflow Data in the Determination of Safe Yield

APPENDIX B: Use of Streamflow Data in the Determination of Safe Yield

The table below indicates the drainage area ratios used to determine ungaged streamflow inputs into the model.

Inflow Location	Original Source	DA	Flow Adjustment	DA	Ratio	Comments
Spruce Run Reservoir	Spruce Run Creek at Glen Gardner	11.3	To Reservoir Inlet	22.3	1.97	Includes Rocky Run, Willoby Brook, Alpaugh Brook
	Mulhockaway Creek at Van Syckels	11.8	To Reservoir Inlet	17.0	1.44	Includes Mulhockaway Tribsutaries and Black Brook
South Branch Confluence Inflow 2	South Branch Raritan at High Bridge 01396500	66.3	Flows from the South Branch Raritan from Budd Lake to confluence with Spruce Run Reservoir Outlet	71.0	1.07	Incorporates area between gage and confluence
South Branch Local Inflow	South Branch Raritan at High Bridge 01396500	66.3	Flows from the drainage area between Spruce Run Confluence and Stanton Gage	36.8	0.55	Includes Cakepoulin and Grandin Creeks
South Branch Raritan Local Inflow	South Branch Raritan at High Bridge 01396500	66.3	Flows from Stanton Station Gage to the Confluence with the North Branch, EXCEPT Neshanic Flows	67.8	1.02	Includes Walnut Brook, Holland Brook and Pleasant Run
South Branch River Neshanic	Neshanic River at Reaville 01398000	25.7	Flows from all Neshanic River Drainage Area	55.7	2.17	Includes all Neshanic Tributaries
Rockaway Lamington	Lamington at Pottersville 01399500	32.8	All flows from the Lamington and South Branch Rockaway Creek EXCEPT Round Valley Releases	99.3	3.03	Used because upstream of Round Valley Release.
North Branch Inflow 2	North Branch Raritan River at Far Hills 01398500	26.2	All flow to the North Branch River EXCEPT from the Rockaway and Lamington Rivers	85.1	3.42	Used because upstream of Round Valley Release.
Millstone Inflow	Millstone River at Blackwells Mills 01402000	258	Flow from the Millstone River to the Confluence with the Raritan River	285	1.1	

APPENDIX C
Monthly Purveyor Demand Data

APPENDIX C: Monthly Purveyor Demand Data

Water Purveyor Data Used to Calculate Demand Patterns
Data in Million Gallons Per Month

Elizabethtown-NJAWC	FISCAL YEAR					
	2003	2002	2001	2000	1999	1998
July	4,891	4,702	4,439	5,631	4,403	4,476
August	4,813	4,315	3,898	3,983	4,470	3,924
September	3,669	3,674	3,757	3,041	3,665	3,552
October	3,593	3,783	3,747	3,109	3,382	3,427
November	3,121	3,713	3,507	2,994	3,149	3,057
December	3,580	3,714	3,668	3,403	3,322	3,134
January	3,700	3,736	3,791	3,534	3,438	3,180
February	3,452	3,386	3,351	3,342	3,006	2,930
March	3,734	3,996	3,661	3,501	3,354	3,274
April	3,586	4,085	3,564	3,393	3,304	3,206
May	3,823	4,284	4,565	3,850	3,668	3,528
June	3,790	4,229	4,336	4,063	4,818	3,735
Total	45,753	47,618	46,284	43,844	43,978	41,424
Average	3,813	3,968	3,857	3,654	3,665	3,452

Middlesex Water Company	FISCAL YEAR					
	2003	2002	2001	2000	1999	1998
July	1,017	981	1,048	1,123	885	866
August	928	1,015	818	898	853	685
September	744	874	785	816	786	644
October	731	811	769	802	705	672
November	671	795	698	750	672	670
December	727	774	676	704	697	631
January	784	737	757	781	640	610
February	648	647	648	726	569	549
March	725	699	737	710	701	631
April	705	730	717	726	630	629
May	758	742	942	923	764	666
June	767	800	922	969	1,007	785
Total	9,204	9,603	9,518	9,928	8,910	8,038
Average	767	800	793	827	743	670

East Brunswick	FISCAL YEAR					
	2003	2002	2001	2000	1999	1998
July	347	274	234	345	317	310
August	273	283	194	219	325	254
September	204	266	187	183	321	223
October	215	228	182	203	247	235
November	208	184	187	184	214	187
December	191	184	213	181	204	203
January	200	190	193	174	187	192
February	188	164	166	164	158	189
March	179	172	176	180	173	211
April	199	188	186	170	180	208
May	233	203	264	205	223	233
June	236	230	255	204	308	258
Total	2,437	2,334	2,184	2,411	2,857	2,705
Average	223	214	203	201	238	225

North Brunswick	FISCAL YEAR					
	2003	2002	2001	2000	1999	1998
July	212	204	208	212	200	190
August	195	222	189	175	192	183
September	153	205	165	158	182	175
October	164	196	160	170	183	167
November	151	187	159	156	172	174
December	166	181	162	168	176	152
January	162	190	176	184	176	155
February	151	149	159	171	143	142
March	166	157	175	176	156	143
April	154	162	174	167	153	147
May	167	174	203	190	171	152
June	165	177	194	195	188	154
Total	2,007	2,202	2,124	2,122	2,093	1,934
Average	167	184	177	177	174	161

New Brunswick	FISCAL YEAR					
	2003	2002	2001	2000	1999	1998
July	328	271	331	342	325	
August	324	344	334	340	339	330
September	319	329	307	294	319	322
October	347	342	322	343	316	329
November	321	252	315	310	303	258
December	324	343	220	346	318	332
January	330	333	364	341	281	226
February	299	285	298	307	274	314
March	345	301	322	324	189	331
April	319	317	313	297	320	306
May	327	316	164	335	285	327
June	336	320	237	322	311	306
Total	3,919	3,751	3,527	3,898	3,580	3,381
Average	327	313	294	325	298	307