OCCOQUAN RESERVOIR:

"NATURAL" DAILY-INFLOW DEVELOPMENT

Prepared by

Erik R. Hagen
Roland C. Steiner
Jan L. Ducnuigeen

July, 1998
Report No. 98-3

Interstate Commission on the Potomac River Basin
6110 Executive Boulevard, Suite 300
Rockville, Maryland 20852

The Interstate Commission on the Potomac River Basin

Section for Cooperative Water Supply Operations on the Potomac

This report was prepared by the Interstate Commission on the Potomac River Basin, Section for Cooperative Water Supply Operations on the Potomac. Funds were provided for this report by the Washington Suburban Sanitary Commission, the Washington Aqueduct Division of the U.S. Army Corps of Engineers, and the Fairfax County Water Authority. The opinions expressed are those of the authors and should not be construed as representing the opinions or policies of the United States or any of its agencies, the several states, the Commissioners of the Interstate Commission on the Potomac River Basin, or the water utilities.

Table of Contents

List of Figures

List of Tables

Abstract

The Occoquan Reservoir is a water supply reservoir located on the Occoquan River in Fairfax and Prince William counties, Virginia. The reservoir is owned and managed by Fairfax County Water Authority. The Co-op Section of the Interstate Commission on the Potomac River Basin (ICPRB) maintains inflow records for the reservoir as part of its mission for efficient utilization of all available water supply facilities for the Washington Metropolitan Area, particularly during drought periods. The prior ICPRB set of daily inflows to Occoquan Reservoir was examined and revised in three important ways.

1. An improved model was used to create a synthetic inflow during the most severe drought of record for the region (in the early 1930's). A series of seasonal regressions more closely predicted gaged flow on the Occoquan River at Occoquan, reducing the average inflow rate by **9.0 percent** as compared to prior inflow records.

2. Prior data sets did not include inflow records to the Occoquan reservoir after December 31, 1986. This work updates the Occoquan inflows to September 30, 1996.

3. The inflow record developed in this analysis represent the natural reservoir inflows that would have occurred in the Occoquan without human influences such as upstream diversions or wastewater discharges. Diversions of water and wastewater discharges to the reservoir watershed were tracked separately.

When possible, the methods used in creating each segment of the dataset were examined quantitatively to compare how well each method compared to the best available estimate of inflow volume. The Occoquan River at Occoquan gage site was the best available estimate of inflow to the Occoquan reservoir since it was located near the site of the current dam. Six regression models were developed corresponding to low-, medium-, and high-flow intervals in the periods October through April and May through September. The October through April low-, medium- and high-flow regression models predicted inflow volume within -1.3 to +0.6 percent of that predicted by the Occoquan gage, and the May through September models' results were between -9.2 to +0.8 percent of the Occoquan gage. During the periods when there were active gages in the Occoquan Reservoir watershed and the area-adjustment models could be used, those models predicted inflow volume within -0.5 to +2.6 percent of that predicted by the Occoquan River at Occoquan gage.

1. Introduction

The Occoquan Reservoir is located on the Occoquan River in Fairfax and Prince William counties, Virginia (Figure 1). The reservoir, owned and managed by Fairfax County Water Authority (FCWA) has a usable storage-capacity of approximately 8.19 billion gallons (BG). Throughout the stream gage record, there were no gages directly measuring the inflow to the Occoquan reservoir. However, a record of "natural" inflows was developed for the water years 1927 to 1996. The development of the inflow record required using a combination of drainage area-adjustment factors and flow records from outside of the reservoir watershed.

The inflow record is called "natural" because it represents those inflows to the reservoir that would have occurred without upstream withdrawals, return flows, or reservoir regulation. Prior analyses (Hirsch, 1978; Black and Veatch, 1996; Schwartz, 1996) incorporated withdrawals and return flows into a single flow record in order to create inflows representative of the current conditions at the time of the analysis (i.e., design-simulation conditions). The drawback to this type of data set is that as conditions change in the basin, the data set is rendered obsolete. A separate accounting of natural flows and human influences facilitates future updates of design-simulation conditions, since it allows the user to modify only those files accounting for upstream diversions or return flows without having to recreate the entire flow record. Upstream withdrawals and wastewater return flows to the reservoir watershed are described in later sections of this report.

For those periods when gages were located in the reservoir watershed, area-adjustment factors were used to create inflows. Area-adjustment factors were applied when a gage located within the reservoir watershed measured flow from a smaller drainage area than that of the reservoir watershed. Measured flow from the gaged drainage area was increased by an amount equal to the area of the larger reservoir watershed divided by the area of the gage station watershed:

$$\frac{(\text{Gaged flow}) * (\text{Area of reservoir watershed})}{(\text{Area of gage station watershed})}$$

The area-adjustment method tends to over-predict peak flows and under-predict recession flows because of differences in the time-of-concentration between the smaller gaged watershed and the reservoir watershed. Over a longer interval, differences cancel when the runoff produced per unit area is equivalent. Thus, an underlying assumption implicit to the area-adjustment procedure is that each part of the reservoir watershed is equally productive with regard to runoff per unit area.

A caveat: the area-adjustment method was selected for its ability to predict the volume of inflow to the reservoir. This technique is not appropriate for estimating the timing and magnitude of peak flows into the reservoir. Therefore, the inflow record created using this method should not be used to analyze the magnitude or frequency of peak daily flow events (e.g., as for flood risk analysis). This inflow record was instead developed and validated for use in simulation models that perform volumetric accounting of reservoir contents, for water supply planning purposes.

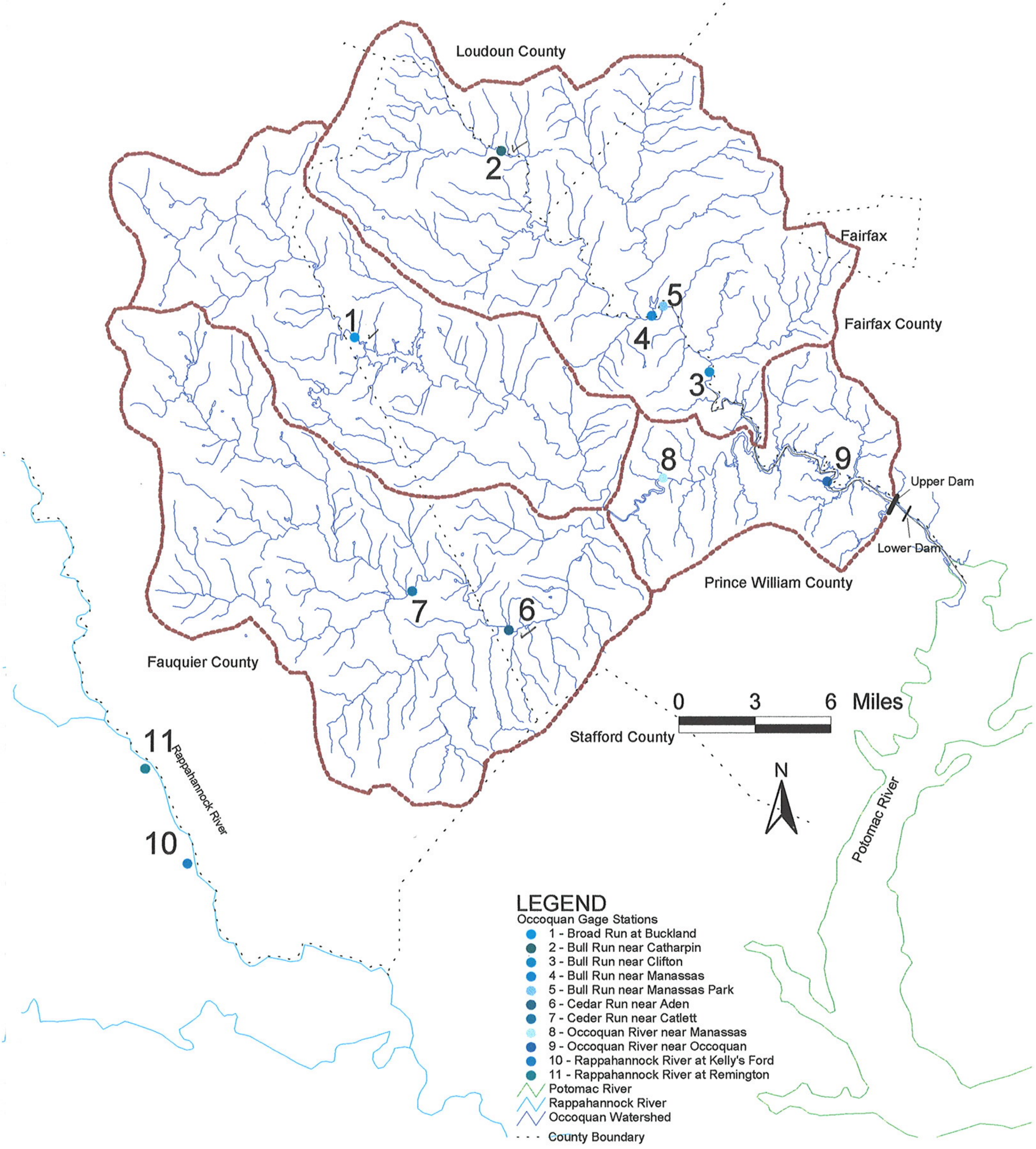

Figure 1: Occoquan reservoir watershed and neighboring Rappahannock River, USGS gaging stations, county boundaries, and sub-watersheds

During the periods 1927-1937 there were no gages in the Occoquan reservoir watershed, and one must look to neighboring watersheds for sources of flow information. The Rappahannock watershed borders the Occoquan watershed and both watersheds are located in similar geologic areas, the Coastal Plain region southeast of the Blue Ridge Mountains. Regression relationships were developed that correlate flow between the gaged portions of the Occoquan and the Rappahannock watersheds during times when flow was measured in both watersheds. The regression equations were then applied to measured flows on the Rappahannock during the years that no gages were located in the Occoquan Reservoir watershed in order to create a set of synthetic Occoquan reservoir inflows. The regression-analysis method does not accurately recreate the statistical variability of the flow events but does provide the best least squares estimate of the volume of inflow over the period of record.

2. Daily inflow development

Table 1 summarizes the stream gages and time periods used in the development of each segment of the Occoquan Reservoir inflow record. The development of each component of the inflow record, throughout the simulation period, is described below.

Table 1: Stream gages used to develop the Occoquan Reservoir inflow record

Synthetic inflow period of record	U.S.G.S. stream gages used for record generation	Gage number	Drainage Area (Sq. miles)
10/1/1927 - 9/30/1937	• Rappahannock River at Kelly's Ford • Rappahannock River at Remington	• 01664500 • 01664000	• N/A
10/1/1937 - 3/31/1956	• Occoquan River near Occoquan	• 01657500	• 570.0
4/1/1956 - 4/24/1963	• Broad Run at Buckland • Bull Run near Manassas • Cedar Run near Catlett	• 01656500 • 01657000 • 01656000	• 50.5 • 148.0 • 93.4
4/25/1963 - 4/30/1969	• Broad Run at Buckland • Cedar Run near Catlett	• 01656500 • 01656000	• 50.5 • 93.4
5/1/1969 - 9/30/1972	• Broad Run at Buckland • Bull Run near Catharpin • Cedar Run near Catlett	• 01656500 • 01656725 • 01656000	• 50.5 • 25.8 • 93.4

Synthetic inflow period of record	U.S.G.S. stream gages used for record generation	Gage number	Drainage Area (Sq. miles)
10/1/1972 - 9/30/1979	• Broad Run at Buckland • Bull Run near Catharpin • Cedar Run near Aden	• 01656500 • 01656725 • 01656100	• 50.5 • 25.8 • 155.0
10/1/1979 - 9/30/1980	• Bull Run near Catharpin • Cedar Run near Aden	• 01656725 • 01656100	• 25.8 • 155.0
10/1/1980 – 12/31/1995	• Broad Run at Buckland • Bull Run near Catharpin • Cedar Run near Aden • Rappahannock River at Remington	• Occoquan Watershed Monitoring Laboratory/ USGS	• 50.5 • 25.8 • 155.0 • NA
1/1/1995- 9/30/1996	• Cedar Run near Catlett	• 01656000	• 93.4

1927-1937

The longest and most severe drought of record in the region occurred from June of 1930 to January of 1932, based on an examination of stream gages in the Patuxent basin. Although no gage information exists on the Occoquan during the time period between 1927-1937, flow records exist on the Rappahannock. Additionally, gage records are available for both the Occoquan (Occoquan River near Occoquan) and Rappahannock (Rappahannock River at Kelly's Ford and Rappahannock River at Remington) for comparison during the period from October 1, 1937 to December 31, 1955.

A series of non-linear regressions was developed for low-, medium-, and high-flow periods for the periods May through September and for October through April between the flow on the Rappahannock River and the flow on the Occoquan River during the overlapping gage record. These regression relationships were applied to the flow on the Rappahannock to create a synthetic inflow record for the Occoquan for the period October 1, 1927 through September 30, 1937. Appendix A provides a discussion of the non-linear regression model development and graphs of each model calibration curve. Non–linear regression techniques were used to avoid bias introduced by using linear regressions on logarithmically transformed data (Ferguson, 1986). The seasonal regression approach was partially based on prior work conducted by Robert Hirsch of the USGS (1978).

The general procedure followed was to randomly divide the 1937-1955 data into two halves, a model calibration and a model validation set. Testing each regression relationship on the validation data set allowed for a means of quantitatively comparing each model. (Validation data is that data not used for the model calibration, which allows for an unbiased test of the relationship predicted by the calibration data.)

Table 2 shows the results for each model. Validation results were expressed in terms of how well each model predicted the reservoir inflow based on gaged flow at the Occoquan River at Occoquan. Table 2 also shows the number of data points used for calibrating each model.

Table 2: Comparison of regression models used for 1927-1937 period

Regression-model [a]	**Number of data points used in model calibration**	**Difference between modeled and actual Occoquan R. at Occoquan flow for model validation data-set (%)** [b, c]
Oct. through April: low-flow	356	0.6
Oct. through April: med.-flow	811	- 0.6
Oct. through April: high-flow	891	- 1.3
May through Sept.: low-flow	441	- 0.3
May through Sept.: med.-flow	615	0.8
May through Sept.: high-flow	348	- 9.2
Overall results	NA	- 1.2

Notes: [a] Low-flows defined as flow on the Rappahannock < 200 cfs.
Med-flows defined as flow on the Rappahannock between 200 and 600 cfs.
High-flows defined as flow on the Rappahannock > 600 cfs.
[b] Positive difference corresponds to a model over-prediction of Occoquan R. at Occoquan flow.
[c] Percent difference is calculated as: [(modeled flow volume – Occoquan R. at Occoquan flow volume) / Occoquan R. at Occoquan flow volume]*100.

The low-flow models were most important for determining inflow during the critical drought of record. Fortunately, the model validation differences were small, within -0.3 and +0.6 percent for low-flow ranges. Medium-flow validation differences were also small, within -0.6 and +0.8 percent. The October through April high-flow model validation difference was -1.3 percent, but the May through September high-flow difference was -9.2 percent. The overall result shows that the model is slightly conservative, under-predicting Occoquan River at Occoquan gaged flow by -1.2 percent when total inflow was compared over the 1937 through 1955 data set.

Figure 2 compares flow volumes as calculated from the regression models with actual gaged flows during the period from October 1937 through September of 1952. The figure qualitatively shows that the models predicted flow volume well, especially at low flows.

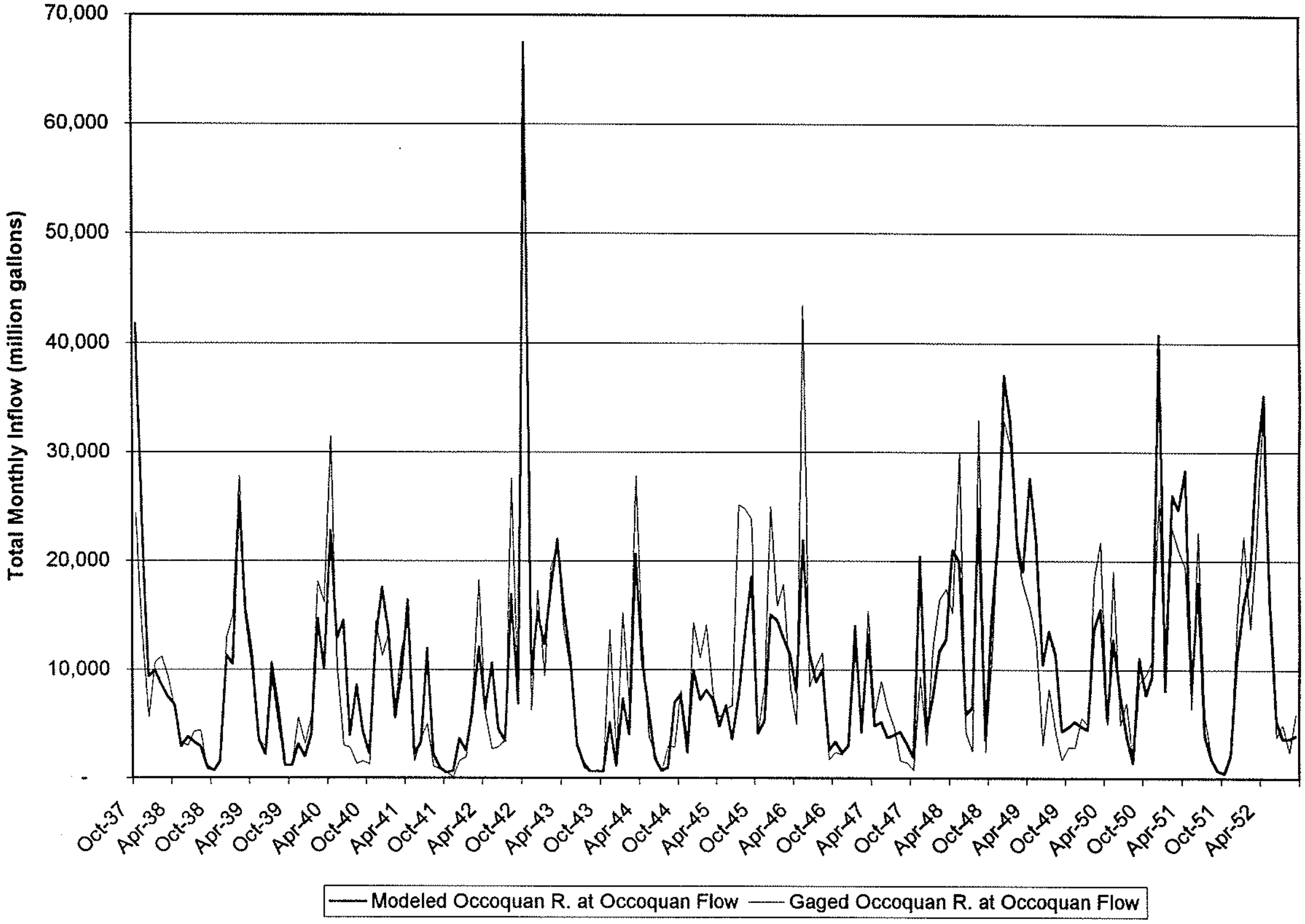

Figure 2: Modeled flow volumes using regression models developed for 1927-1937 compared to gaged flow volumes, volumes summed by month

1937-1956

The Occoquan River near Occoquan gage became operational on October 1, 1937. The Occoquan River at Occoquan gage provided the best available estimate of inflow to the Occoquan reservoir since it was located near the site of the current dam. The daily gaged stream-flows from the Occoquan River near Occoquan gage were multiplied by an area adjustment factor of 1.038 (equals 591.9 ÷ 570.0) to convert Occoquan gage flows to Occoquan reservoir watershed inflows for the period October 1, 1937 to March 31, 1956.

The drainage area to the reservoir of 591.9 square miles was estimated using a planimeter and USGS topographic maps as discussed in ICPRB report no. 98-1.

1956-1963

The stream gage on the Occoquan River near Occoquan was discontinued on March 31, 1956 due to construction of the Occoquan upper dam: the gage site was submerged after construction of the reservoir. Therefore, inflows to the reservoir were based on gaged flow to the reservoir's three main tributaries: Bull Run, Broad Run, and Cedar Run. The three gages used were Bull Run near Manassas, Broad Run at Buckland, and Cedar Run near Catlett. These gages have watershed areas of 148.0, 50.5, and 93.4 square miles respectively. Flows from the three gages were combined and multiplied by an area adjustment factor of 2.028 = (591.9 ÷ [148.0 + 50.5 + 93.4]) to create an Occoquan Reservoir inflow record for April 1, 1956 to April 24, 1963.

A comparison was made between the reservoir inflow calculated using the three gages with the reservoir inflow volume calculated using the Occoquan River near Occoquan gage (the best available estimate of inflow to the reservoir between September 1, 1950 and March 31, 1956. The area-adjustment method applied to the three gages under-predicted the total reservoir inflow calculated using the Occoquan River near Occoquan gage by 2.6 percent. Figure 3 shows a sample hydrograph of the reservoir inflows using the two methods.

1963-1969

Starting in 1963, treated wastewater was released above the Bull Run near Manassas gage, altering natural flow levels (Hirsch, 1978). Use of this gage was therefore avoided in developing natural inflows. The feasibility of using the remaining gages on Cedar Run at Catlett and Broad Run at Buckland was examined to see if these gages were adequate for estimating inflow to the Occoquan reservoir. These gages were determined to closely predict that inflow based on the Occoquan River near Occoquan gage (-0.5 percent), therefore they were selected for use during the period April 25, 1963 to April 30, 1969. These gages have watershed areas of 93.4 and 50.5 square miles, respectively. Flows from the two gages were combined and multiplied by an area adjustment factor of 4.113= (591.9 ÷ [93.4 + 50.5]) to create an Occoquan Reservoir inflow record. Figure 4 shows a sample hydrograph of the reservoir inflows calculated using area-adjustment as compared to the inflow predicted by the Occoquan at Occoquan gage.

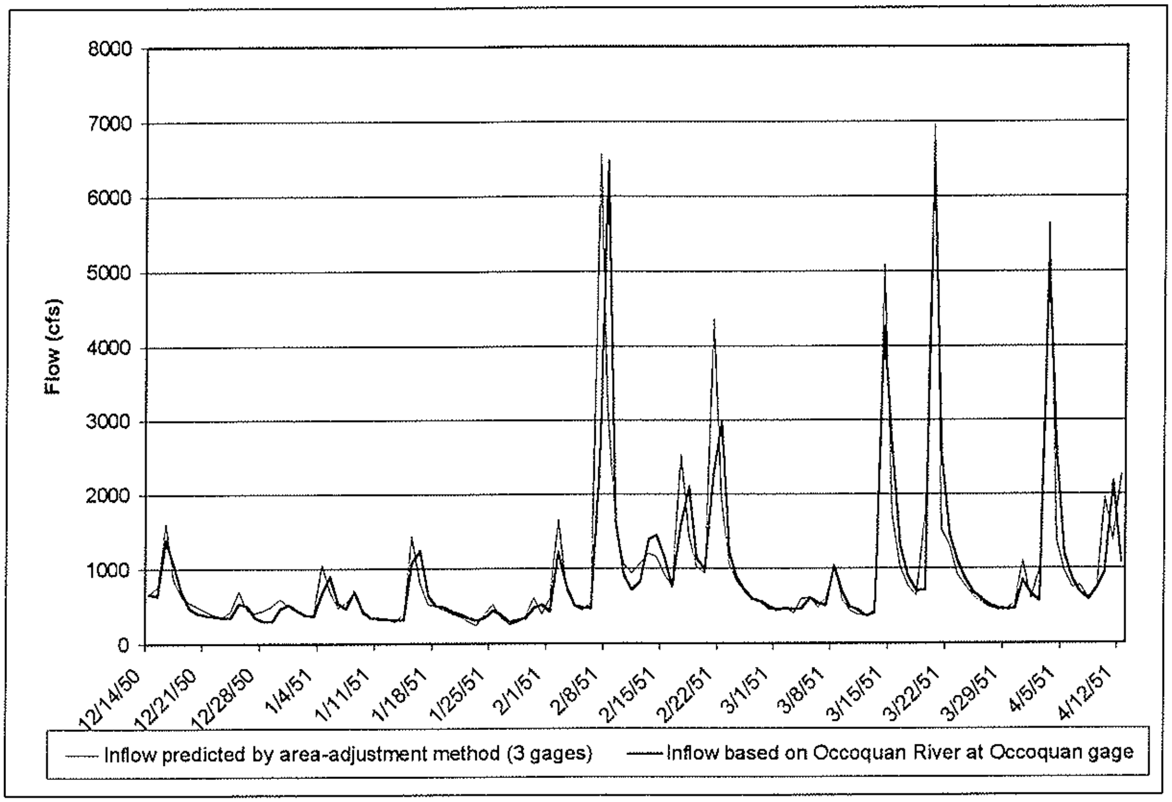

Figure 3: Example inflow based on gages on the Cedar, Broad, and Bull Runs compared to the best available estimate of inflow (the Occoquan River near Occoquan gage)

Figure 4 illustrates how the magnitude of peak flows was over-predicted by the two gages and the magnitude of recession flow (i.e., that flow occurring immediately after peak flow) was under-predicted. The difference is due to differences in time of concentration between smaller and larger watersheds. The time of concentration is the time it takes a drop of water falling in the farthest corner of the watershed to reach the lowest part of the watershed. Rain falling in a smaller watershed takes less time to concentrate at a gage site. Over a longer period, differences cancel out for the area-adjustment method if the volume of water produced in the smaller watershed per unit area is equivalent to the volume of water per unit area produced in the larger watershed.

1969-1972

The Bull Run near Catharpin gage became operational May 1, 1969. This gage was located upstream of any wastewater treatment plant discharge, so it provided useful information in developing a set of natural inflows. The three gages used were Bull Run near Catharpin, Broad Run at Buckland, and Cedar Run near Catlett. These gages have watershed areas of 25.8, 50.5, and 93.4 square miles respectively. Flows from the three gages were combined and multiplied by an area adjustment factor of 3.488 (equals 591.9 ÷ [25.8 + 50.5 + 93.4]) to create an Occoquan Reservoir inflow record for May 1, 1969 to September 30, 1972.

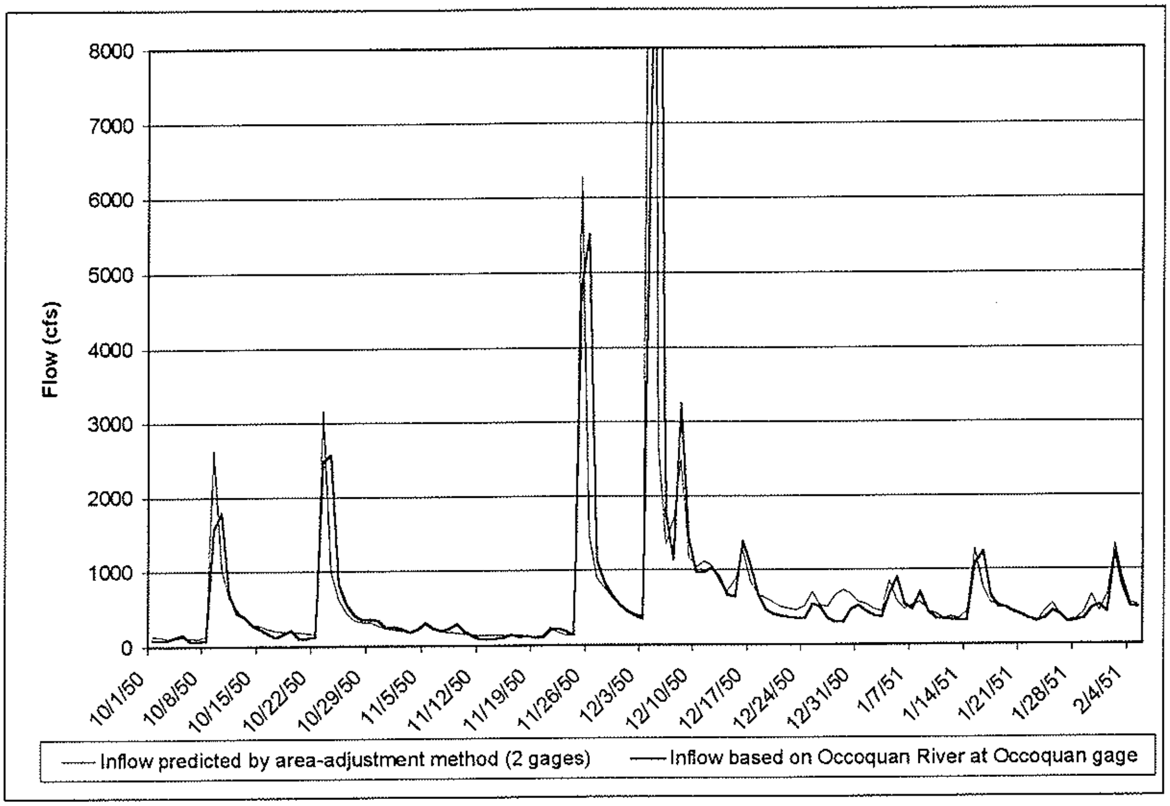

Figure 4: Example inflow based on gages on the Cedar Run and Broad Runs, compared to the best available estimate of inflow (the Occoquan River near Occoquan gage)

No direct comparison of these three gages was made since the operation of the Bull Run near Catharpin gage did not overlap with the Occoquan River near Occoquan gage. The comparison of the area adjustment method for Broad Run at Buckland and Cedar Run near Catlett gage information was -0.5 percent.

Note that prior ICPRB inflow records for this period were based in part on the Occoquan River near Manassas gage located below the confluence of Cedar and Broad Runs. The Occoquan River near Manassas gage is located downstream of Lake Manassas, an impoundment constructed on Broad Run in the late sixties. Lake Manassas began filling in 1968 (Hirsch, 1978), so flows at the Occoquan River near Manassas gage were influenced by diversions to Lake Manassas as well as by municipal withdrawals from Lake Manassas in subsequent years. Use of this gage was therefore avoided in developing natural inflows.

1972-1979

The Cedar Run near Aden gage became operational October 1, 1972. The Cedar Run near Aden gage is preferable to the Catlett gage, because the Aden gage measures runoff from a larger sub-watershed area than the Catlett gage and is thus likely to better represent flow in the Occoquan reservoir watershed. Inflow was created using the area-adjustment method applied to flows measured at the Cedar Run near Aden, the Bull Run near Catharpin, and the Broad Run at Buckland gages. Flows from the three gages were combined and multiplied by an area adjustment factor of 2.559 (equals 591.9 ÷ [155.0 + 25.8 + 50.5]) to create an Occoquan Reservoir inflow record between October 1, 1972 and September 30, 1979.

The comparison using these three sites was not directly computed because there was no period when these gages operated concurrently with the Occoquan River near Occoquan gage. However, the difference is likely to be less than that calculated for the Broad Run at Buckland and Cedar Run at Catlett gages, because the Aden gage measures flow from a larger sub-watershed area than Catlett, and the Bull Run near Catharpin gage represents additional flow information. The Broad Run at Buckland and Cedar Run at Catlett gages under-predicted the total volume of inflow based on the Occoquan River at Occoquan gage by -0.5 percent.

1979-1980

The Broad Run at Buckland gage did not operate during the period October 1, 1979 to September 30, 1980. Inflow was calculated using the area-adjustment method applied to flows measured at the Cedar Run near Aden and the Bull Run near Catharpin gages. Flows from the two gages were combined and multiplied by an area adjustment factor of 3.274 (equals 591.9 ÷ [155.0 + 25.8]) to create an Occoquan Reservoir inflow record for October 1, 1979 to September 30, 1980.

No direct comparison of these two gages was made since the Bull Run near Catharpin gage did not overlap with the Occoquan River near Occoquan gage. The comparison of the area adjustment method for Broad Run at Buckland and Cedar Run near Catlett gage was -0.5 percent.

1980-1987

The Broad Run at Buckland gage was re-activated on October 1, 1980. Inflow was calculated as for during the period 1972 to 1979, i.e., inflow was created using the area-adjustment method applied to flows measured at the Cedar Run near Aden, the Bull Run near Catharpin, and the Broad Run at Buckland gages. Flows from the three gages were combined and multiplied by an area adjustment factor of 2.559 (equals 591.9 ÷ [155.0 + 25.8 + 50.5]) to create an Occoquan Reservoir inflow record between October 1, 1980 and January 6, 1987.

1987-1995

The Bull Run near Catharpin and Broad Run at Buckland gages ceased being maintained by the USGS in January of 1987. However, the Occoquan Watershed Monitoring Laboratory (OWML) at Virginia Polytechnic Institute began monitoring the Cedar Run near Aden gage in January of 1987, and the Bull Run near Catharpin and Broad Run at Buckland gages in January of 1988. In addition to the OWML flow data, the USGS began monitoring the Cedar Run near Catlett gage on September 20, 1989.

Inflow was calculated as for during the period 1980-1987 i.e., inflow was created using the area-adjustment method applied to flows measured at the Cedar Run near Aden, the Bull Run near Catharpin, and the Broad Run at Buckland gages (area-adjustment ratio = 2.559). For the period when gage information was available from only the Cedar Run near Aden station, the appropriate area-adjustment ratio of 3.819 (equals 591.9 ÷ 155.0) was used to create reservoir inflow.

The OWML gage records have missing records for one or more of the stations on several dates. In these cases, the appropriate area-adjustment value was used. For example, if gage information was available from only the Cedar Run near Aden and the Bull Run near Catharpin gages, then inflow was calculated using the area-adjustment method applied to flows measured at the Cedar Run near Aden and the Bull Run near Catharpin gages. If flow records were missing from the Cedar Run near Aden gage, then USGS records for the Cedar Run near Catlett were substituted and the area-adjustment factor changed accordingly. (Comparison of the inflow using just the Cedar Run near Catlett gage is given in the section below which discusses the period 1995-1996.)

If flow records were missing from the Cedar Run near Aden gage in the period before the USGS Cedar Run near Catlett gage became active, then the regression model developed for the period 1927-1937 was applied to USGS gage flows for the Rappahannock River. (The regression model is discussed in detail in Appendix A.)

1995-1996

See graph

The inflow record to Occoquan reservoir from January 1, 1995 to September 30, 1996 was based on USGS records maintained for the Cedar Run near Catlett gage. This gage has a drainage area of 93.4 square miles. The record of estimated inflow to the Occoquan reservoir was obtained by multiplying the gage flows by an area-adjustment factor of 6.337 (equivalent to 591.9 divided by 93.4). Note that because this gage continues to operate as of April 1998, inflow to the Occoquan reservoir can be easily updated beyond September 30, 1996 as records are posted by the USGS.

The Cedar Run near Catlett gage was operational between September 30, 1950 and March 31, 1956 as was the gage at Occoquan River at Occoquan. The prediction of inflow volume based on the area-adjustment method applied to the Cedar Run near Catlett gage site was +0.8 percent higher than the inflow based on the Occoquan River near Occoquan (the best available estimate of inflow).

← Doesn't work in droughts

Note that ongoing updates of natural flows could also be conducted following the area-adjustment method outlined in the 1987-1995 section, using the Broad Run at Buckland, the Cedar Run near Aden, and the Bull Run near Catharpin records that are available from the Occoquan Watershed Monitoring Laboratory.

3. Current and projected diversions from Lake Manassas

Lake Manassas is an impoundment constructed on the Broad Run portion of the Occoquan watershed. The lake began filling in 1968 and has a watershed of approximately 60 square miles. The City of Manassas withdraws water from Lake Manassas and supplies finished water to Prince William County Service Authority in western Prince William County. Withdrawals from Lake Manassas reduce the natural flows that would have occurred in Broad Run.

The City of Manassas was contacted to determine current and projected withdrawals. The 1995 withdrawals averaged 5.8 mgd and 1996 withdrawals averaged 6.3 mgd. The withdrawals followed a seasonal pattern, peaking in the summertime months. The mean monthly variation in demand is shown in Table 3 for the years 1995 through 1996. Mean monthly production factors are used to disaggregate future annual average daily demands to monthly average daily demands.

Withdrawals from Lake Manassas are projected to increase to 8 mgd in 2020, and reach 12 mgd in year 2050 (Dee Wright, City of Manassas Sewer and Water Department, personal communication, April, 1998). Note that the effect of evaporation from Lake Manassas on natural flows to the Occoquan reservoir was not considered in this analysis.

Table 3: Demand and mean monthly production factors for the City of Manassas, based on 1995 through 1996 data

Month	1995 Demands (MG)	1996 Demands (MG)	Mean Monthly Production Factor
January	165,888	164,012	7.4%
February	151,583	166,242	7.2%
March	163,237	172,712	7.6%
April	168,890	172,372	7.7%
May	176,317	193,938	8.3%
June	172,149	219,382	8.8%
July	195,911	226,336	9.5%
August	238,340	226,105	10.5%
September	195,483	209,844	9.1%
October	175,881	194,450	8.3%
November	158,526	179,943	7.6%
December	163,458	187,979	7.9%
Totals	2,125,663	2,313,315	100.0%
Average MGD	5.8	6.3	NA

4. Current and projected UOSA wastewater return flows

Inflow to the Occoquan reservoir is significantly increased above naturally occurring flow levels by wastewater releases from the Upper Occoquan Sewage Authority's (UOSA) wastewater treatment plant near Manassas. The UOSA plant serves four jurisdictions: Fairfax County, Prince William County, Manassas, and Manassas Park. Black and Veatch (1996) contacted each of the four jurisdictions in 1995 to establish their wastewater flow projections through year 2050. The combined UOSA flow into the reservoir from all jurisdictions is projected to increase from 20.3 mgd in year 1995 to 66.9mgd in year 2050.

Table 4 shows the projected wastewater return flows for the four jurisdictions as given in the Black and Veatch report. Manassas, Manassas Park, and Prince William County reported projections on an annual basis through the year 2005, and estimated year 2050 return flows. Between year 2005 and 2050, annual return flows were estimated by linear interpolation for these jurisdictions. Fairfax County reported projections on an annual basis through the year 2020 and provided an estimate of year 2050 flows. Between year 2020 and 2050, annual return flows were estimated by linear interpolation for Fairfax County.

Table 4: Projected UOSA wastewater return flows

Fiscal Year	City of Manassas Flow (mgd)	City of Manassas Park Flow (mgd)	Fairfax County Flow (mgd)	Prince William County Flow (mgd)	Total Flow (mgd)
1995	4.184	1.150	9.48	5.5	20.314
1996	4.200	1.240	9.92	5.4	20.760
1997	4.323	1.310	10.37	5.78	21.783
1998	4.432	1.350	10.84	6.18	22.802
1999	4.570	1.390	11.32	6.63	23.910
2000	4.710	1.430	11.81	7.11	25.060
2005	4.780	1.630	14.1	9.52	30.030
2010	5.286	2.123	15.43	11.115	33.954
2020	6.000	2.870	18.06	14.936	41.865
2030	6.000	3.616	22.264	18.757	50.638
2040	6.000	4.363	25.819	22.579	58.760
2050	6.000	5.110	29.373	26.400	66.883

5. Storage loss due to sedimentation

The current storage volume of the reservoir was estimated from a bathymetric survey of the Occoquan reservoir, conducted by the Occoquan Watershed Monitoring Laboratory in April of 1995. The volume of the Occoquan reservoir at the normal pool elevation of 122 feet is 8.52 billion gallons. The volume of water in dead storage is 0.328 billion gallons (dead storage is that water volume stored below the lowest water intake structure below elevation 80 feet). The difference in these two volumes is the water available for water supply, 8.19 billion gallons.

The volume of storage in the Occoquan reservoir is expected to decrease over time due to the effects of sedimentation. The original estimate of Occoquan reservoir volume was 11 billion gallons, and was developed prior to 1955. No record exists of how this calculation was made. The large difference in the estimates of original and current

Occoquan volume may be due to inaccuracies in the original estimate of reservoir volume as well as from sediment deposition in the reservoir. Black and Veatch found likely inaccuracies in the 1948 USGS quad-maps that might have been used to originally determine reservoir volume (Black and Veatch, 1996). A good assessment of the sedimentation rate is not currently possible because the original estimate of reservoir volume is uncertain and only one bathymetric survey has since been conducted (in 1995).

However, a storage loss rate of 69 million gallons a year assumes that the original 11 billion gallon estimate of volume is accurate, and that the sediment accumulation is distributed evenly throughout the years. Using this storage loss rate, the total storage in 2020 would be 6.8 billion gallons, and in 2050 the storage would be 4.7 billion gallons. Alternatively, the Black and Veatch study (1996) suggests that a **mid-range** estimate of sedimentation-rate would result in an estimated storage volume of **6.5 billion gallons in 2050.**

6. Evaporation and precipitation

Evaporation can be a significant factor in the reservoir water balance equation, especially during summertime periods of drought. The National Climatic Data Center (NCDC) maintains pan evaporation data for the Piedmont Research Station located in Orange County, Virginia near the town of Culpeper and approximately 50 miles from the reservoir. Average and maximum monthly pan evaporation for the Piedmont Research Station is given in Table 5 for the years 1972 through 1996.

Average monthly precipitation for the Occoquan Reservoir is given in Table 5 for the years 1931-1985. Precipitation data was compiled from the NCDC for weather stations located in Manassas, Virginia. Manassas is located within the reservoir watershed.

Table 5: Average evaporation and precipitation values for Occoquan Reservoir

Month	Average Pan Evaporation, 1972-1996 (inches)	Maximum Pan Evaporation, 1972-1996 (inches)	Average Precipitation, 1931-1985 (inches)
January	1.3[a]	--	2.7
February	1.1[a]	--	2.3
March	1.5[a]	--	3.1
April	5.4	6.5	3.0
May	6.1	7.4	3.9
June	7.0	8.5	3.4
July	7.2	9.0	3.9
August	5.9	6.9	4.1
September	4.7	5.5	3.4
October	3.6	4.4	3.1
November	2.7[a]	--	2.8
December	1.8[a]	--	2.9

Note: [a] Evaporation at the Piedmont Research station was not measured during the months of November through March. Evaporation rates for these months from Hirsch (1978).

Actual evaporation from the reservoirs is likely to be less than the pan evaporation rates given in Table 5. A coefficient of 0.7 can be used to adjust pan evaporation to approximate reservoir evaporation rates (Linsley, 1949, 1982). Using the adjusted pan evaporation rate, evaporation could account for up to 1.4 billion gallons of water loss from the Occoquan reservoir during the months of April through October. (This calculation assumes no rainfall inputs, the reservoir surface area corresponding to the full-pool reservoir elevation, the maximum pan evaporation rates given in Table 5, and a pan adjustment coefficient of 0.7.)

7. Summary

When possible, the methods used in creating each segment of the dataset were examined quantitatively to compare how well each method compared to the best available estimate of inflow volume. The Occoquan River at Occoquan gage site was the best available estimate of inflow to the Occoquan reservoir since it was located near the site of the current dam. Six regression models were developed corresponding to low-, medium-, and high-flow intervals in the periods October through April and May through September. The October through April low-, medium- and high-flow regression models predicted inflow volume within -1.3 to +0.6 percent of that predicted by the Occoquan gage, and the May through September models' results were between -9.2 to +0.8 percent of the Occoquan gage. During the periods when there were active gages in the Occoquan Reservoir watershed and the area-adjustment models could be used, those models predicted inflow volume within -0.5 to +2.6 percent of that predicted by the Occoquan River at Occoquan gage.

Table 6 summarizes the calculated daily inflows to the Occoquan reservoir by month from October 1927 through September 1996. Figure 5 summarizes annual inflow to Occoquan Reservoir. Data are available in electronic format from ICPRB for both daily and monthly inflows.

Table 6: Monthly inflows to the Occoquan Reservoir, 1927 to 1996

UNITS = 'MG/1000' = BG

	1927	1928	1929	1930	1931	1932	1933	1934	1935	1936	1937	1938	1939	1940	1941	1942	1943	1944
January		5.5	9.4	5.8	1.6	6.2	17.3	2.9	19.4	33.8	36.6	11.1	15.6	5.9	13.8	2.0	9.8	15.9
February		12.4	11.3	11.5	0.6	7.1	13.9	1.2	24.2	35.3	31.0	11.7	28.9	18.8	6.9	7.8	20.1	7.1
March		7.8	20.8	11.6	1.8	14.1	13.6	18.1	16.3	52.5	12.1	9.8	16.5	16.8	12.3	18.9	22.3	28.9
April		20.7	25.4	7.9	3.7	10.1	44.6	8.4	27.8	15.0	46.1	6.6	12.2	32.7	14.9	6.2	14.2	13.5
May		10.4	20.3	2.6	5.4	24.4	15.1	4.9	9.1	4.1	14.5	3.4	3.4	10.8	1.6	2.8	10.1	4.0
June		3.8	9.9	1.2	2.0	2.9	4.1	5.6	3.7	2.0	12.0	3.1	3.1	3.1	3.8	3.0	3.0	2.3
July		3.0	4.5	0.8	2.4	2.2	4.8	1.6	3.6	2.3	4.0	4.5	9.5	2.9	5.2	3.6	1.0	0.7
August		23.6	1.1	0.7	3.7	0.9	10.0	2.8	1.8	1.3	19.5	4.5	4.8	1.4	1.1	28.6	0.6	3.1
September		9.3	0.8	0.6	1.2	0.7	5.2	13.9	15.6	0.7	5.6	0.8	1.2	1.6	0.9	7.2	0.6	3.0
October	19.1	3.4	24.2	0.5	0.5	9.0	2.1	4.2	3.1	5.4	25.4	0.7	1.3	1.4	0.6	61.6	0.5	8.5
November	10.5	2.3	7.2	0.5	0.5	35.6	1.5	6.6	9.7	1.2	14.2	1.6	5.8	15.1	0.1	6.5	14.3	3.8
December	16.6	6.1	6.2	0.6	0.6	12.5	1.7	23.7	9.1	13.4	5.8	13.5	3.3	11.7	1.7	18.0	2.4	14.9
Total	**46.2**	**108.3**	**141.1**	**44.2**	**24.0**	**125.8**	**133.8**	**93.9**	**143.5**	**167.1**	**226.8**	**71.3**	**105.6**	**122.2**	**62.9**	**166.2**	**99.0**	**105.6**

	1945	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962
January	11.6	16.5	12.1	12.7	31.5	5.1	9.8	23.1	27.0	9.5	2.2	3.6	14.5	25.7	5.9	11.5	16.4	11.9
February	14.7	18.6	4.6	17.0	21.6	19.0	23.9	14.3	11.8	3.5	7.9	17.7	21.5	18.4	4.9	28.3	49.2	18.9
March	7.9	8.8	16.0	18.1	18.5	22.6	21.8	22.7	30.0	12.0	19.0	20.5	18.6	38.5	10.4	16.6	24.2	42.0
April	5.8	5.1	6.1	15.8	16.3	5.2	20.2	36.0	13.9	5.3	6.5	9.7	17.7	21.0	16.6	25.9	24.7	20.4
May	6.6	45.2	9.3	31.0	13.2	19.8	6.7	15.0	20.8	4.4	11.5	1.9	2.2	19.5	2.8	21.2	10.5	7.7
June	6.9	8.8	6.6	4.4	3.2	5.1	23.5	3.9	7.7	0.9	18.4	1.4	1.3	2.4	2.8	9.4	4.9	4.0
July	26.1	10.7	4.9	2.6	8.6	7.2	6.1	5.1	2.2	0.7	2.5	44.0	0.3	11.1	1.1	2.0	2.9	2.1
August	25.7	12.1	1.7	34.2	4.4	1.6	2.0	2.5	0.9	1.0	47.7	5.6	0.3	3.3	0.9	7.0	2.4	0.5
September	24.7	1.8	1.5	2.5	1.7	9.1	0.7	6.2	0.8	0.6	2.3	5.8	1.9	0.8	5.7	8.0	3.1	0.4
October	4.2	2.5	0.8	11.0	3.0	9.9	0.4	1.1	0.5	0.4	3.6	11.8	4.3	0.9	1.7	1.4	1.4	0.5
November	8.8	2.3	9.7	23.1	2.9	11.4	2.6	25.3	0.7	0.7	2.6	14.7	4.6	1.1	3.8	1.4	2.9	7.0
December	25.9	3.2	3.2	34.1	5.8	26.7	15.4	14.4	7.2	4.7	1.6	12.5	34.2	1.4	7.4	1.7	11.6	4.9
Total	**169.1**	**135.5**	**76.5**	**206.7**	**130.8**	**142.5**	**133.1**	**169.7**	**123.4**	**43.6**	**125.6**	**149.0**	**121.4**	**143.9**	**64.1**	**134.4**	**154.2**	**120.3**

	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980
January	18.3	32.4	18.4	1.3	16.1	27.2	8.3	13.8	18.5	9.9	22.6	27.7	17.8	46.8	2.3	62.7	53.2	29.8
February	8.0	20.9	29.3	20.5	11.3	6.7	9.0	22.7	36.0	39.2	27.0	7.6	16.3	13.1	4.2	8.6	55.0	5.5
March	37.3	14.7	34.5	14.2	31.4	18.9	13.6	12.7	16.5	19.6	17.5	11.8	41.7	10.7	12.5	29.2	29.6	32.5
April	3.7	20.8	8.4	9.2	4.2	4.0	4.6	23.8	15.1	20.6	41.9	13.4	8.2	19.1	8.4	8.2	13.5	20.9
May	2.2	8.7	3.4	11.7	7.3	6.6	1.5	5.7	25.1	17.6	15.0	9.2	8.2	3.7	2.1	28.6	9.0	10.2
June	4.7	1.0	1.0	1.6	2.6	16.9	2.5	2.8	13.5	121.1	6.2	9.6	3.0	2.7	0.7	3.0	22.4	1.5
July	0.4	1.0	0.5	0.2	2.8	4.5	1.6	11.1	1.7	10.3	5.0	0.9	13.0	2.1	0.5	4.5	2.7	0.9
August	0.7	0.4	3.0	0.1	23.4	1.7	5.2	1.9	3.2	2.8	11.5	2.2	6.7	0.6	0.5	9.4	15.8	0.3
September	0.2	0.8	0.7	14.9	1.7	0.6	6.2	0.4	2.4	1.2	6.5	5.4	66.8	2.6	0.4	1.0	44.9	0.1
October	0.2	2.3	1.9	13.8	2.2	0.8	1.5	0.9	13.0	5.7	4.3	1.4	13.3	50.8	1.7	0.6	68.9	0.5
November	5.5	3.4	0.6	3.5	1.7	5.4	2.9	23.7	13.4	36.9	2.2	1.3	11.5	6.6	11.8	1.5	14.9	1.6
December	4.7	8.4	0.7	9.7	26.1	5.2	14.0	15.1	14.1	47.5	35.3	45.1	13.2	12.3	35.2	10.3	6.0	1.1
Total	**85.9**	**114.9**	**102.4**	**100.7**	**130.6**	**98.4**	**70.9**	**134.5**	**172.6**	**332.4**	**195.0**	**135.6**	**219.6**	**171.3**	**80.2**	**167.7**	**336.0**	**104.8**

	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	Grand Total
January	0.8	8.9	5.4	12.6	8.3	5.8	14.7	23.2	6.6	24.7	33.0	11.1	27.1	28.0	24.7	45.2	1170.2
February	12.4	49.8	24.9	44.0	31.2	18.7	19.1	17.9	7.0	13.1	4.5	10.1	13.8	30.7	7.5	16.1	1227.3
March	2.8	20.5	34.7	55.5	6.6	13.3	17.3	8.8	19.3	10.8	19.3	17.2	64.1	61.1	11.3	16.4	1440.4
April	2.9	11.5	77.5	43.8	2.9	8.6	33.8	7.8	11.1	21.0	8.9	12.7	32.5	11.7	3.7	16.3	1137.3
May	5.2	6.7	15.3	20.7	4.4	2.6	5.7	21.2	61.8	22.7	3.6	7.5	30.2	3.8	9.2	18.0	810.4
June	2.7	26.7	4.5	2.9	2.2	0.5	1.7	1.2	25.6	3.5	2.2	6.3	3.4	2.4	8.3	12.0	507.0
July	3.4	2.3	1.1	9.0	0.3	0.5	1.1	0.6	11.6	4.7	1.6	9.5	1.0	12.9	4.2	3.7	327.8
August	11.6	4.8	0.4	25.3	0.3	1.1	0.1	0.4	2.1	4.9	2.4	3.9	0.6	20.9	0.8	9.6	441.7
September	2.7	1.5	0.3	1.1	0.2	0.3	14.5	0.2	2.9	1.1	2.3	6.4	1.7	3.5	0.2	35.8	378.2
October	2.8	1.5	4.9	2.0	4.7	0.2	1.0	0.5	13.6	10.0	2.0	3.5	1.1	1.7	3.5		467.4
November	1.5	7.7	22.3	9.5	23.0	1.7	1.6	4.1	10.4	8.3	2.9	21.7	13.2	2.7	16.7		558.5
December	4.8	10.8	35.1	8.5	9.9	19.8	21.5	2.8	5.9	16.6	13.0	41.7	19.9	5.1	14.0		911.4
Total	**53.5**	**152.8**	**226.5**	**235.0**	**94.1**	**72.9**	**132.2**	**88.8**	**177.9**	**141.4**	**95.7**	**151.7**	**208.6**	**184.4**	**104.2**	**173.0**	**9377.6**

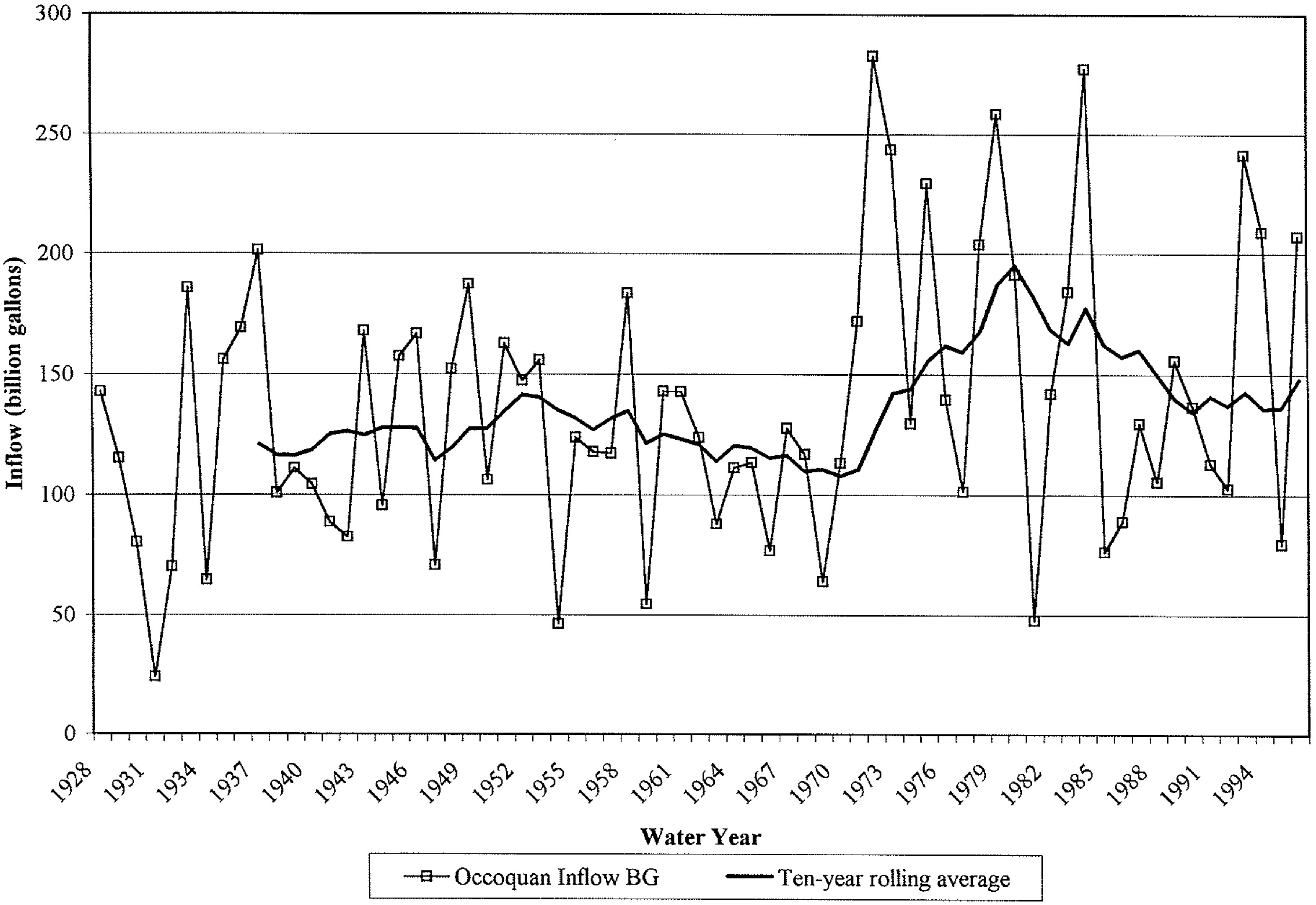

Figure 5: Annual inflow to Occoquan Reservoir, 1928-1995

8. References

Black and Veatch, 1996. *Technical Memorandum No. 1: Safe Yield of the Occoquan Reservoir*, prepared for the Fairfax County Water Authority.

Ferguson, R. 1986. River Loads Underestimated by Rating Curves. *Water Resources Research*. Volume 22, January 1986. No. 1. American Geophysical Union.

Hirsch, R. 1978. *Risk Analyses for a Water-Supply System– Occoquan Reservoir, Fairfax and Prince William Counties, Virginia*. US Geological Survey, Open-File Report 78-452.

Linsley, R.K., Kohler, M.A., Paulhus, J.L.H., 1982. *Hydrology for Engineers*. 3rd ed. McGraw-Hill, Inc., New York, NY.

Linsley, R.K., Kohler, M.A., Paulhus, J.L.H., 1949. *Applied Hydrology*. McGraw-Hill, Inc., New York, NY.

Schwartz, S. 1996. *Operating Alternatives for Occoquan Treatment Capacity*. Prepared for Black and Veatch, Washington, D.C.

Appendix A: Occoquan inflow regression-model development (1927-1937)

Description of regression models

No stream-flow gage information exists on the Occoquan watershed in northern Virginia during the critical time period between 1927-1937. However, flow records do exist for the Rappahannock River during that period. A series of non-linear regressions was developed for low-, medium-, and high-flows for the periods May through September and October through April between gaged flow on the Rappahannock and Occoquan rivers during October 1, 1937 to December 31, 1955. The independent variable was flow on the Rappahannock River at Kelly's Ford. The dependent variable was flow on the Occoquan River at Occoquan. These regression relationships were applied to the flow on the Rappahannock at Kelly's Ford to create a flow record for the Occoquan River at Occoquan gage between October 1, 1927 and September 30, 1937. The flows predicted by the regression equations were further adjusted by an area-adjustment factor of 1.038 (equals 591.9 ÷ 570.0) to convert Occoquan River at Occoquan flow into reservoir watershed inflow.

Extending the regression data set

There were two USGS gauging stations in the Rappahannock watershed that were useful for the regression analysis during the time that the Occoquan River at Occoquan USGS gage was operational (between October 1, 1937 and December 31, 1955). These stations were the Rappahannock River at Remington and the Rappahannock River at Kelly's Ford. Since the regression analysis was based on a single independent variable (flow on the Rappahannock River at Kelly's Ford), flows on the Rappahannock at Remington were adjusted to simulate flows on the Rappahannock at Kelly's Ford for the period 1952 to 1955. This flow adjustment allowed for regression over the maximum number of overlapping data points with that of the Occoquan River at Occoquan gage. Preliminary model validation work suggested that a better prediction of Occoquan River at Occoquan flow could be obtained when the extended data set was used.

The Rappahannock at Remington station is located very close to the Rappahannock at Kelly's Ford gage site and flow at the two gages is well correlated (R squared = 0.990, Figure I). A relationship between the two gages was calculated by comparing the total volume of flow during the overlapping period when both gages were operating. The ratio of the cumulative flow at Kelly's Ford divided by the cumulative flow at Remington from October 1, 1942 to September 30, 1952 was 1.041. Flow at Remington was converted to an equivalent flow at Kelly's Ford by multiplying the Remington flow by this conversion factor. Figure II shows an example hydrograph comparing the simulated flow at Kelly's Ford (i.e., the adjusted flow at Remington) with the gage flow at Kelly's Ford.

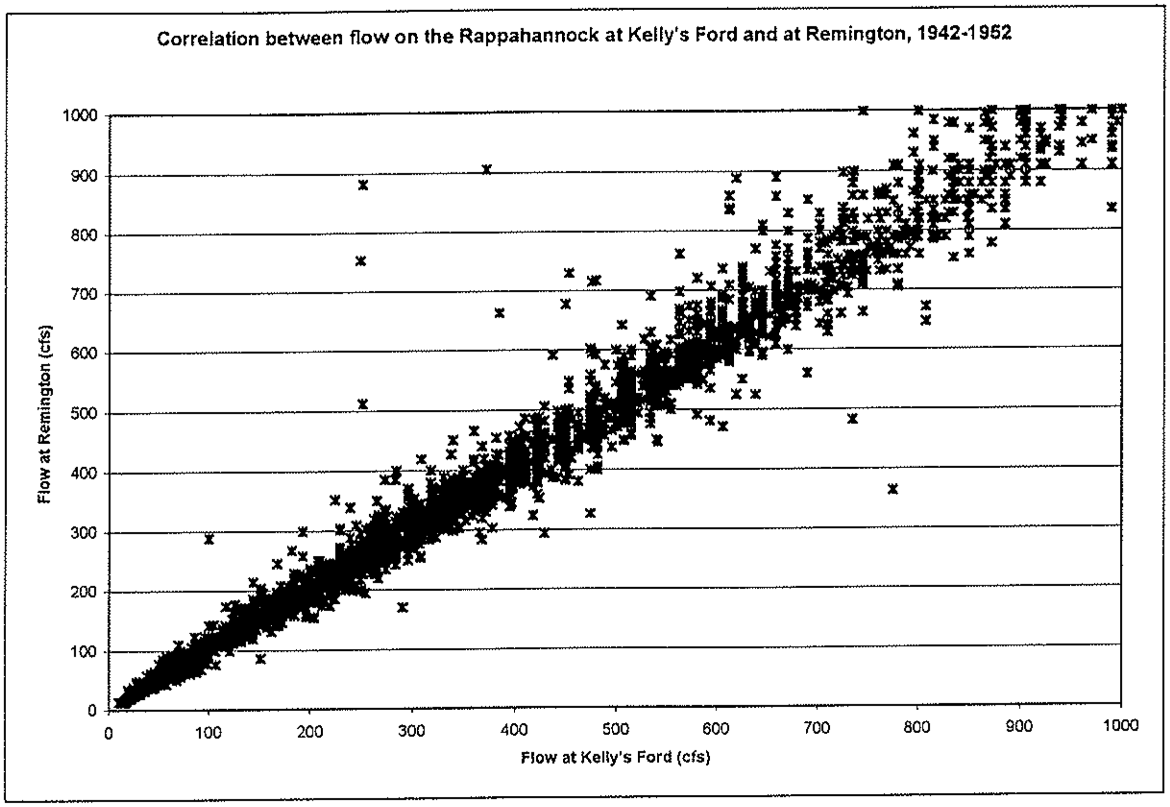

Figure I: Correlation between flow at two gage sites on the Rappahannock

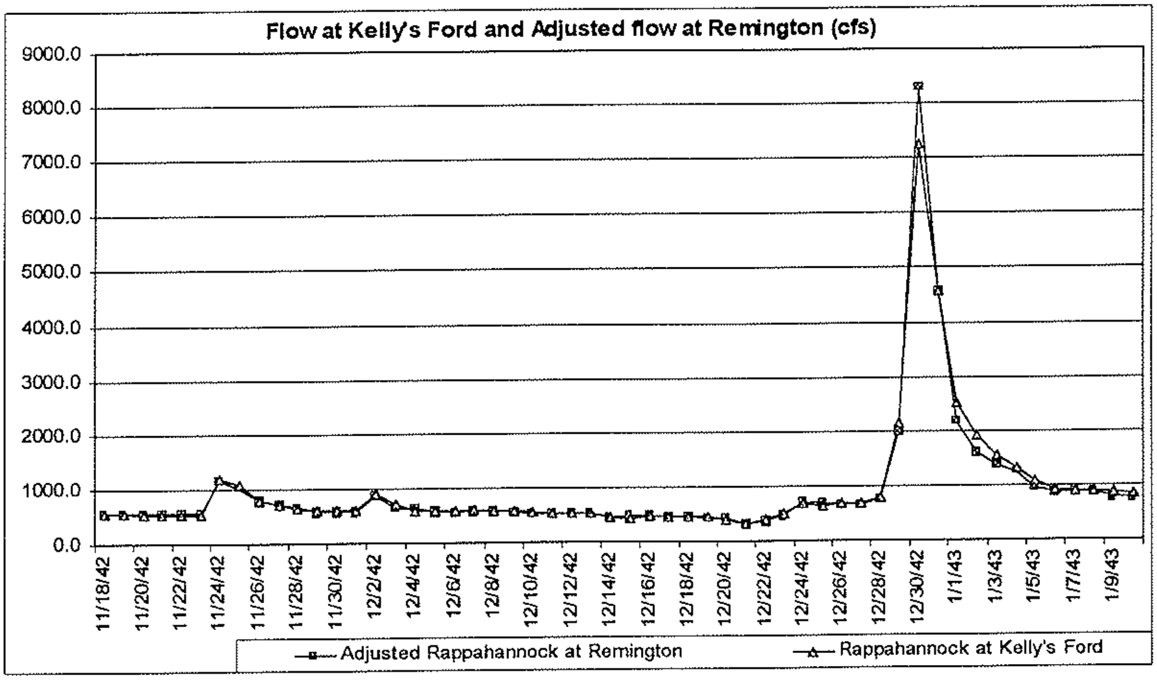

Figure II: Example hydrograph comparing simulated flow at Kelly's Ford on the Rappahannock (based on Rappahannock at Remington gaged flow) with gaged flow at Kelly's Ford

May through September medium-flow model

Special consideration was needed for the medium-flow, May through September model. During the summer, heavy thunderstorms can occur on the local watershed scale, whereas wintertime storm fronts are usually much larger and encompass both watersheds. Local summertime thunderstorms can obscure the relationship between normal flows, particularly at the medium flow range (as based on an examination of preliminary model validation results). To assist in predicting the summertime flow in the Occoquan, precipitation records for the Occoquan and Rappahannock were obtained and local Occoquan thunderstorm events were removed from the calibration data set for the medium-flow regression. Seven data points were removed from the medium-flow calibration data set, from a total of 622 calibration data points. Table I lists each data point and shows the sum of the current and antecedent precipitation for both watersheds.

Table I: Data points removed from the medium-flow May through September calibration data set.

Date	Flow on Rappahannock at Kelly's Ford (cfs)	Flow on the Occoquan R. at Occoquan (cfs)	Sum of current-day and 2-day antecedent precipitation at Manassas station in Occoquan watershed (in)	Sum of current-day and 2-day antecedent precipitation at Culpeper station in Rappahannock watershed (in)
7/11/42	268	1340	1.25	0
6/2/44	209	642	0.75	0.04
7/18/45	380	10500	3.35	0.84
7/19/45	350	3340	3.99	1.29
7/20/45	300	2990	2.27	0.45
6/9/47	470	1140	2.01	0.94
7/16/50	420	1570	0.93	0.14

The calibration graphs and calibration curve equations are shown in Figures III through VIII. The May through September medium flow calibration graph shows the data points in Table I that have been removed from the calibration data set.

Comparison to prior model

An earlier ICPRB model was used to predict flow at the Occoquan River at Occoquan gage (Q_o), based on gaged flow on the Rappahannock at Kelly's Ford, Q_r. The regression relationship was assumed to be of the form $Q_o = \alpha Q_r^{\beta}$. When regressed over the entire range of Rappahannock flows, a model of this type tends to over-predict low-flows. During the drought of record (between June of 1930 through January of 1932), the prior model predicted a total inflow of 31.8 billion gallons (BG) and the revised model predicted a total inflow of 29.0 BG (-9.0 percent).

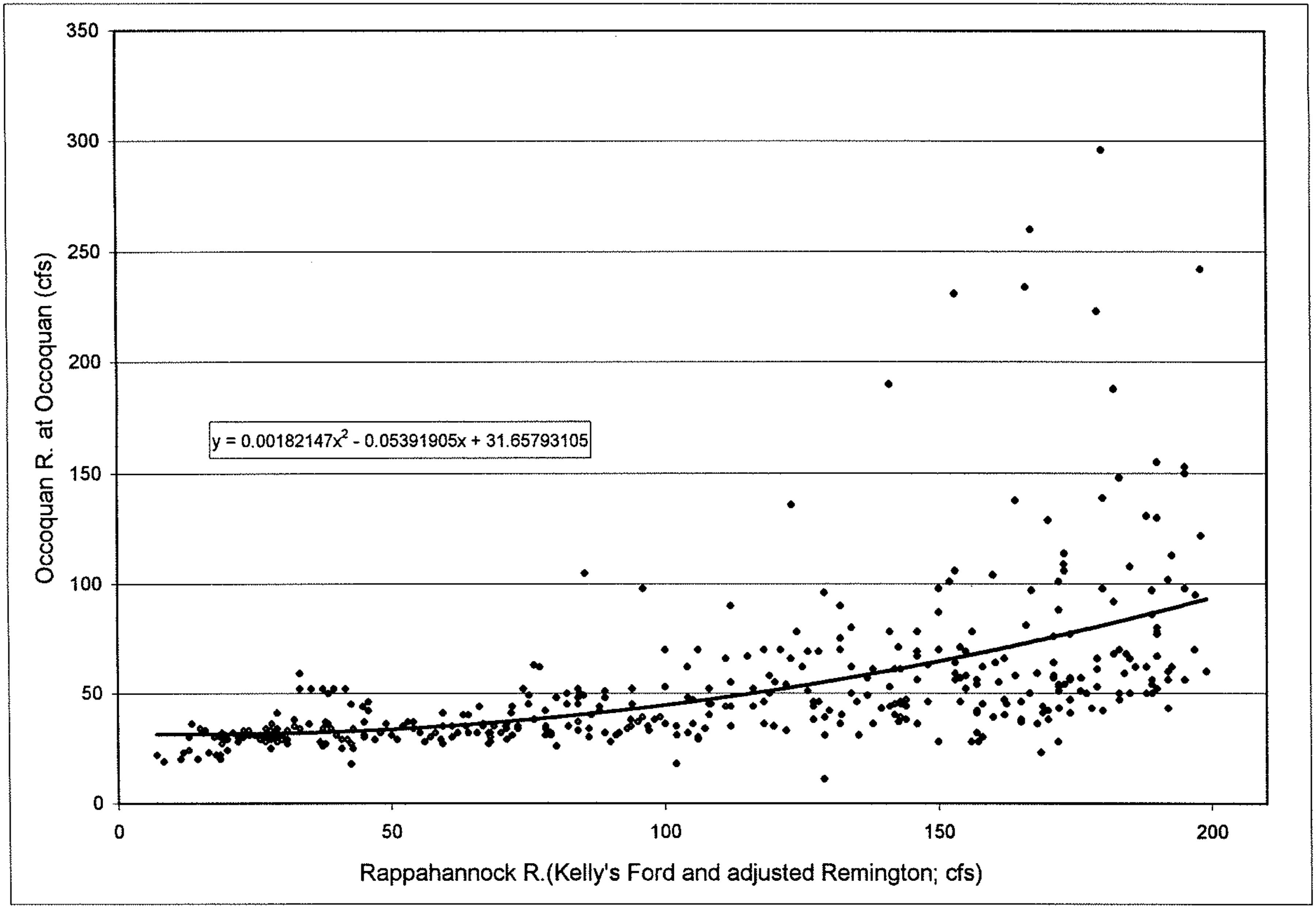

Figure III: May through September low-flow model calibration, 1937-1955

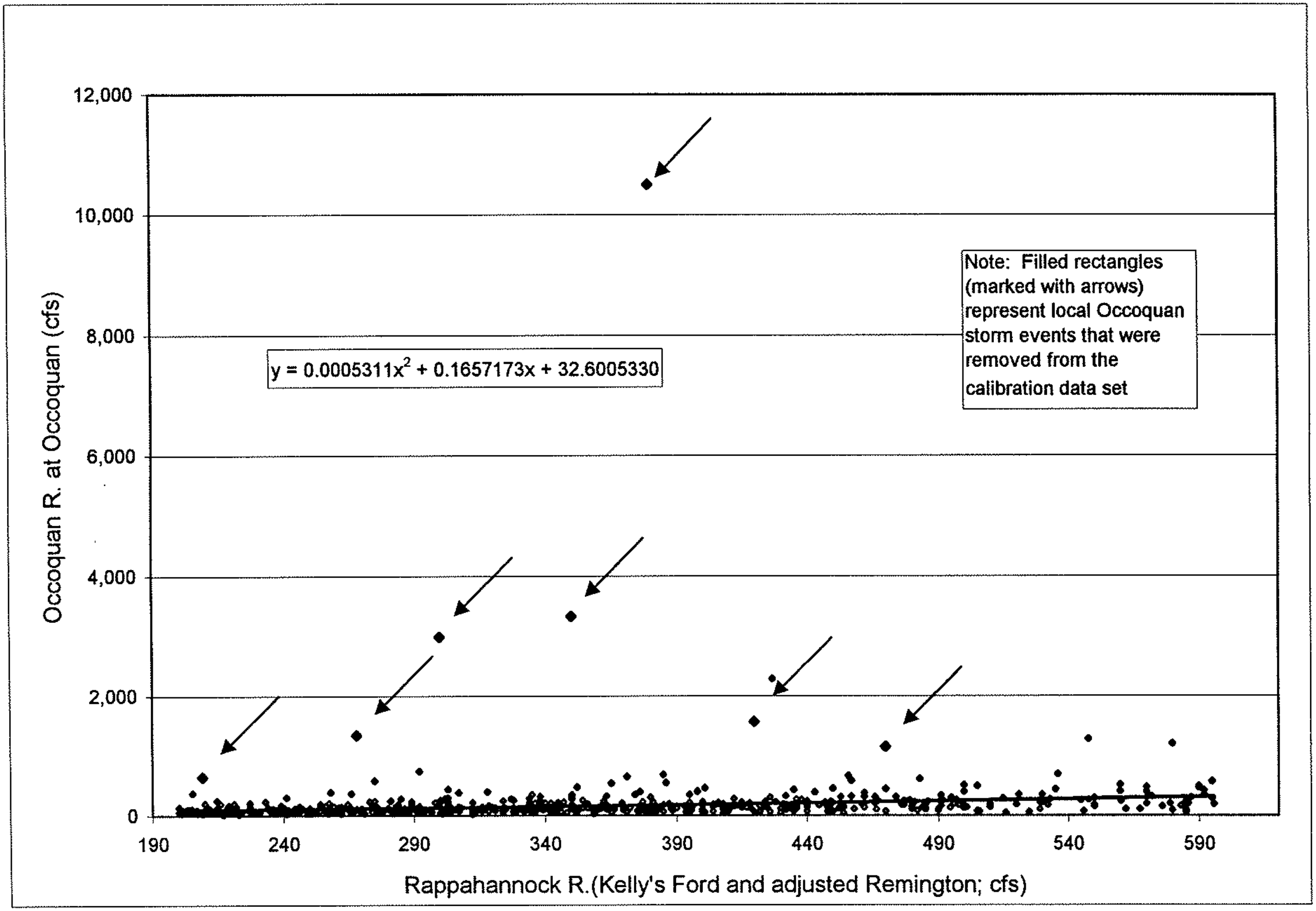

Figure IV: May through September medium-flow model calibration, 1937-1955

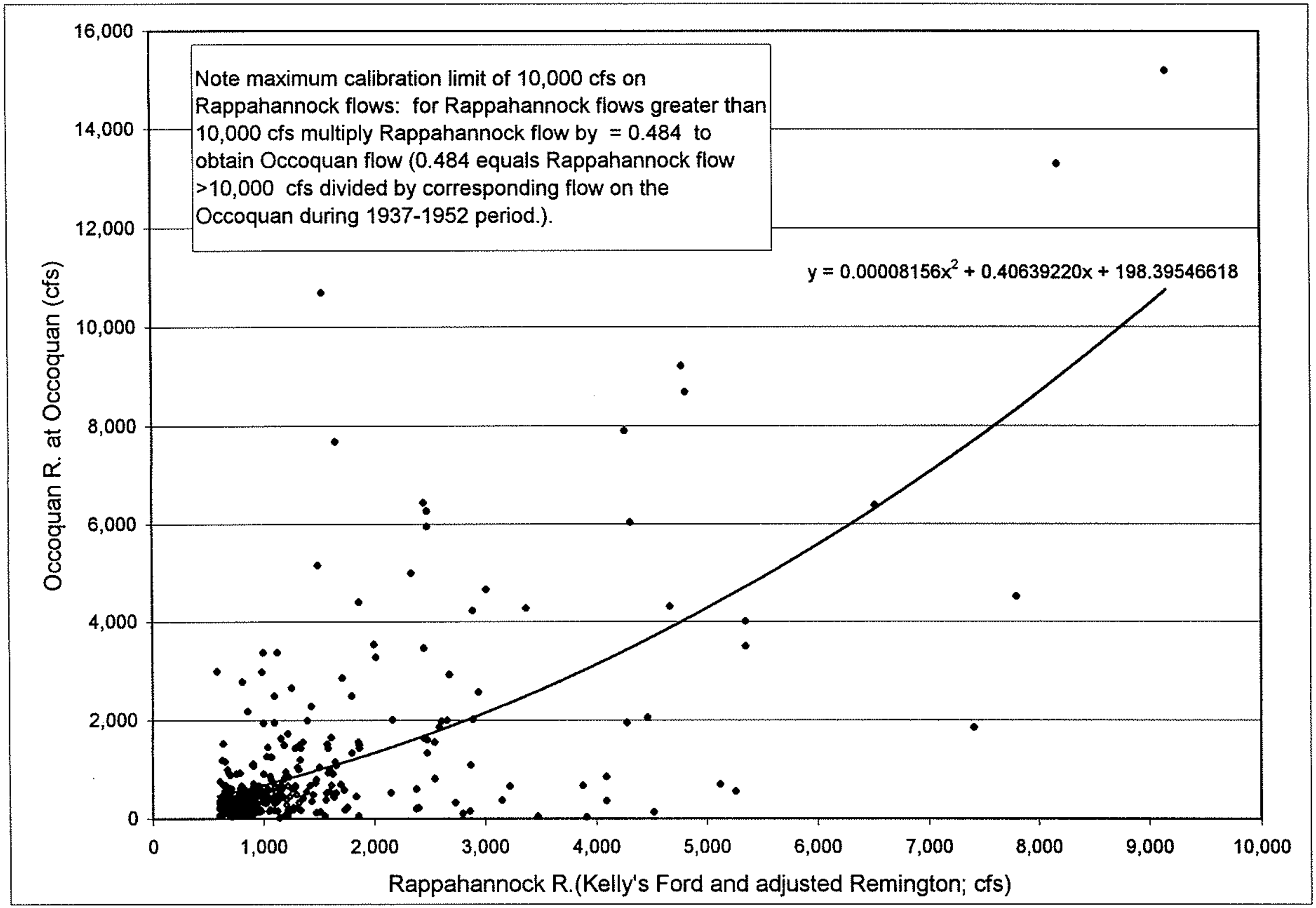

Figure V: May through September high-flow model calibration, 1937-1955

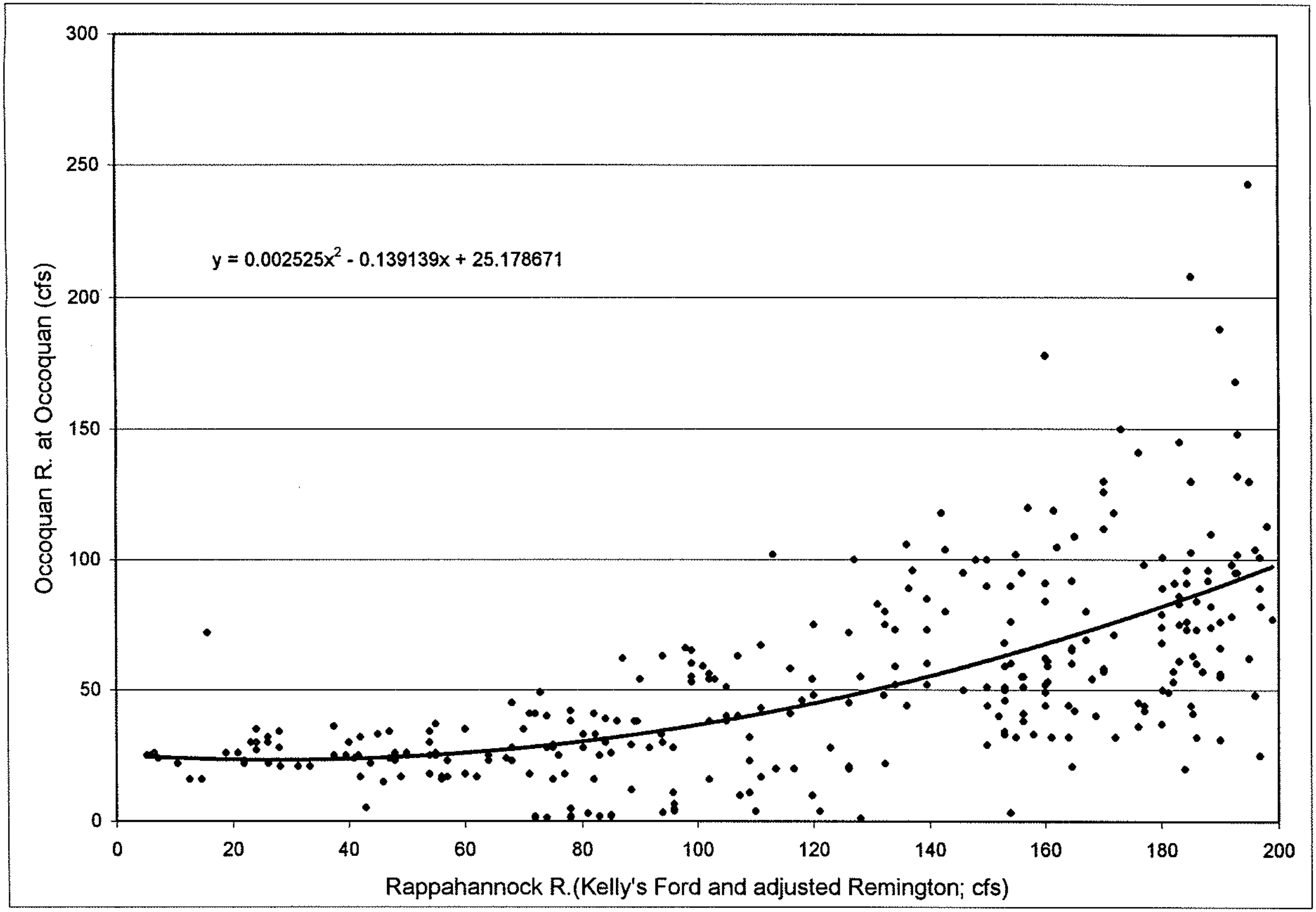

Figure VI: .October through April low-flow model calibration, 1937-1955

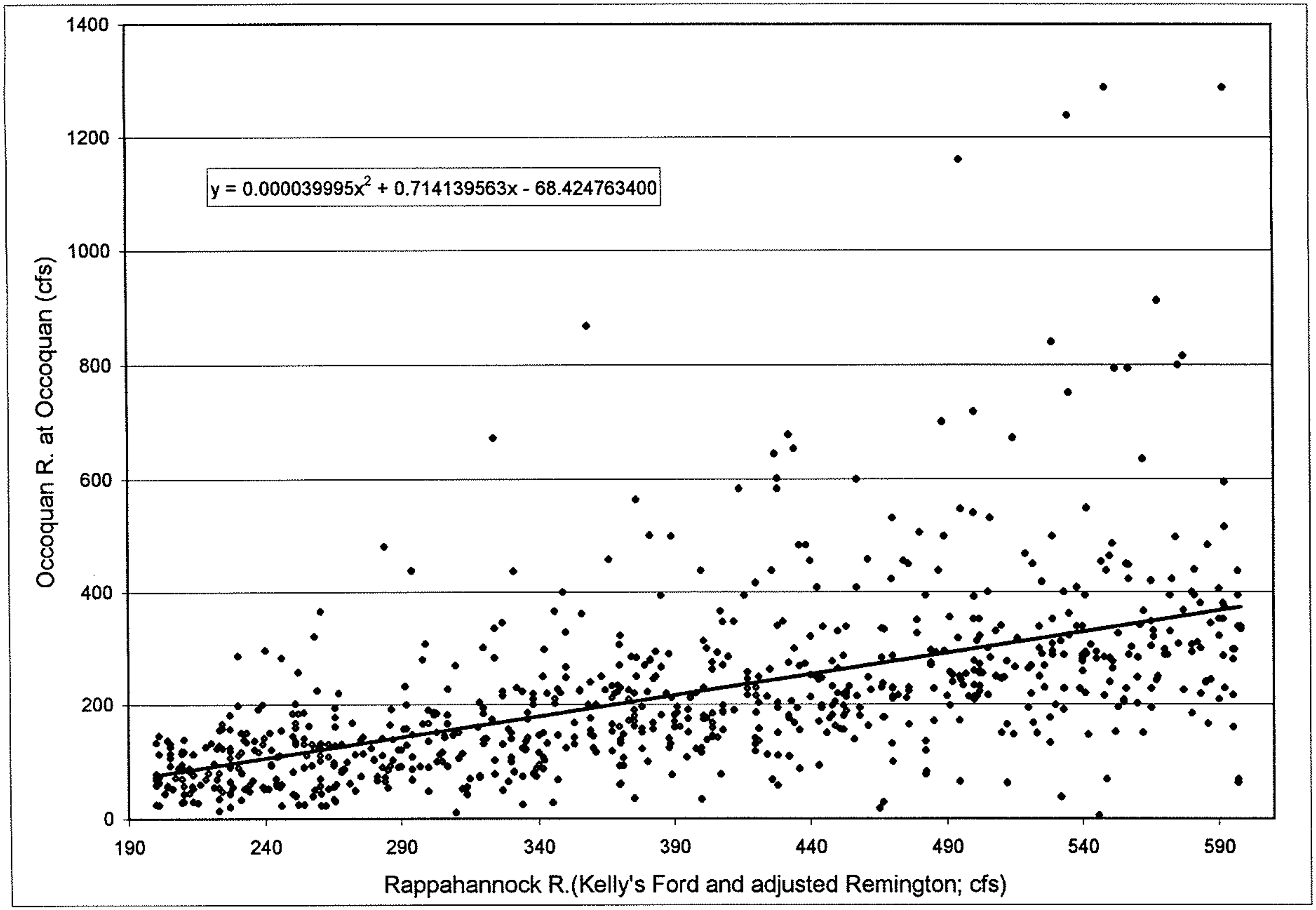

Figure VII: October through April medium-flow model calibration, 1937-1955

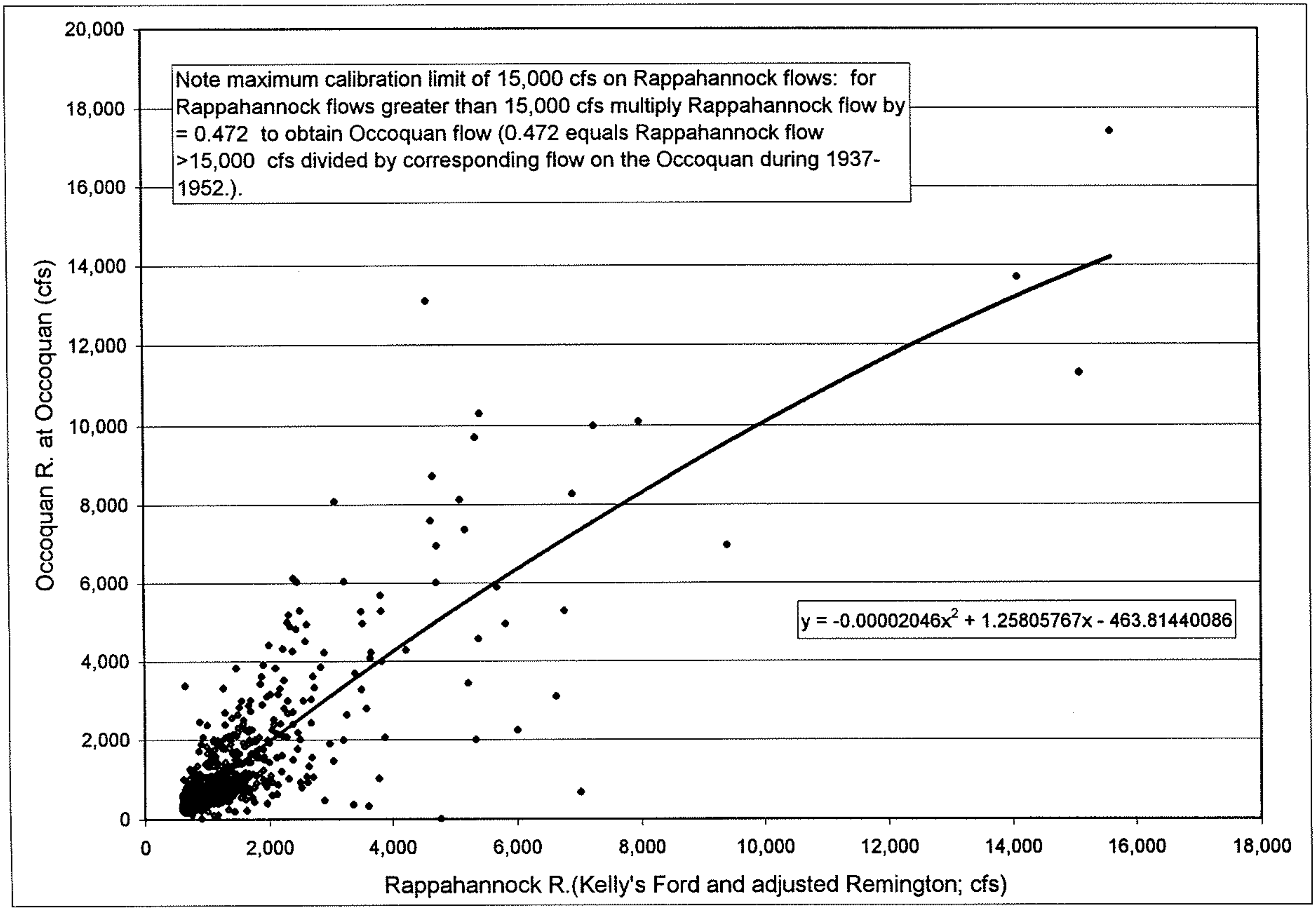

Figure VIII: October through April high-flow model calibration, 1937-1955