The City of New York
Department of Environmental Protection

NYC's Hydrologic Database
Water Budget for Croton Reservoir System

Final Report

March 1, 2002

Prepared in accordance with conditions of the New York State Department of Environmental Conservation, Division of Water contract for State Assistance dated March 19, 1999 for the Safe Drinking Water Act grant.

This final report summarizes the NYC-DEP Croton reservoir system hydrologic database project. Funded through a State Assistance contract with the NYS Department of Environmental Conservation, the hydrologic database project compiled, evaluated and digitized existing stream data; identified data gaps; and constructed two new stream gauging stations to fill those gaps. As a result, a Croton system water budget has been prepared for the calendar year 2000 and a procedure has been established for preparing water budgets in subsequent years.

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Executive Summary

The Croton Water Supply System is the oldest and smallest of New York City's upstate water supplies and is located in the southern New York counties of Dutchess, Putnam, and Westchester. The system consists of twelve cascading reservoirs and three controlled lakes. The building of dams on of the Croton, Muscoot, Cross, and Titicus Rivers created the reservoirs in the later part of the 19th and early 20th centuries. Water cascades from upstream reservoirs to downstream reservoirs through natural river channels, which historically were un-gauged. Water leaves the system at the New Croton Reservoir by either entering the New Croton Aqueduct for delivery into the distribution system, or it is released from the Cornell Dam to the Croton River. On average, the Croton system supplies 10% of the city's 1.2 billion gallon daily supply.

Water budgets vary, but they are commonly used for resource allocation and reservoir modeling where they can provide a detailed accounting of system inputs and outputs. This project focused on the reservoir modeling aspect of water budgets.

Initial project planning identified a lack of streamflow data from un-gauged areas of the New Croton/ Muscoot Reservoir watershed. The majority of project time was spent in the development of two new stream gauging stations to fill these gaps. As a result, the watershed area of un-gauged tributaries to the New Croton/ Muscoot Watershed decreased by 14% and currently 81% of the watershed area for the entire Croton Water Supply watershed is now gauged.

Following the development of the DEP gauging stations, work shifted to the preparation of water budgets for the calendar year 2000. Water budgets serve as management tools to examine the input and outflow of water to a system.

A database was compiled for reservoirs of the Croton Water Supply system that contains data on the inputs, outputs and storage volumes of the system reservoirs for the time period January 1, 1993- December 31, 2000. Budgets have been calculated for all 12 reservoirs of the Croton system. While data quality for the system is good, this work identified reservoir elevation data as the next area for improvement of water budget data on these reservoirs. Data and budgets produced for this project are maintained in the East of Hudson District Hydrology database. For more information contact the EOH District Hydrologist.

Figure 1. Gauged Area of the Croton Watershed.

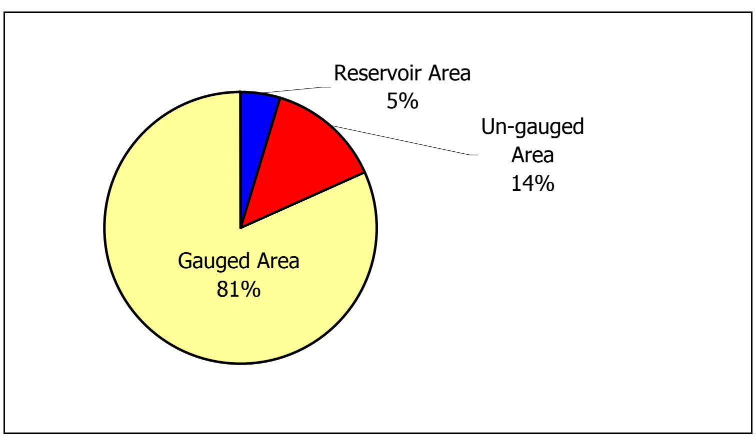


Table of Contents

List of Figures

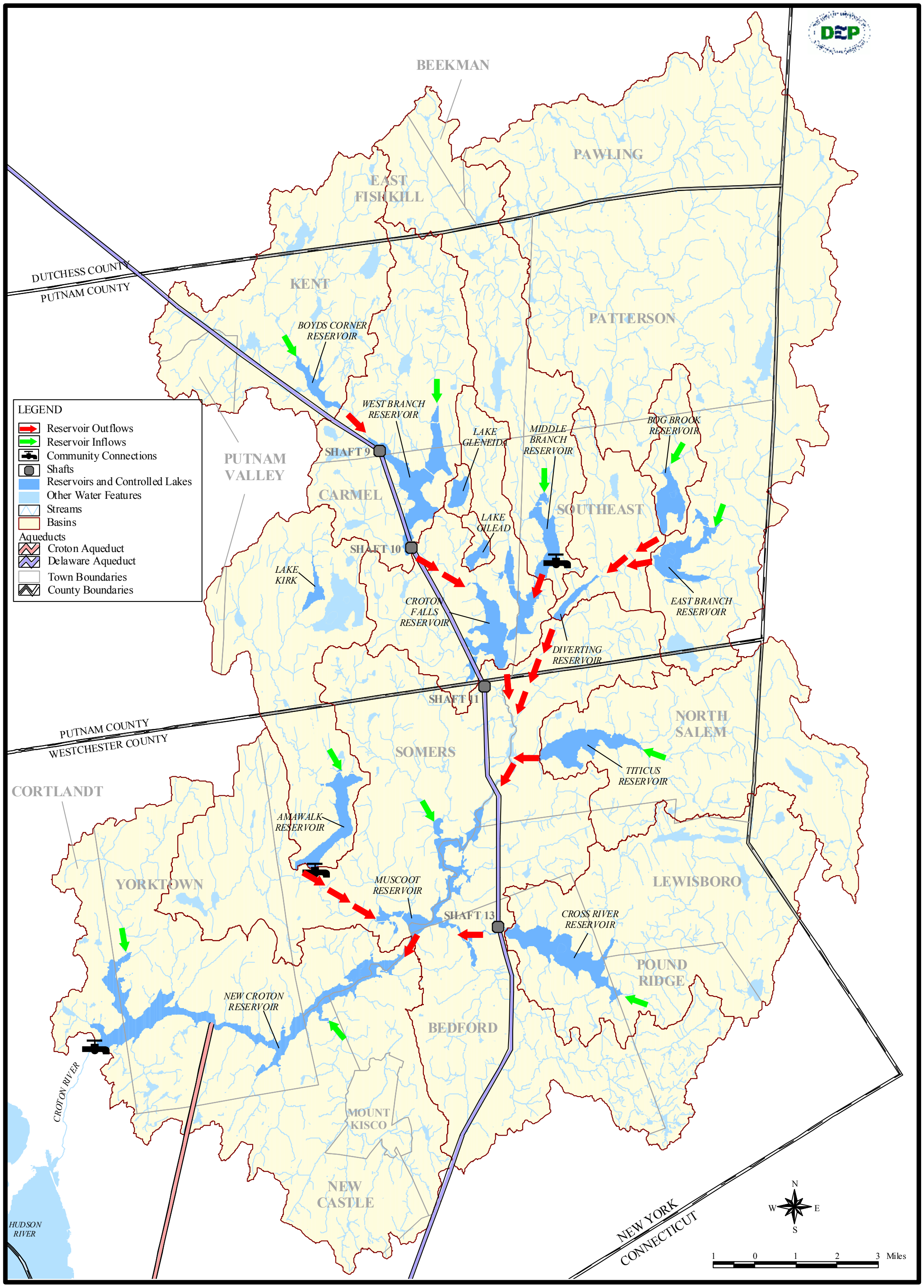
List of Tables

Introduction

This document summarizes data analysis and work performed on the SDWA project "NYC's Hydrologic Database" administered by the NYSDEC as a State assistance contract. The Hydrologic Database project was established to identify and fill gaps in the Croton hydrologic system, to develop a database sufficient for the calculation of water budgets, and to provide a common data platform for reservoir Input, Output, Elevation and Storage data. Once the common platform was established, a budget was compiled for each reservoir. Work performed for this project was divided into five components: 1-Compiling existing data and identifying data gaps, 2- Gauge installation and rating curve development to fill data gaps, 3- Un-gauged stream flow estimates, 4- Water Budget preparation, 5-Future recommendations.

Water budgets are an accounting system of the inputs and outputs to a given region. The region of interest can range from a single soil profile to an entire drainage basin. The Croton Water Supply system, the first of NYC's three upstate water supplies, is a series of reservoirs built in the latter half of the 19th century. The system is made up of 12 reservoirs and three controlled lakes and was created by dams on the river channels of the Croton River and its tributaries. On average the Croton system supplies 10% of the city's 1.2 billion gallon daily supply. Most water received as inputs by the reservoirs is in the form of watershed runoff from natural stream channels. Precipitation falling upon the watershed determines in large part the amount of watershed runoff, and that which falls directly on the reservoir surface is another important input. Since the system is a cascading series of reservoirs, outputs from the 'upper' reservoirs are often inputs to the lower reservoirs. Water leaves the reservoirs by one of four ways: through a conservation release at the base of the dams; when reservoir elevations exceed spillway elevations, excess supply is passed over a designed spillway; evaporation from the surface; and finally through aqueducts or pipes to NYC and local water supplies.

Figure 2. Croton Watershed Stream Flow Diagram.



1. Existing Data

The first step of the project was a review of existing data on reservoir inputs and outputs. Once reviewed, data gaps were identified and a strategy was developed to fill those gaps. In some instances, estimates were necessary since data gaps from nonexistent or malfunctioning equipment occurred. Previous reports have indicated that water budgets for the Croton system were not straightforward due to a lack of data and the nature of unrecorded flow between the reservoirs (DEP, 1998). While this statement still applies somewhat, data collection on stream-flow between the reservoirs has improved dramatically since the mid 1990’s.

1.1 Watershed Runoff

Flow to and between the reservoirs is primarily through open river channels. Historically there have been few discharge measurements made on these streams. To resolve the lack of stream flow and reservoir release data, DEP contracted with the United States Geological Survey (USGS) to establish a network of stream gauging stations. Prior to this agreement the only station that existed in the system was on the Croton River below the Cornell Dam of the New Croton Reservoir, near Croton on Hudson, NY. While the station record is long (1933-present) its use for water budgeting is limited to documenting Croton System releases, and does not provide Croton System input data. Work on installing the additional gauges progressed quickly with seven gauging stations being installed in 1994, seven more in 1995, one in 1996, and two others in 1999. For calendar year 2000 water budgets, 18 USGS gauging stations were operating within the Croton system watersheds. Table 1 lists the USGS Stations in the watershed. See Figure 3 for a map of USGS and DEP gauging station locations.

Table 1. United States Geological Survey Stream Gauging Stations in the Croton Watershed

Station Name	USGS Station ID	DEP Site Code	Basin area (mi^2)	Period of record	
				Start	End
West Branch Croton River at Richardsville, NY	01374559	WESTBR7	11.0	10/1/95	Present
Horse Pound Brook near Lake Carmel, NY	01374598	HORSEPD1	4.94	8/16/96	Present
West Branch Croton River near Lake Carmel, NY	0137462010	WESTBRR	42.9	3/29/94	Present
Middle Branch Croton River near Carmel, NY	1374654	MIDBR3	13.7	12/9/95	Present
East Branch Croton River near Putnam Lake, NY	0137449480	EASTBR	62.1	10/1/95	Present
East Branch Croton River at Brewster, NY	01374505	EASTBOGRR	81.2	3/31/94	Present
East Branch Croton River near Croton Falls, NY	01374531	DIVERTR	86.4	6/1/94	Present
West Branch Croton River near Croton Falls, NY	01374701	CROFALLSR	80.4	1/25/94	Present
Muscoot River at Baldwin Place, NY	01374930	MUSCOOT10	13.5	10/1/95	Present
Muscoot River below dam at Amawalk, NY	01374941	AMAWALKR	19.7	3/23/94	Present
Titicus River at Purdys Station, NY	01374821	TITICUSR	23.8	3/23/94	Present
Cross River near Cross River, NY	01374890	CROSS2	17.1	12/8/95	Present
Cross River at Katonah, NY	01374901	CROSSRVR	29.9	3/17/94	Present
Angle Fly Brook at Whitehall Corners, NY	01374976	ANGLE5	3.01	12/8/95	Present
Stone Hill River South of Katonah, NY	01374918	STONE5	18.7	6/10/99	Present
Kisco River below Mount Kisco, NY	01374987	KISCO3	17.6	10/21/95	Present
Hunter Brook South of Yorktown, NY	0137499350	HUNTER1	7.40	6/11/99	Present
Croton River at New Croton Dam, near Croton on Hudson, NY	01375000	CROTONR	378	7/29/33	Present

A file containing the mean daily flow from each of the USGS gauges was created using the ‘outwat’ program in the USGS Automated Data Processing System (ADAPS) database. This file is setup as a template for water budget production. Mean Daily stream flow data were compiled from the file and converted to provide much of the input and output volumes for the 2000 water budgets.

A caveat to the USGS data is that it can take up to two years for the data to move from provisional to final status. Compounding the issue is the fact that USGS data operates on the “water year” calendar spanning October 1st - September 30th. Data for January through September 2000 will be finalized in the next several months. Data from October through December 2000 will not be finalized until after the 2001 water year is completed (9/30/2001). **Therefore, all data from USGS gauging stations in this report are provisional and subject to revision until that data is published in the annual water yearbooks.**

1.2 Evaporation and Precipitation

Two sets of precipitation data are collected in the Croton watershed. One set is collected by EOH Division of Operations and Engineering as part of the Croton Daily Record. Gauges are of the standard National Weather Service (NWS) non-recording type. Readings are scheduled daily at approximately 8 am. In the winter, water equivalent precipitation is measured by melting accumulated ice and snow. In addition, the Watershed Hydrology group of DWQC collects another set of precipitation data as part of its meteorological monitoring program. This data is collected with a tipping bucket recording gauge so daily values are for the midnight-to-midnight period. Data from the Watershed Hydrology group were used in the water budget calculations summarized in this report.

Along with ground water contributions, evaporation losses are a poorly quantified component of the hydrologic cycle in the New Croton System. In water budget calculations, evaporation is sometimes left as a value that can be changed to balance the water budget, or is estimated to be equal to the precipitation that has fallen on the reservoir, canceling that input from the water budget equations. Estimates can also be made by theoretical and empirical methods such as solar radiation or pan evaporation. For this project, a first estimate was made using 30 inches per year from mean annual lake evaporation data for the Southeastern NY region (Dunn and Leopold 1978). This value will be divided equally throughout the year and applied to each reservoir. A second estimate of evaporation was developed after communication with the Northeast Regional Climate Center in Ithaca, NY (Personal Communication, North East Regional Climate Center, August, 2001). The Center calculated average monthly evaporation values based upon 15-years of evaporation data collected at LaGuardia Airport. These data provide an annual average of 54 inches of evaporation. For this project, evaporation data from the Northeast Regional Climate Center were used in the water budget calculations.

1.3 Croton Reservoir System Daily Records

In the Croton Reservoir system, daily measurements of reservoir elevations, withdrawal of water into aqueducts and storage values for each of the 12 reservoirs are manually recorded onto hardcopy worksheets which are filed at the office of the East of Hudson District Engineer. As part of this project, DEP staff digitized these records for the period 1993-2000. Additional data on storage changes, conservation releases, spillway flows, and community connections were added to the database where applicable. Each reservoir has a number of different inputs and outputs resulting in slightly different data formats. A procedure has been set up for the future transfer of this information to the Reservoir modeling group.

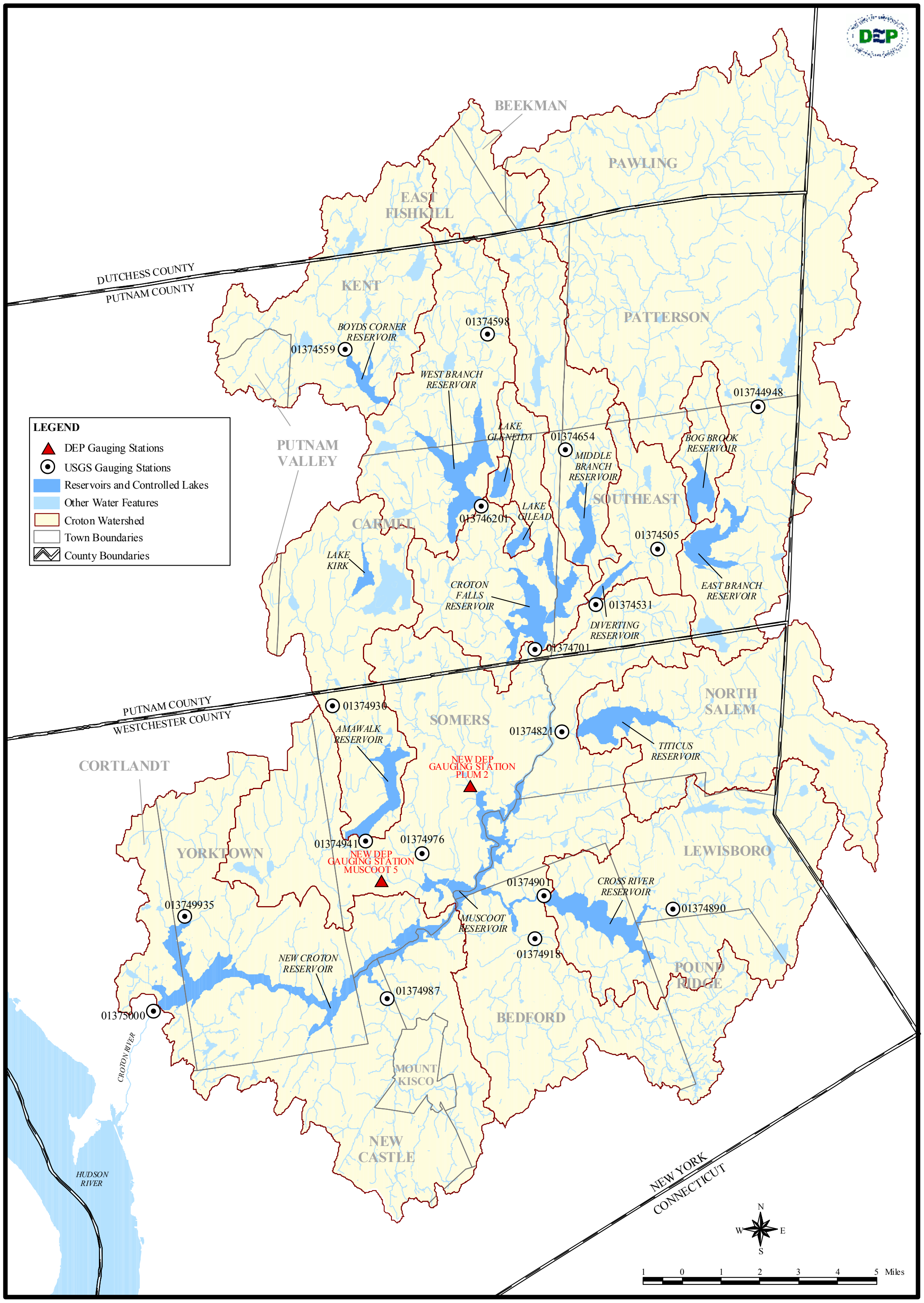
1.3.1 Elevation and Storage

For the daily water budget calculation exercise, a time-step data discrepancy was recognized between stream flow/precipitation data and reservoir elevation and storage data. Stream flow and precipitation data for the water budget are mean daily values calculated from data collected on a 10-, 15- or 60- minute frequency. Reservoir elevation data, however, are single point estimates recorded on a 24-hour frequency. These values are then converted to a single point mean daily storage volume from hardcopy tables of storage volume relative to spillway elevation. The tables used for this process are not dated and are assumed to date back to system construction. This discrepancy became apparent when average daily streamflow data smoothly incorporated high runoff events, while reservoir elevation data did not.

1.3.2 Conservation Releases

Part 672 of 6 NYCRR "Reservoir Releases Regulations" requires DEP to maintain minimum required flows in the streams below the reservoirs. Releases are made from the reservoirs to meet these requirements. For most reservoirs release flow is included in the measurement by a USGS gauging station. Exceptions to this are found at the Boyd Corners and Middle Branch reservoirs.

Figure 3. USGS Gauging Stations within the Croton Watershed.



2. Filling Data gaps -- New Gauge construction

From its beginnings, this project emphasized filling stream flow data gaps. Since the outputs of all the reservoirs contributing to Muscoot and New Croton are gauged, un-gauged tributaries to the New Croton/ Muscoot reservoir basins were evaluated to determine where large stream flow gaps could be filled. Two USGS gauge stations were installed on the largest un-gauged tributaries to these reservoirs (Stonehill River and Hunter Brook) to establish stream flow records by July 2000. Seeking to fill additional stream flow data gaps, DEP selected the next largest tributaries for gauging. Two sites, the Muscoot River at Wood Street (DEP site MUSCOOT5) and Plum Brook near Lincolndale (DEP site PLUM2), were chosen, and construction started in July 2000.

2.1 Construction Details

DEP operates multiple gauging stations and an SOP is in place for their installation. The first step involves the installation of a visual staff gauge. Next a Keller model 173 pressure transducer was installed to measure water level in the stream. The transducer was installed in a PVC stilling well and attached to the staff gauge framework. The transducer is connected to a Campbell Scientific CR10X data recorder, which converts the electronic signal to a water level. Power is supplied via a 12 volt battery and is maintained by a 10W solar panel. An environmental enclosure mounted on a steel pole houses the battery and data logger. To provide a secure platform the pole is set in a concrete footing below the frostline. A custom program was developed for the CR10X to measure and record the water level at the stations. The program records and stores values at 10 minute intervals. Installation went smoothly and the stations started stage data collection on August 10, 2000.

2.2 Rating Curve Development

With the stations recording water level (stage) in the stream, the next step was to establish a relationship between stream-flow (discharge) and stage. Training was provided by the DEP Watershed Hydrology group on measuring stream discharge. Discharge measurements could then be collected to define the stage-discharge relationship. To develop the relationship, a regression analysis is used on the stage-discharge data. A total of 33 discharge measurements were completed during the project and adequately define the stream flows between 6.47 and 546 cfs at the Muscoot River site and between 0.453 and 125 cfs at the Plum Brook site. Tables 2 and 3 show a summary of the discharge measurements completed while figure 4 depicts the rating curves at each location. Programming for the data recorder required an additional level of sophistication with the addition of stream-flow.

Table 2. Discharge Measurement summary at Muscoot River site

DATE	WIDTH (feet)	AREA (ft2)	MEAN VEL. (ft/sec)	GAUGE HEIGHT (feet)	MEAS. DISCHARGE (cfs)	RATING DISCHARGE (cfs)	% DIFF
18-Jul-00	16.7	15.4	1.37	2.47	21.1	20.8	1.37
24-Jul-00	25.8	51.8	0.408	2.43	21.1	18.6	13.6
23-Aug-00	34.8	52.3	0.413	2.48	21.6	21.4	0.93
29-Aug-00	35.6	43.5	0.403	2.42	17.5	18.0	-2.97
14-Sep-00	25.9	50.4	0.424	2.44	21.4	19.1	11.9
20-Sep-00	35.5	59.2	0.753	2.77	44.6	43.2	3.29
28-Sep-00	35.1	51.0	0.464	2.52	23.7	23.8	-0.63
31-Oct-00	29.8	31.8	0.493	2.42	15.7	18.0	-12.9
06-Nov-00	30.1	30.8	0.512	2.41	15.7	17.5	-10.3
27-Nov-00	35.4	55.6	0.552	2.61	30.7	30.0	2.38
14-Dec-00	35.2	61.0	0.816	2.89	49.8	55.1	-9.68
24-Jan-01	34.6	53.6	0.567	2.62	30.4	30.7	-1.05
20-Feb-01	36.5	55.8	0.608	2.69	34.0	36.2	-6.09
13-Mar-01	40.1	76.8	1.09	3.10	83.7	80.7	3.71
20-Mar-01	38.1	78.6	0.942	3.04	74.0	72.8	1.69
20-Mar-01	38.1	75.7	0.811	2.94	61.4	60.7	1.19
04-Jun-01	38.8	68.7	0.758	2.82	52.1	47.9	8.68
18-Jun-01	49.1	111	2.48	4.04	274	282	-2.88

Table 3. Discharge Measurement summary at Plum Brook site

DATE	WIDTH (feet)	AREA (ft2)	MEAN VEL. (ft/sec)	GAUGE HEIGHT (feet)	MEAS. DISCHARGE (cfs)	RATING DISCHARGE (cfs)	% DIFF
19-Jul-00	15.0	9.60	0.250	3.84	2.36	2.29	3.0
23-Aug-00	15.9	9.22	0.231	3.84	2.13	2.29	-7.0
29-Aug-00	15.3	9.18	0.196	3.82	1.80	1.99	-9.7
8-Sep-00	15.2	9.08	0.129	3.76	1.18	1.24	-4.6
14-Sep-00	14.8	9.21	0.210	3.82	1.94	1.99	-2.6
20-Sep-00	19.4	12.8	1.10	4.25	14.1	14.4	-2.3
28-Sep-00	16.0	9.73	0.374	3.92	3.64	3.73	-2.5
30-Oct-00	14.8	8.37	0.153	3.74	1.28	1.03	24.2
6-Nov-00	15.2	8.62	0.105	3.73	0.906	0.935	-3.1
27-Nov-00	17.0	11.4	0.752	4.12	8.58	9.25	-7.2
14-Dec-00	16.7	11.4	0.729	4.10	8.29	8.57	-3.2
18-Dec-00	21.9	15.6	1.44	4.38	22.4	21.0	6.6
24-Jan-01	14.5	9.86	0.609	4.00	6.00	5.60	7.1
13-Mar-01	29.1	28.8	2.16	4.89	62.3	61.6	1.2
4-Jun-01	17.1	14.9	0.78	4.19	11.7	11.9	-1.5

Figure 4. Stage Discharge Rating- Muscoot River at Wood Street near Katonah, NY

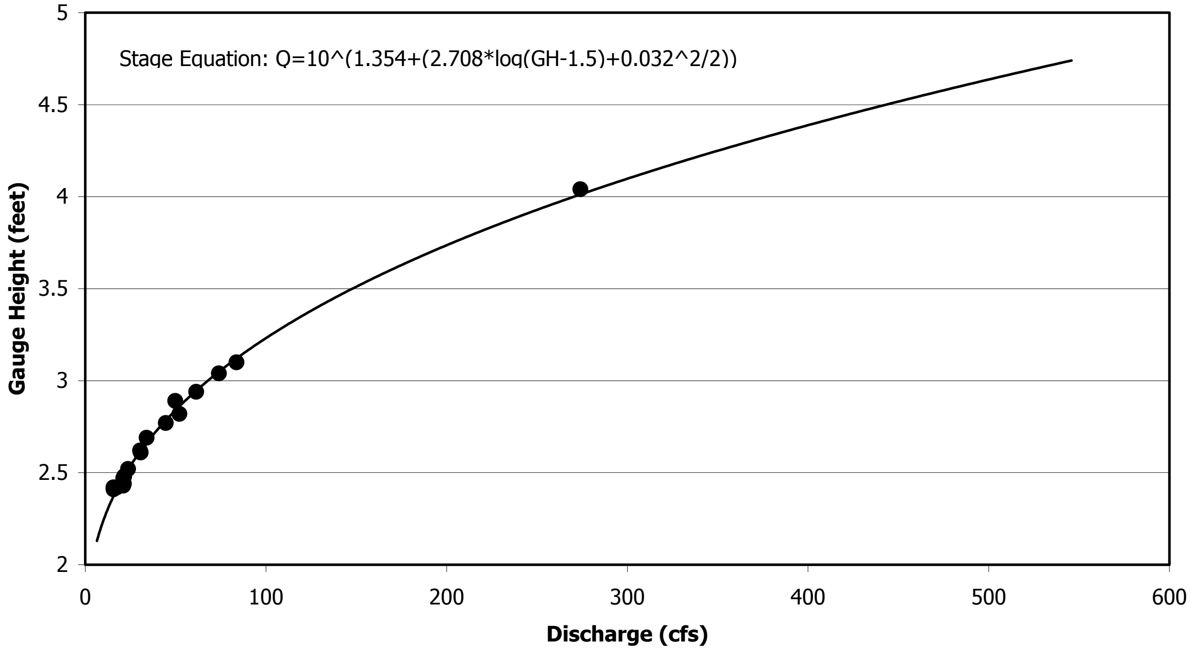


Figure 5. Stage Discharge Rating- Plum Brook near Lincolndale, NY

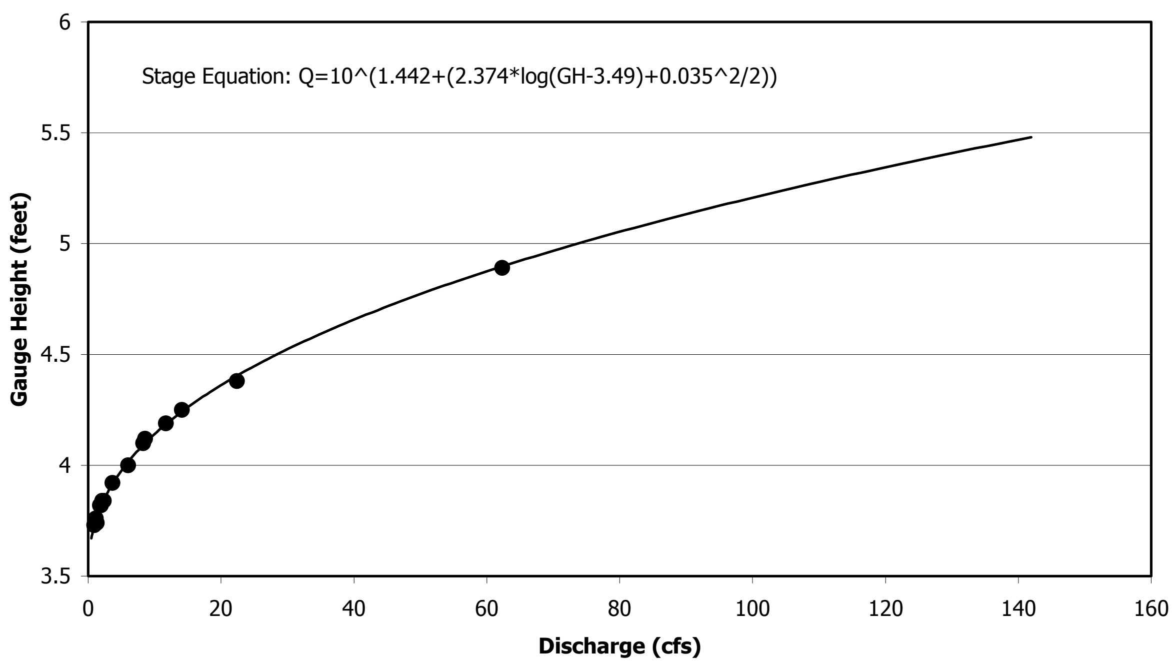
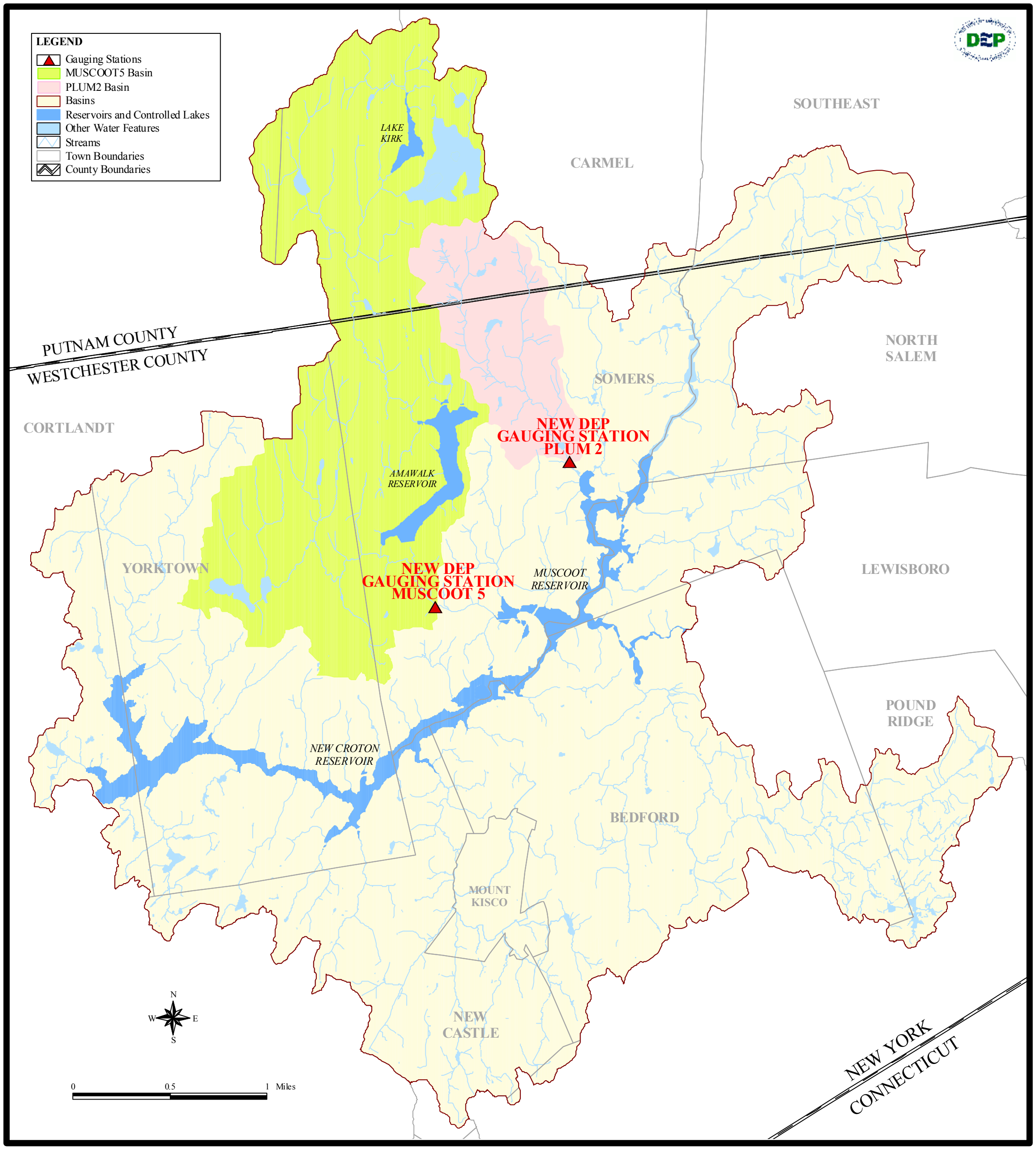


Figure 6. Watersheds recorded by new gauging stations



2.3 Continuing Maintenance

The sites have been operating for over one year. Some problems with vandalism and theft of a solar panel at the Plum brook site prompted staff to reconfigure a more secure installation. Several equipment malfunctions led to the loss of some data. Missing data were estimated using data from another USGS gauge as a reference (see next section for the method of estimating un-gauged flows). Data collection occurs on a twice-monthly basis and a routine maintenance schedule was implemented to help ensure station accuracy. Data collected is processed and imported into a flow database established for the project. Monthly hydrographs and status reports are prepared for data review and quality control. These are submitted to the group supervisor for approval. DEP Hydrology has incorporated these sites into its routine program and will continue their operation in the future. To facilitate data storage and validation site records will soon be stored in the USGS ADAPS database. Figures 7-9 show various images of the gauging stations and the discharge measurements process.

Figure 7. DEP Gauging Station at Plum Brook

Figure 8. Discharge Measurement at Plum Brook

Figure 9. Campbell Datalogger at Muscoot River site

3. Un-gauged area flow estimates

Not all of the tributaries to the reservoirs have gauging stations installed on them. An estimate of these un-gauged flows is thus required for water budgets. Many methods are available for estimating stream flow indirectly. The method described by Gordon and McMahon (1992) is a straightforward means of producing a rough estimate of stream flow. The method assumes a constant flow per unit area of watershed and the equation takes the form:

$$x_1 = x_2\left(\frac{A_1}{A_2}\right)$$

where x_1 is the mean flow for the un-gauged site, x_2 is the flow for the gauged site and A_1 and A_2 are the areas of the un-gauged and gauged watersheds, respectively. Since the areas of the watersheds and sub watersheds are well known for the Croton System, selection of the reference watershed is the most critical factor in obtaining a reasonable estimate. Reference watersheds were chosen based on location, land-uses, and basin area. Previous work done by the DEP GIS group in determining the above greatly facilitated the selection process. Table 4 shows the reference watersheds and there relation to the un-gauged watershed areas. For each reservoir mean daily data for the reference gauge was multiplied by the appropriate ratio yielding a daily ungauged estimate.

Table 4. Reference Watersheds and ratios

Reservoir	Cumulative Watershed Area (mi^2)	Reservoir Watershed Area (mi^2)	Ungauged Area (mi^2)	Reference Watershed	Reference Watershed Area (mi^2)	Ratio
Boyd Corners	22.4	22.4	11.0	West Branch Croton River at Richardsville	11.0	1.00
West Branch	43.0	20.6	14.1	Horse Pound Brook near Lake Carmel	4.94	2.85
Middle Branch	20.9	20.9	7.24	Middle Branch Croton River near Carmel	13.7	0.529
East Branch/ Bog Brook	78.3	78.3	14.7	East Branch Croton River near Putnam Lake	62.1	0.238
Diverting	85.8	7.5	4.43	Middle Branch Croton River near Carmel	13.7	0.323
Croton Falls	80.6	37.6	35.9	Muscoot River at Baldwin Place	13.5	2.66
Titicus	24.7	24.7	23.6	Cross River near Cross River	17.1	1.38
Amawalk	19.7	19.7	5.28	Muscoot River at Baldwin Place	13.5	0.391
Cross River	30.0	30.0	11.5	Cross River near Cross River	17.1	0.673
Muscoot	314	73.3	32.2	Angle Fly Brook at Whitehall Corners	3.01	10.7
New Croton	374	59.9	31.9	Angle Fly Brook at Whitehall Corners	3.01	10.6

4. *Outflow Estimates*

A USGS gauging station measures outflow from most reservoirs in the Croton system. However, at Boyd Corners, Middle Branch and Muscoot Reservoirs no stations are available for direct measurements. In these cases an estimate of outflow was prepared utilizing reservoir elevations and engineering equations that corresponded with the reservoir's outflow structure.

There are four possible outflows from the Boyd Corners dam: A Venturi metered conservation release, a main dam spillway, an emergency spillway, and a set of twin 30" release pipes. After referencing as built drawings of the dam reconstruction, rating curves for the main, emergency and tailwater spillways were obtained and tabulated. From the curves, a trend equation was developed and applied to estimate outflow from elevation data. Field surveys observed much vegetation in the emergency spillway such that that estimate is likely to be much greater than actual flow. Elevation measurements for deriving weir head and storage values are made from staff gauges on the intake structure and main dam. The staff gauges are calibrated in feet relative to mean sea level and the value 579.80 is used as the zero for storage reporting. The 'official' storage table for Boyd corners denotes a change from the original spillway elevation of 593 to 580.5 feet Croton Datum. Croton Datum is 0.45 feet less than mean sea level datum (NGVD 28). Thus the elevation value of 580.95 feet was used as the offset for storage calculations. The storage table did not appear to be updated with the reconstructed dam.

Outflow from the Middle Branch Reservoir goes over an approximately 100 ft masonry block weir. Water elevation on the spillway is not routinely measured. Reservoir elevation measurements are taken about 2 miles upstream from the spillway. Review of the spillway drawings and two field surveys conducted allowed determination of coefficients for utilizing a theoretical weir formula. Data from the field surveys showed only about 85 of the 100 feet shown on the drawings to be effective as a spillway. In addition two different flow conditions were observed. In the first survey flow over the weir was 0.1 feet deep and had a well formed and aerated knapp. On the second visit flow over the weir was about 0.5 feet with no visible knapp. Based on these observations, it was deemed appropriate to use a sharp crested weir formula (Grant, 1997) to estimate flow. It should be noted that conditions were not ideal for the application of this formula. Use of the formula during submerged conditions (>0.5 feet) will likely lead to an overestimation of flow.

A long (>1000 feet) masonary dam separates Muscoot and New Croton Reservoirs. Outflow from Muscoot Reservoir normally occurs over the dam's spillway. Flow over the spillway was obtained from a table developed by the Bureau of Water Supply using a theoretical weir formula. In addition to the spillway, a gatehouse exists at the dam to allow flow to pass from Muscoot Reservoir into New Croton Reservoir when the Muscoot elevation is below the spillway elevation. Some leakage occurs through these gates, delivering an estimated 5-10 mgd of flow from the Muscoot Reservoir. Discharge values of this leakage were estimated from a table that provided flow through the gate openings based on relative reservoir elevations and degree of gate opening.

4.1 Water Budget Development

Water budgets were created using the general mass balance equation.

Inputs ± Changes to Storage = Outputs. (Eq. 4-1)

Watershed inputs included measured stream-flow, estimates of un-gauged stream flow and precipitation. Outputs from the reservoirs included conservation releases and spillway flows, which are commonly measured together at stream gauge in the channel downstream of the reservoir. NYC aqueduct drafts, community withdrawals for local water supplies and estimates of evaporation were also included among the outputs.

Water budgets by Larsen (1998) and DEP (1996,1997) have been calculated using an annual time step. Dunne and Leopold (1978) explain their budget using monthly values. Monthly or annual budgets have the luxury of using values averaged over time, which tends to cancel measurement errors and rapid system changes. For this project a daily time-step was requested, since the flows were to be used for modeling applications. One concern with the use of a daily time step on the existing data is the start of a day. Stream flow and precipitation data define the standard midnight-to-midnight period as one day. Elevation data, which are taken from daily observations made at approximately 8:00 am, define the start and end of the day at 8:00 am instead of at midnight, causing some issues concerning the comparability of the data sets.

Ideally the equation above should balance and rearranging the terms to the left would solve for zero. The data, as discussed above, are not ideal and instead of zero we were left with a remainder. This remainder term is the sum of the unaccounted flows in the system and measurement error.

Inputs ± Changes to Storage – Outputs = Remainder (Eq. 4-2 - Unaccounted Flows)

The water budgets prepared utilized equation 4-2 for an accounting of the system. Existing data discussed in section 1 and un-gauged stream flows discussed in section 3 were the principal components. This data is all assumed correct. Other components of the budgets for Muscoot, Middle Branch and Boyd Corners reservoirs were unspecified. These required certain assumptions to estimate data used in the calculations.

5. Results

Annualized total flows are shown in tables 5 and 6. Separate Microsoft Excel files contain the daily data and plots of residual values. Values are internally consistent such that output flows for the upper reservoirs are used as input flows for the lower reservoirs. Details of Table 5 follow. Total inputs equaled the sum of all streamflow (gauged and un-gauged estimates), precipitation, and water entering from other reservoirs. Total outputs equaled the sum of all aqueduct drafts, spillway and release flows, other water supply drafts and evaporation estimates. Changes in storage were calculated by subtracting the current day’s storage volume from the previous day’s storage volume. Equation 4-2 was used for calculating the unaccounted volumes. Median statistics were chosen to summarize the unaccounted volumes. A resistant measure of central tendency, use of median values prevents extreme values from skewing the data. Some daily elevation data appeared incorrect based on a review of other input and output data, these were assumed to be transcription errors, and edited to reflect actual conditions.

Table 6 was developed for consistency with previous DEP water budgets. Average annual volumes are taken from the 2000 data and used with outflow data to calculate residence times for each of the reservoirs. Reservoir surface areas are from the DEP GIS data and correspond with the spillway elevation. Reservoir watershed areas are cumulative throughout the system and are from DEP GIS data.

Table 5. Calendar year 2000 Water Budget data

Reservoir	Total Annual Inputs (MG)	Total Annual Outputs (MG)	Storage Change (MG)	Annual Unaccounted Flow (MG)	Unaccounted Flow Statistics- Median		
					Daily Volume (MG)	Elevation (ft)	Storage Volume (%)
Boyd Corners	8088	15655	-695	-6872	-8.0	-0.11	-2.27%
West Branch	296145	293040	2483	622	-34.0	-0.10	-0.39%
Middle Branch	7629	6587	-38	1080	3.0	0.02	0.07%
East Branch/ Bog Brook	27168	28975	-1194	-613	-5.0	-0.01	-0.05%
Diverting	29194	26497	-27	2724	0.0	-0.01	-0.04%
Croton Falls	24664	25542	-177	-701	-1.0	0.00	0.00%
Amawalk	4499	8198	-1137	-2562	-8.0	-0.04	-0.16%
Titicus	8150	8569	-52	-367	-2.0	-0.01	-0.05%
Cross River	9981	10326	21	-366	-2.0	-0.01	-0.02%
Muscoot	109354	95637	-59	13776	17.0	0.06	0.35%
New Croton	113266	125725	-76	-12383	-26.0	-0.04	-0.11%

Table 6. Reservoir Summary Characteristics for 2000 Water Budget data.

Reservoir	Average Daily Volume (MG)	Reservoir Surface Area (sqmi)	Watershed Area (sqmi)	Residence Time (yr)
Boyd Corners	1049	0.348	22.4	0.07
West Branch	7905	1.57	43.0	0.03
Middle Branch	4023	0.631	20.9	0.61
East Branch/ Bog Brook	9124	0.884	78.3	0.31
Diverting	863	0.197	85.8	0.03
Croton Falls	14030	1.62	80.5	0.55
Amawalk	4369	0.876	19.7	0.53
Titicus	5390	1.07	24.7	0.63
Cross River	10291	1.44	30.0	1.00
Muscoot	5016	1.46	314	0.05
New Croton	23934	3.12	374	0.19

6. Discussion

While the system wide budget showed very good results, some individual reservoir results did not balance as well. Not surprisingly data from the headwater reservoirs (except Boyd Corners) produced the most balanced budgets. System wide, our analysis showed an unaccounted surplus of 1173 million gallons, which is within 2% of the average annual storage. Some uncertainty exists with all water budget data, so for a completely balanced budget, adjustments will be needed.

We chose the median daily value of unaccounted volume to evaluate the budgets. This value expressed as a reservoir elevation provides an easily conceivable measure for assessing a budget's accuracy. Water surface elevations cannot be precisely measured to less than 0.02 feet since there is always wave action and other environmental factors involved. Therefore, budgets with an unaccounted volume of less than 0.02 feet reservoir elevation are considered balanced.

The budget for Boyd Corners reservoir had the highest error based on median daily unaccounted volume. Outflow from the reservoir is mostly unmetered with the exception of a Venturi on the conservation release. The dam, rehabilitated in 1989, has "as-built" engineering drawings of the spillway structures with rating curves to estimate outflow. We used the elevation data and the rating curves from the drawings to make an outflow estimate; this method produced unexpected results. Outflow appears to be seriously overestimated by 7 billion gallons and large drawdowns of the reservoir in April and July could not be accounted for since they happened over short time spans. The elevation measuring equipment at the Boyd Corners Dam was not operational. The wire-weight gauge would have provided precise recorded measurements of drawdowns and storm pulses that may have returned more realistic outflows, and this equipment must be repaired for the future.

The lack of accurate outflow data for Boyd Corners reservoir identified an ideal location for a gauging station. The reach downstream from the dam includes all flows from the spillways and releases in a defined channel. A USGS gauging station was installed at this location during the autumn of 2001. This newest gauge will provide future budgets with an accurate value for the Boyd Corners output, as well as a major surface input value for West Branch Reservoir.

The budget for West Branch Reservoir indicated a large water surplus. This reservoir can be considered part of two systems, Croton and Delaware. Its dual nature makes it the most difficult of the Croton system reservoirs to balance. It is connected to the Delaware Aqueduct at shafts 9 and 10. This reservoir can operate in three different modes: reservoir, float, and bypass (off). Reservoir mode is most commonly used and results in 800 million to 1 billion gallons entering at shaft 9, passing through the reservoir, and leaving from shaft 10 daily. Occasionally, the reservoir is shifted to either float or bypass mode of operation. Under float conditions, water either enters or leaves the reservoir at shaft 9 depending on reservoir elevation. Under bypass conditions, the aqueduct is effectively isolated from the reservoir. The overestimate of Boyd Corners outflow more than explains the surplus observed at West Branch. Correcting for the overestimate would leave West Branch with an annual deficit of approximately 5 billion gallons which could be accounted for by as little as a 1-2% error in the daily aqueduct flow.

Middle Branch Reservoir with a value of 0.02-feet unaccounted volume was within the tolerance deemed acceptable for the project. But some problems did arise in budget calculations that warrant discussion. Two problems at Middle Branch are: 1. The elevation measurement location, for determining storage volumes and, 2. No direct measurement of reservoir outflow. The reservoir elevation measurement location is at the inlet side of the reservoir. It is about 2 miles from the spillway and no correction is made for this distance or seiches, which may exist in the reservoir. The lack of direct outflow measurements requires use of a weir formula. This weir formula uses reservoir elevation to calculate spillway head and then to estimate the outflow. So any outflow estimate error is compounded by error in reservoir elevation. Installation of a DEP gauging station and development of a rating curve at the Middle Branch spillway could correct for both of these issues.

Reservoirs with acceptable unaccounted volume were in particular: East Branch/ Bog Brook, Diverting, Croton Falls, Titicus and, Cross River. These all had median values of unaccounted volume less than that which would cause a 0.02-feet change in reservoir elevation. USGS gauges are present at the outflow and inflow of each of these reservoirs with the exception of Titicus Reservoir, which has no inflow gauge. The inflow of Titicus was estimated with the Cross River inflow and correcting for area. These watersheds are quite similar in size and landuse, which are in line with the assumptions of areal estimates.

Budget analysis showed an annual deficit of 2 billion gallons at Amawalk reservoir. However, the year 2000 could not be considered normal for its reservoir operations. Spillway renovation undertaken during the year caused elevations to be drawn down substantially. As a consequence of reduced elevation, surface area was also reduced. Inflows and surface outflows are unlikely to be affected by the reduction in surface area. But, reduced areas will markedly reduce evaporation estimates. Only 500 MG was estimated for annual evaporation from Amawalk. So even a 50% reduction in evaporation could make up 10% of the deficit. Other potential explanations are errors from the gauged and ungauged inputs or from the output gauge.

The case of Muscoot and New Croton reservoirs is another example of poor balance when outflow is not directly measured. In this case the outflow of Muscoot Reservoir was estimated by using a theoretical weir formula. Taken together their combined budget indicates approximately a 3.4 billion gallon surplus. Taken separately, New Croton has an 11 billion gallon deficit while Muscoot has a 14 billion gallon surplus. Clearly the weir formula used for the Muscoot output is well underestimating flow. The formula is from DEP records and does date back to 1946 so a revision is in order. Compounding the weir problem again is elevation data. Elevation is used for calculating the head parameter of the weir equation and for determining storage volume. Both reservoirs have existing but inoperable elevation devices- a staff gauge at Muscoot and a recording wire weight gauge at New Croton. The inoperation of the gauges requires staff to hand measure elevation. After considering the Muscoot output error a considerable surplus remains. The two new stream flow gauges installed may account for some of this error in the future. In the 2000 budget, data was only available for the last 5 months of 2000 leaving the first 7 to be estimated. In the future, a full year of data from the stations and repair of the reservoir elevation devices will improve the water balance.

7. Recommendations

NYC's Hydrologic Database Project has a solid foundation established. To avoid complications with provisional data, future water budgets should be based on the USGS water year calendar year. An effort should be made to repair or replace existing but inoperable elevation devices at New Croton, Muscoot and Boyd Corners reservoirs. Additionally, two new stream gauging stations and a recording elevation station should be developed to measure outflow at Middle Branch, Boyd Corners and Muscoot Reservoirs, respectively. For the long term, DEP should support fully the development of the East of Hudson telemetry system. This system, currently proposed, would include real time elevation sensors at each reservoir location. The real time monitoring should record data at a frequency sufficient to allow it to be comparable with mean daily input data. Other long term projects include estimating evaporation rates from existing meteorological data and verifying with pan evaporation data. Examining ground water and soil moisture regimes and their impact on the entire NYC Water Supply.

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