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ANALYSIS OF SEDIMENT LOADING TO THE UPPER HUDSON RIVER DURING THE APRIL 1994 HIGH FLOW EVENT

March 1997

Project No: GECO0500

HydroQual, Inc.
Environmental Engineers and Scientists

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SECTION 1
INTRODUCTION

The fate of sediment-bound contaminants, e.g., PCBs, in the Upper Hudson River is primarily controlled by sediment transport processes in the river. Quantitatively analyzing the transport of suspended sediments in this riverine system requires an understanding of resuspension and deposition processes for both cohesive and non-cohesive sediments. Equally important in a sediment transport analysis is the development of a sediment budget to determine if net erosion or sedimentation is occurring in the various reaches during a particular time period.

To construct a sediment budget for the Upper Hudson River, sediment loading at upstream and downstream locations, e.g., Fort Edward and Waterford, must first be determined from available data. Tributary loadings between the upstream and downstream locations, e.g., Moses Kill, Snook Kill, Batten Kill and Hoosic River, must also be calculated for the time period under consideration. A mass balance can then be constructed such that

$$\Sigma L = L_{down} - L_{up} - \Sigma L_{trib} < 0 \quad (\textit{net sedimentation}) \tag{1-1}$$

or,

$$\Sigma L = L_{down} - L_{up} - \Sigma L_{trib} > 0 \quad (\textit{net erosion}) \tag{1-2}$$

where L_{down} = downstream sediment load, L_{up} = upstream sediment load and L_{trib} = tributary sediment load. Whether net sedimentation or erosion is occurring in this system will have a significant impact on future PCB concentrations. Thus, accurately determining upstream and tributary sediment loading to the Upper Hudson River is of critical importance in any evaluation of PCB transport and fate for this system.

Several analyses of sediment loading to the Upper Hudson River have been conducted with varying degrees of success (e.g., HydroQual, 1995; USEPA, 1996; Phillips, 1996). Estimating tributary sediment loads has always been problematic in these studies due to a lack of data. However, the U.S. Environmental Protection Agency (USEPA) conducted a solids loading study between Fort Edward and Waterford during the April 1994 high flow event that can be used to construct a sediment budget for the Upper Hudson River during this time period, which was the objective of the analysis described herein.

SECTION 2

ANALYSIS OF SEDIMENT LOADING DATA

Total suspended solids concentration and flow rate data have been used to develop a sediment budget for the Upper Hudson River between Ft. Edward and Waterford during a 30-day period in 1994. This period was dictated by the availability of total suspended solids (TSS) data for major tributaries to the system. As discussed in the previous section, construction of a sediment budget requires determining sediment loads at various locations in a riverine system

$$L = \int_{n}^{n+1} QC \, dt \tag{2-1}$$

where L = total sediment load for the period $t^n \leq t \leq t^{n+1}$, Q = flow rate, C = suspended sediment concentration, and t = time. Load calculations required using available data to develop time series for TSS and flow rates, e.g., C(t) and Q(t), at various locations for the 30-day period. Descriptions of the data and methodology used to generate C(t) and Q(t) are presented in the next sub-section. A flow balance for the Upper Hudson River during the flood period is developed in the second sub-section. Results of the sediment loading calculations are then discussed, followed by a presentation of the resulting sediment budget for this 30-day period. This section concludes with a discussion of the uncertainty in the present analysis.

2.1 FLOW RATE AND TSS DATA

Total suspended solids (TSS) data were collected by the USEPA at eighteen stations on the Upper Hudson River and its tributaries between March 26 and April 29, 1994. These dates coincide with a Hudson River flood event. Ten of the eighteen stations were selected for this analysis: six stations located on the Hudson River and four stations located on tributaries. The other eight stations were excluded from this analysis for the following reasons: (1) a station was outside the region of interest; (2) limited TSS data were collected at a station; or (3) a station was at an intermediate location in a particular reach. The main stem stations were: Fort Edward (Rogers Island, Northern Tip), Thompson Island Dam, Schuylerville, Stillwater, Mechanicville (shore) and Waterford. The tributary TSS data were collected at the mouth of each of these streams: Snook Kill, Moses Kill, Batten Kill and Hoosic River. See Figures 2-1 and 2-2 for locations of the TSS sampling locations.

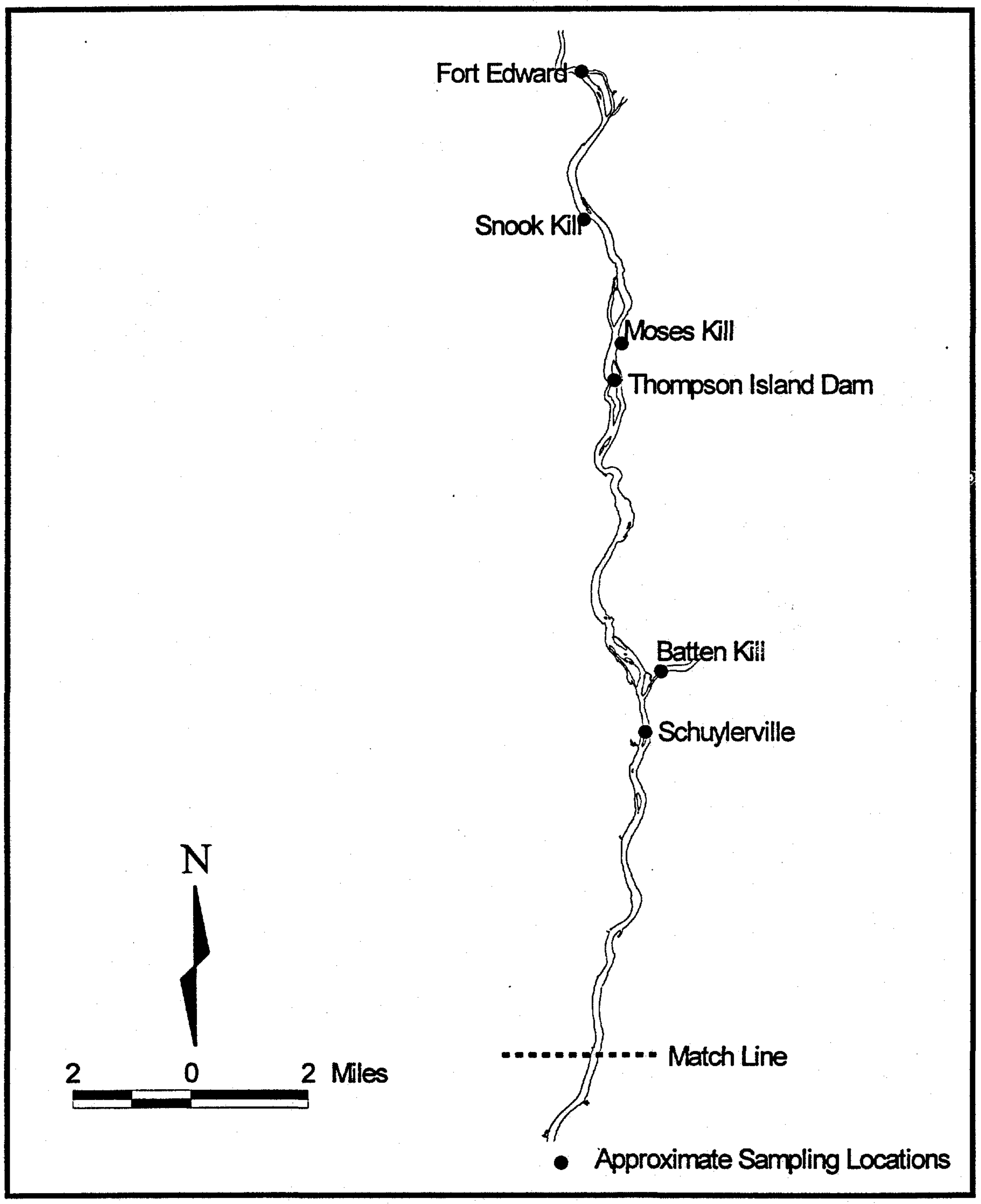

Figure 2-1. Suspended solids sampling locations used in present analysis (Fort Edward to Schuylerville).

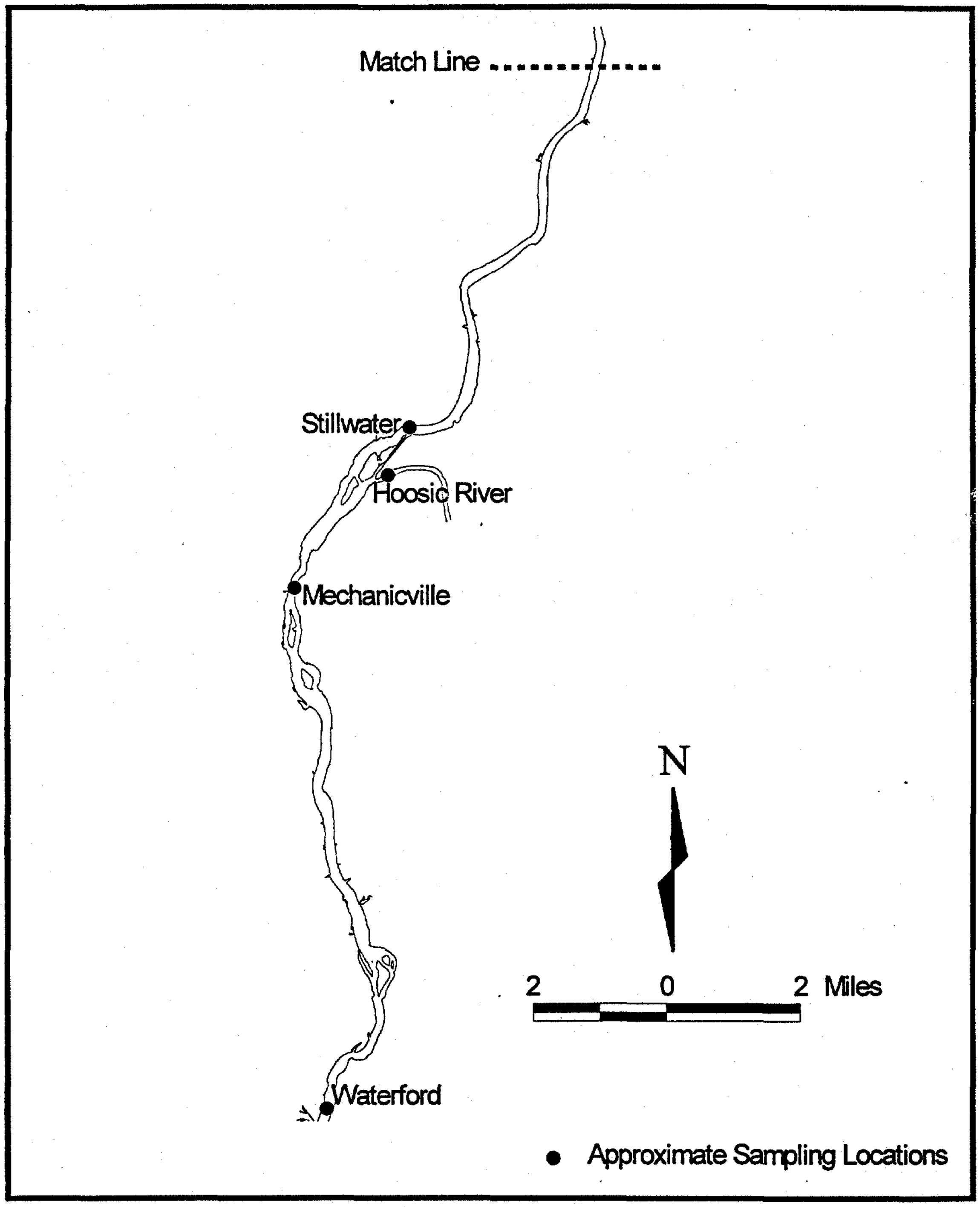

Figure 2-2. Suspended solids sampling locations used in present analysis (Stillwater to Waterford).

TSS data were collected at all stations at least once per day in April 1994. On April 15, 16, 17 and 19, data were collected twice daily at Rogers Island, Snook Kill, Moses Kill, and Thompson Island Dam. From April 10 through April 29, TSS data were collected twice daily at Waterford. Temporal plots of TSS data at these ten USEPA stations during the 30-day period under consideration are shown on Figures 2-3 and 2-4. Note that the data are shown as solid dots on these figures. To facilitate calculation of sediment loads, daily or twice-daily TSS data were converted to hourly values using linear interpolation, the results of which are shown as solid lines on Figures 2-3 and 2-4.

Discharge data from five U.S. Geological Survey (USGS) gauging stations were used to determine flow rates at the ten TSS sampling locations. Flow rate data were available at these USGS stations (Figures 2-5 and 2-6): Hudson River at Fort Edward (gauge 01327750), Hudson River at Stillwater (gauge 01331095), Hudson River above Lock 1 near Waterford (gauge 01335754), Hoosic River near Eagle Bridge (gauge 01334500), and Kayaderosseras Creek near West Milton (gauge 01330500). Hourly discharge data for the Hudson River at Fort Edward, Hoosic River near Eagle Bridge and Kayaderosseras Creek near West Milton were accessible and used in the analysis. Hourly discharge data were unavailable for at least one of these three stations between April 3 and 6. During those times, the average daily discharge at that station was input for each hour for the entire 24-hour period for that date. Discharge data for the Hudson River at Stillwater and Waterford were only available as estimated daily average flow rates. Note that uncertainty is introduced into this analysis due to the use of flow rates at these locations that have been estimated by USGS. A summary of drainage areas for the Upper Hudson River gauging stations and the four tributaries is presented in Table 2-1.

Table 2-1. Upper Hudson River Drainage Areas

Location	Drainage Area (mi^2)
Hudson River at Ft. Edward	2,817
Snook Kill	122
Moses Kill	69
Batten Kill	432
Hudson River at Stillwater	3,773
Hoosic River	710
Hudson River at Waterford	4,620

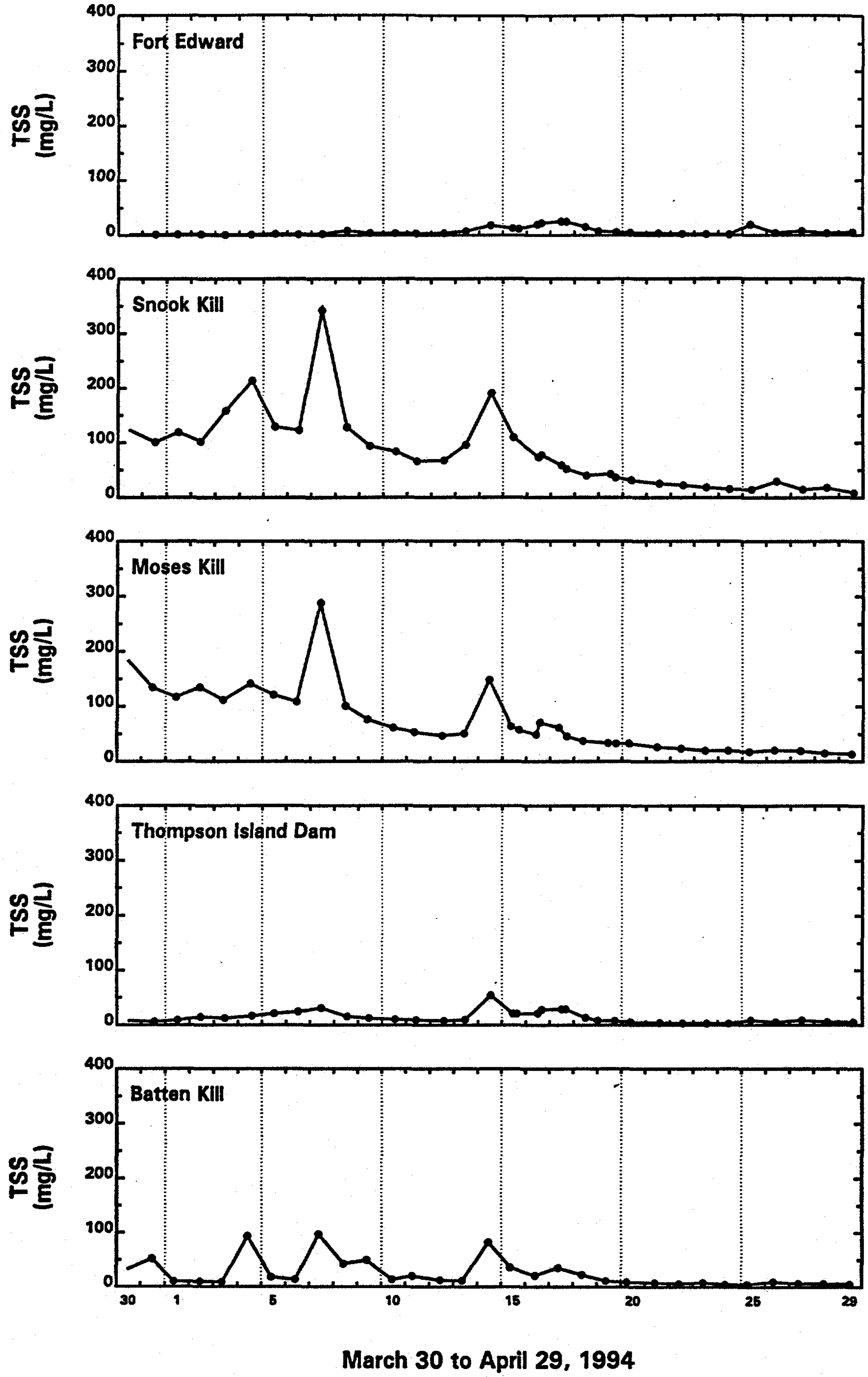

Figure 2-3. Measured (solid dot) and interpolated (line) TSS concentrations from March 30 to April 29, 1994 (Fort Edward to Batten Kill).

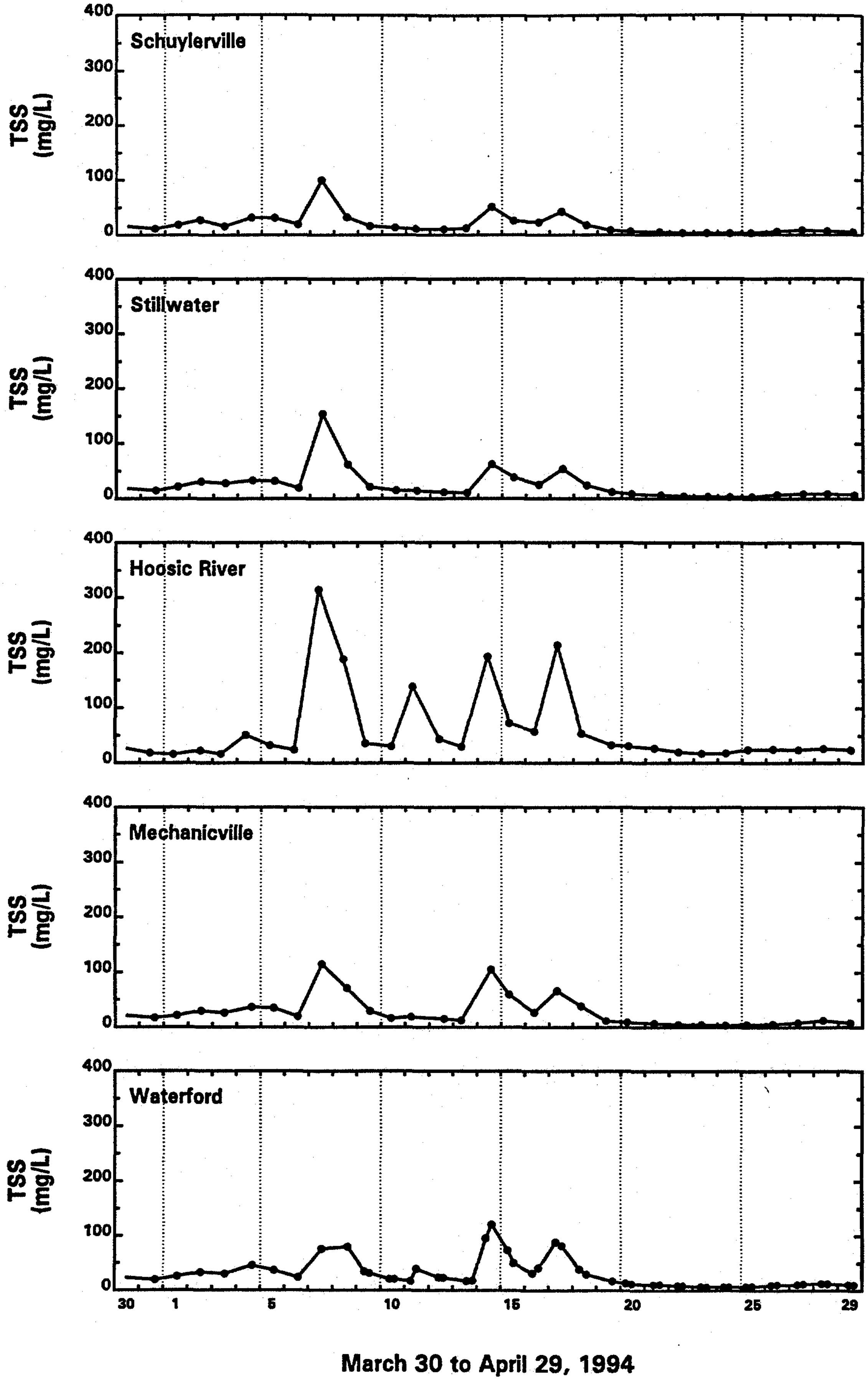

Figure 2-4. Measured (solid dot) and interpolated (line) TSS concentrations from March 30 to April 29, 1994 (Schuylerville to Waterford).

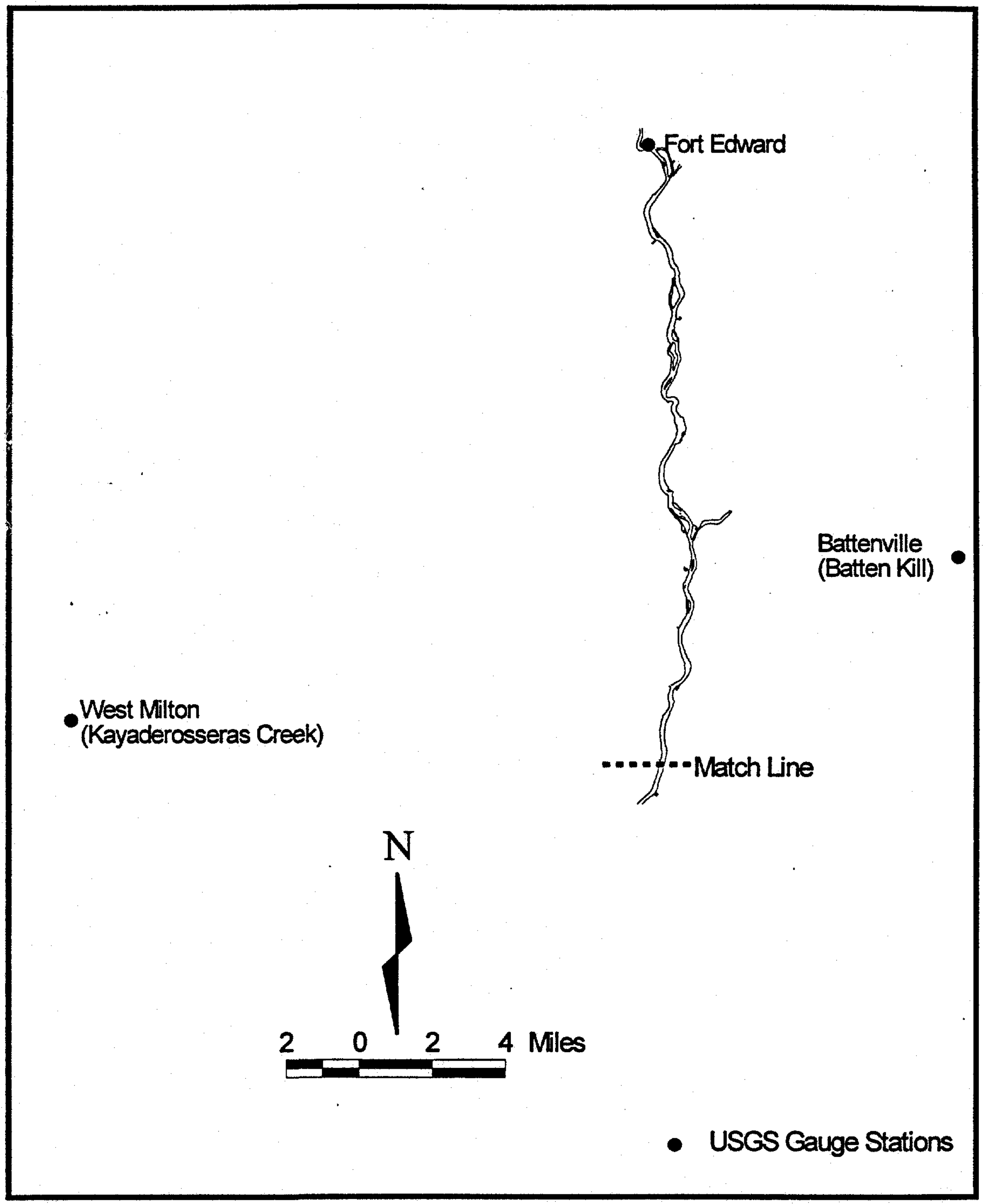

Figure 2-5. Locations of USGS gauging stations (Fort Edward, Batten Kill and Kayaderosseras Creek).

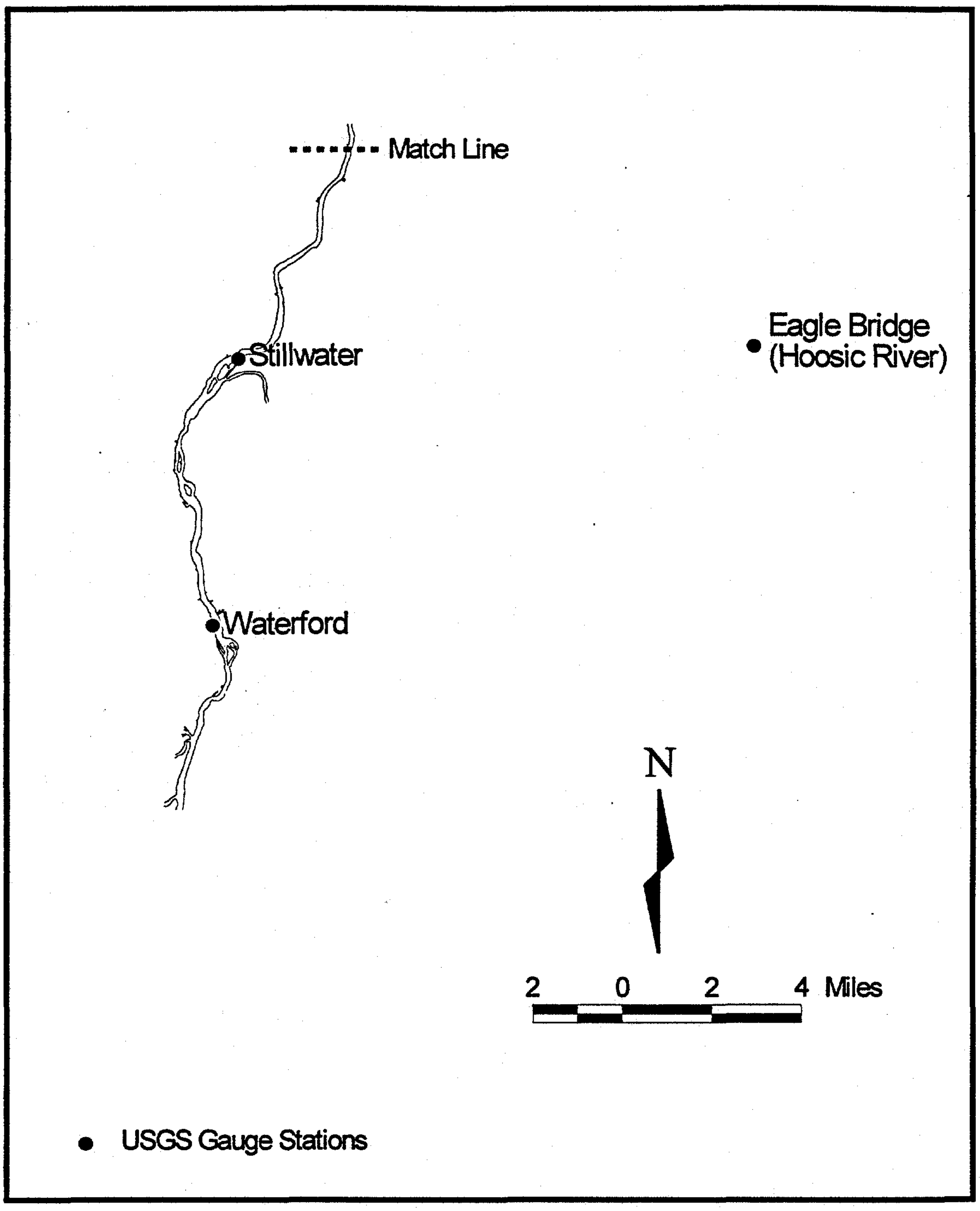

Figure 2-6. Locations of USGS gauging stations (Stillwater, Waterford and Hoosic River).

Kayaderosseras Creek flow rate data were used to estimate the discharge from Snook Kill, Moses Kill, Batten Kill and ungauged tributaries between Schuylerville and Stillwater because these tributaries have similar drainage areas and are all located in the same region of the Upper Hudson River. Kayaderosseras Creek has a drainage area (90 mi^2) that is comparable to the drainage areas of Snook Kill, Moses Kill, Batten Kill and the ungauged tributaries, which are 122, 69, 432 and 333 mi^2, respectively. Using drainage area proration, flow rates for Snook Kill and Moses Kill were estimated by multiplying the discharge from Kayaderosseras Creek by 1.36 and 0.77, respectively.

Batten Kill flow rates were estimated using a correlation between measured flows in Batten Kill and Kayaderosseras Creek. Flow rate data were collected for Batten Kill at the USGS Battenville gauge from 1922 to 1968 (see Figure 2-5). The drainage area at Battenville is 394 mi^2, which represents 91% of the total drainage area of Batten Kill. The USGS gauge on Kayaderosseras Creek began operation in 1927. Hence, a 41-year period exists when daily flow data were collected at both locations. A correlation was found to exist between Battenville and Kayaderosseras Creek flow rates (Figure 2-7)

$$Q_{bat} = 4.03\ Q_{kay} + 163 \tag{2-2}$$

where Q_{bat} = daily average flow rate at Battenville (cfs) and Q_{kay} = daily average flow rate at Kayaderosseras Creek (cfs). Note that $R^2 = 0.68$ for the correlation between Battenville and Kayaderosseras Creek flow rates. The discharge at the mouth of Batten Kill was estimated using a drainage area proration (DAP) factor of 1.10 on the predicted flows at Battenville (Q_{bat}).

Discharge from the ungauged tributaries between Schuylerville and Stillwater, which have a combined drainage area of 333 mi^2, cannot be estimated using conventional drainage area proration on Kayaderosseras Creek gauge data. This assertion is based upon the following data. An USGS gauging station was operated at Schuylerville from March 10, 1977 to September 30, 1979. The mean flow rates at Fort Edward, Schuylerville, Stillwater and Waterford for this period were 5,943, 7,448, 7,605 and 9,653 cfs, respectively. Flow balances were constructed for this 935-day period for three reaches along the Upper Hudson River (see Figure 2-8): Fort Edward to Schuylerville (reach 1); Schuylerville to Stillwater (reach 2); and Stillwater to Waterford (reach 3). The resulting average runoff rates were 2.42, 0.47 and 2.42 cfs/mi^2 for reaches 1, 2 and 3, respectively. It is seen that the Fort Edward-Schuylerville and Stillwater-

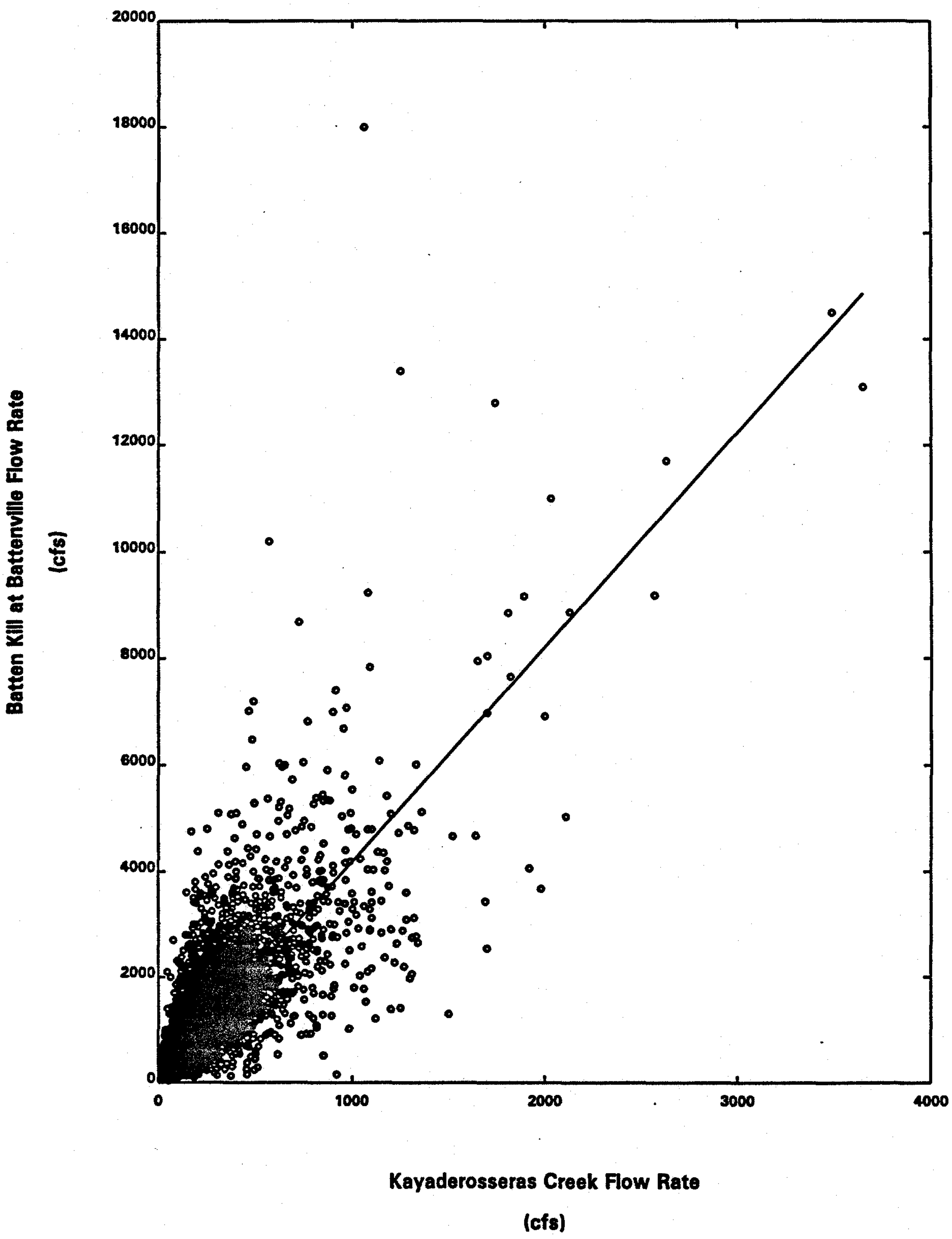

Figure 2-7. Correlation between daily average flow rates measured in Kayaderosseras Creek (at West Milton) and Batten Kill (at Battenville).

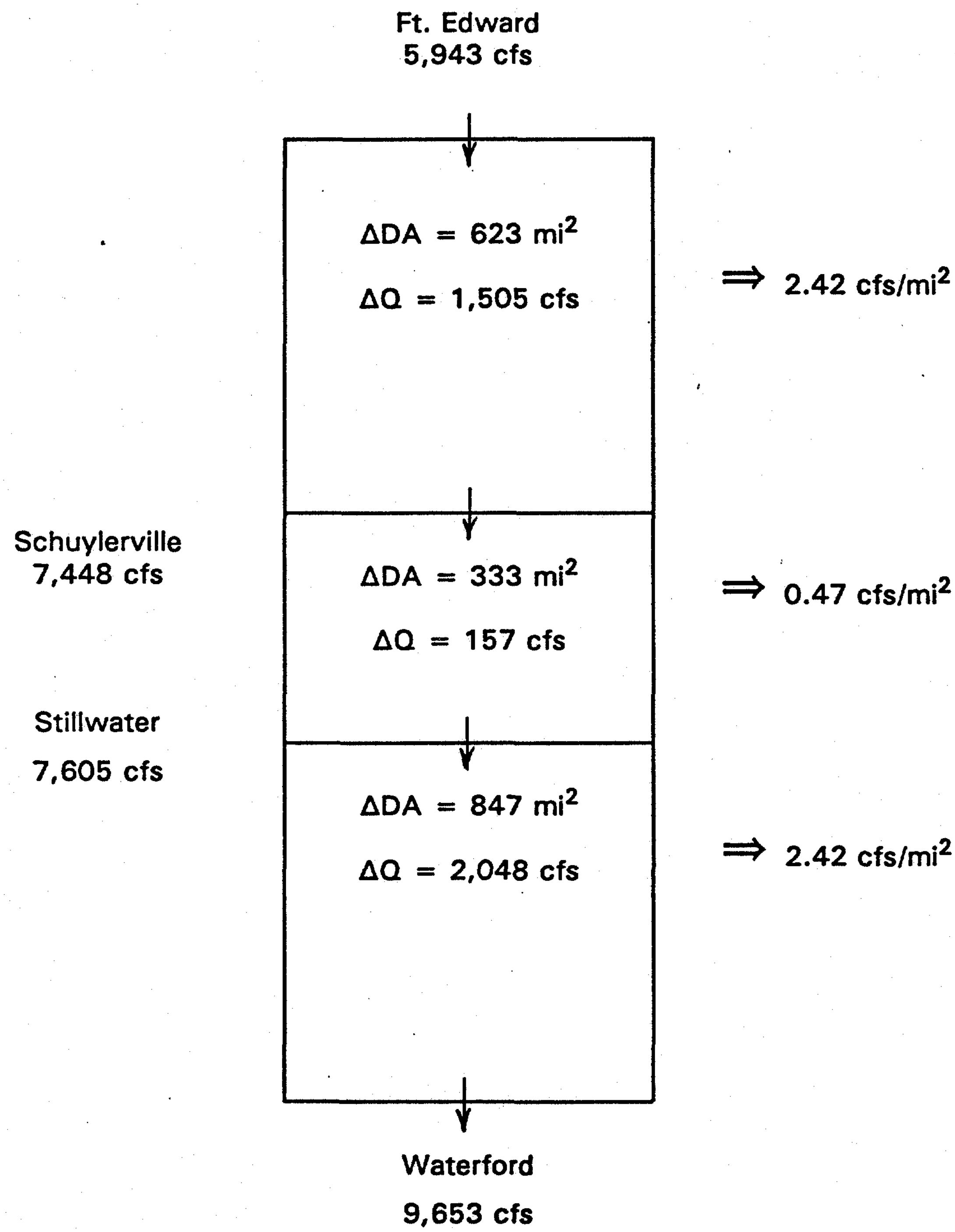

Figure 2-8. Mean flow balance and runoff rates during 1977 to 1979 period for three reaches on the Upper Hudson River: Fort Edward to Schuylerville, Schuylerville to Stillwater, and Stillwater to Waterford.

Waterford reaches have the same runoff rate while the reach between Schuylerville and Stillwater contributes a significantly smaller amount of water to the system (on a cfs/mi^2 basis). In fact , the ratio of the runoff rates between reaches 1 and 2 can be expressed as

$$r = \frac{R_1}{R_2} \tag{2-3}$$

where R_k = runoff rate of reach k (cfs/mi^2). For the 1977-79 period, r = 5.2.

It is possible that the 1977-79 period is not representative of average conditions on the Upper Hudson River and that the r value observed during that time is too high. To investigate this possibility, data during the period extending from March 10, 1977 to June 30, 1992 (5,592 days) were analyzed, during which time the USGS gauges at Fort Edward, Stillwater and Waterford were all operating. After July 1, 1992, the Stillwater and Waterford gauges were not always functional due to various construction activities in the vicinity of these gauges. The mean flow rates at Fort Edward, Stillwater and Waterford during this 15-year period were 5,239, 6,604 and 8,138 cfs, respectively. A mean flow balance for the Fort Edward-Stillwater and Stillwater-Waterford reaches for this period is shown on Figure 2-9. The average runoff rates were 1.43 and 1.81 cfs/mi^2 for the Fort Edward-Stillwater and Stillwater-Waterford reaches, respectively. However, the 1977-79 flow balance showed that the hydrologic characteristics of reaches 1 and 3 were very similar. Hence, a valid approximation is that reach 1 has the same runoff rate as reach 3 (1.81 cfs/mi^2) during this 15-year period, resulting in an estimated mean tributary inflow of 1,128 cfs between Fort Edward and Schuylerville and 287 cfs from tributaries between Schuylerville and Stillwater (see Figure 2-10). This results in an estimated runoff rate for reach 2 of 0.71 cfs/mi^2. Thus, for this 15-year period, r $\approx$ 2.6, which is a factor of two less than the 1977-79 period.

Flows from the ungauged tributaries between Schuylerville and Stillwater were then estimated as follows. As a first approximation, r was assumed to equal 3.9, which is the average of the estimated values for the 1977-79 and 1977-92 periods. Thus, $R_2 = R_1 / r$ or $R_2 = 0.26\, R_1$. Drainage area proration assumes that the runoff rate (i.e., cfs/mi^2) is approximately constant for a given reach. Reach 2 tributary flows (Q_{R2}) were calculated from Kayaderosseras Creek gauge data (which is assumed to be representative of the runoff rate in reach 1) by adjusting the typical DAP factor as follows

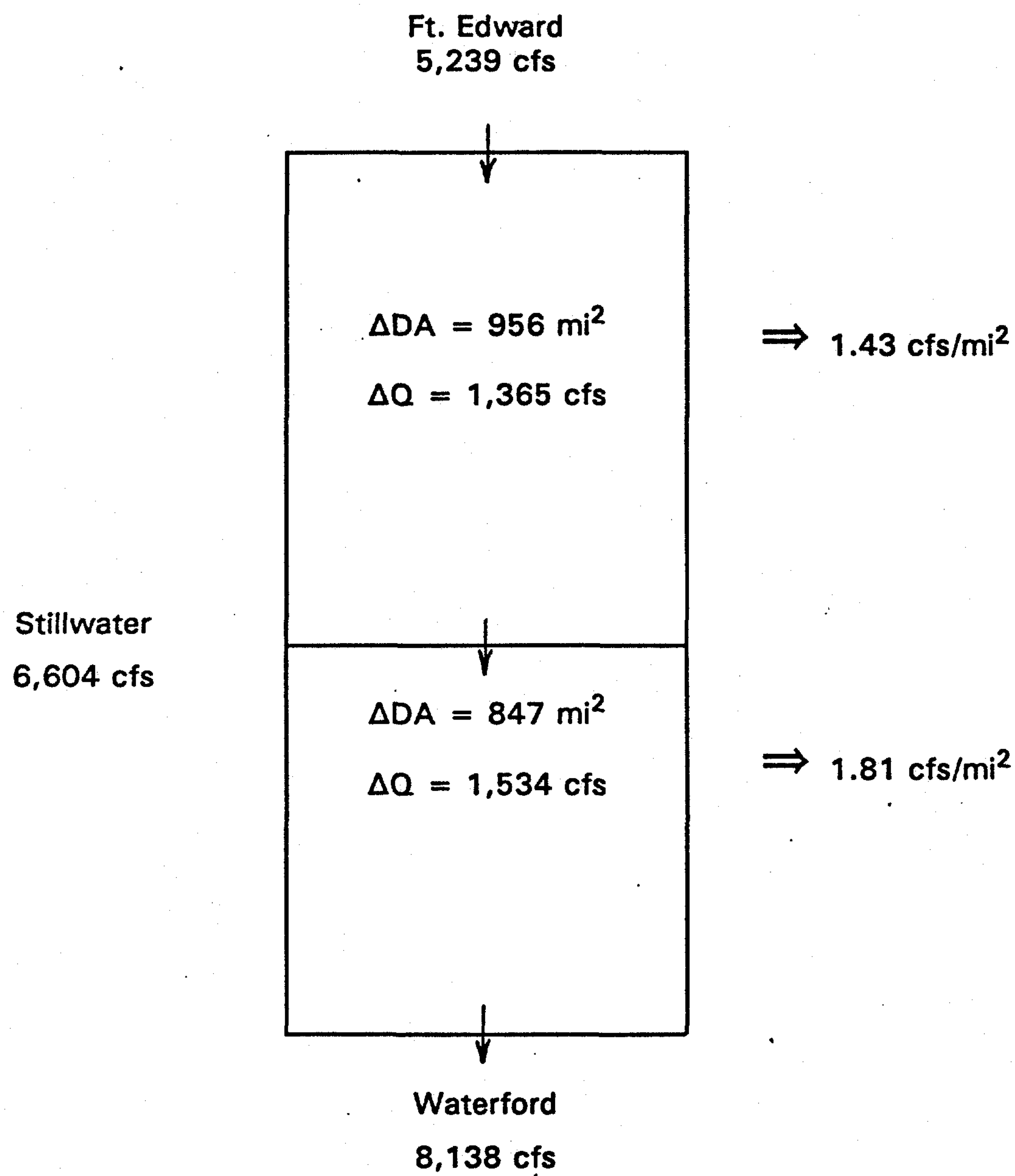

Figure 2-9. Mean flow balance and runoff rates during 1977 to 1992 period for two reaches on the Upper Hudson River: Fort Edward to Stillwater and Stillwater to Waterford.

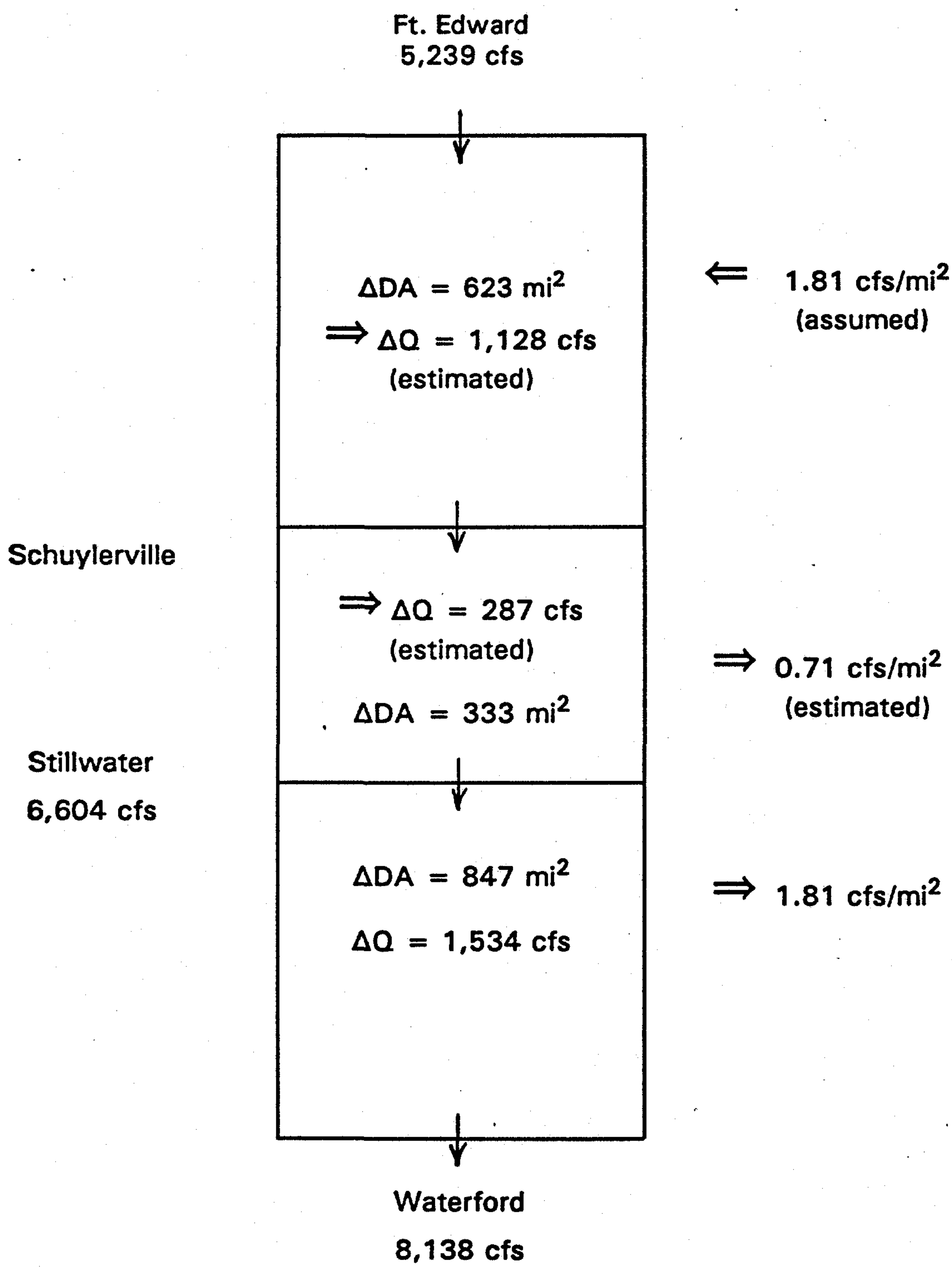

Figure 2-10. Mean flow balance and estimated runoff rates during 1977 to 1992 period for three reaches on the Upper Hudson River: Fort Edward to Schuylerville, Schuylerville to Stillwater, and Stillwater to Waterford.

$$Q_{R2} = 0.26\ (333/90)\ Q_{kay} = 0.96\ Q_{kay} \qquad (2\text{-}4)$$

Discharge for the Hoosic River was based on measured flow rates at the Hoosic River near Eagle Bridge gauge. The drainage area at the Eagle Bridge gauging station is 510 mi^2. The Hoosic River drainage area increases by 39%, to 710 mi^2, between the Eagle Bridge gauging station and the confluence with the Hudson River. Therefore, to estimate the total discharge of the Hoosic River, flow rate data from the Eagle Bridge gaging station were multiplied by 1.39.

Similar to the Hoosic River, discharge from the ungauged tributaries between Stillwater and Waterford (reach 3), with a total drainage area of 137 mi^2, were approximated by applying drainage area proration to Eagle Bridge gauge data. Hence, the ungauged tributary flow in reach 3 was estimated by multiplying measured flow rates at the Eagle Bridge gauging station by 0.27.

The validity of the procedures used to estimate tributary flow rates was examined by comparing predicted and observed flow rates at Stillwater and Waterford. For the 15-year period extending from March 10, 1977 to June 30, 1992, daily average flow rates were predicted for Snook Kill, Moses Kill, Batten Kill, Hoosic River and the ungauged tributaries using measured flow rates at the Kayaderosseras Creek and Eagle Bridge gauging stations. Flow rates at Stillwater and Waterford were predicted by combining the estimated tributary flow rates with measured discharges at Fort Edward. Cross-plots of measured and predicted daily average flow rates for the 1977-92 period at Stillwater and Waterford are presented on Figures 2-11 and 2-12, respectively. Means of the absolute value of the relative error, i.e., |predicted - measured|/measured, for this 15-year period were 11 and 9% for Stillwater and Waterford, respectively. On a longer time-scale, better agreement occurs between predicted and observed 30-day flow averages, see Figures 2-13 and 2-14. For the 30-day flow averages, the absolute value of the relative error had an average value of 6% at both Stillwater and Waterford. For the entire 15-year period, the predicted mean flow rates at Stillwater and Waterford are 6,506 and 8,219 cfs, respectively, which are in excellent agreement with the measured average values of 6,604 and 8,138 cfs. In fact, the predicted long-term average flow rates are within 2% of the observed values. Therefore, these results show that the methods used in this analysis to estimate tributary flow rates to the Upper Hudson River are sufficiently accurate for development of a credible sediment budget for this riverine system.

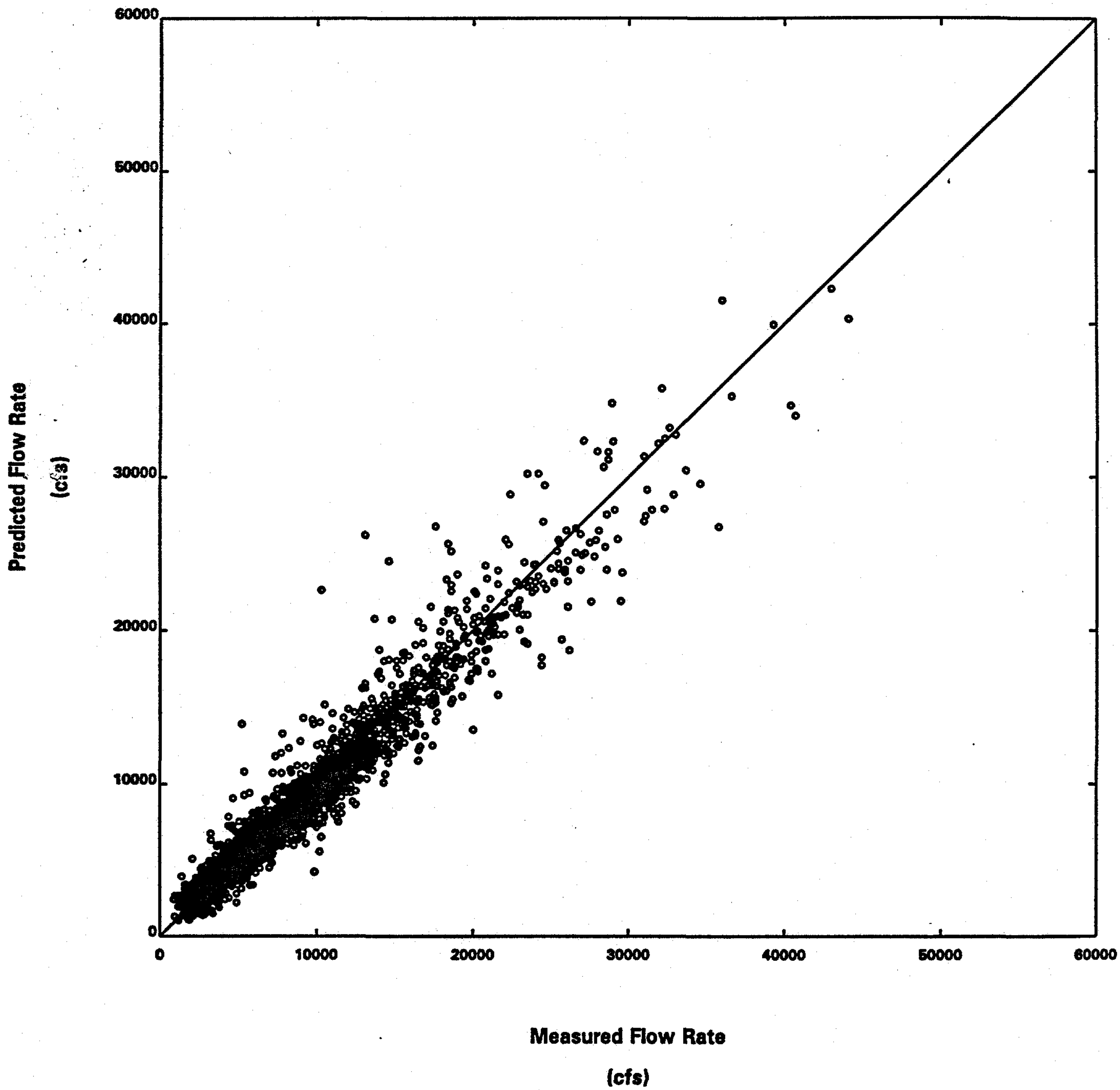

Figure 2-11. Comparison between measured and predicted daily average flow rates at Stillwater during 1977 to 1992 period.

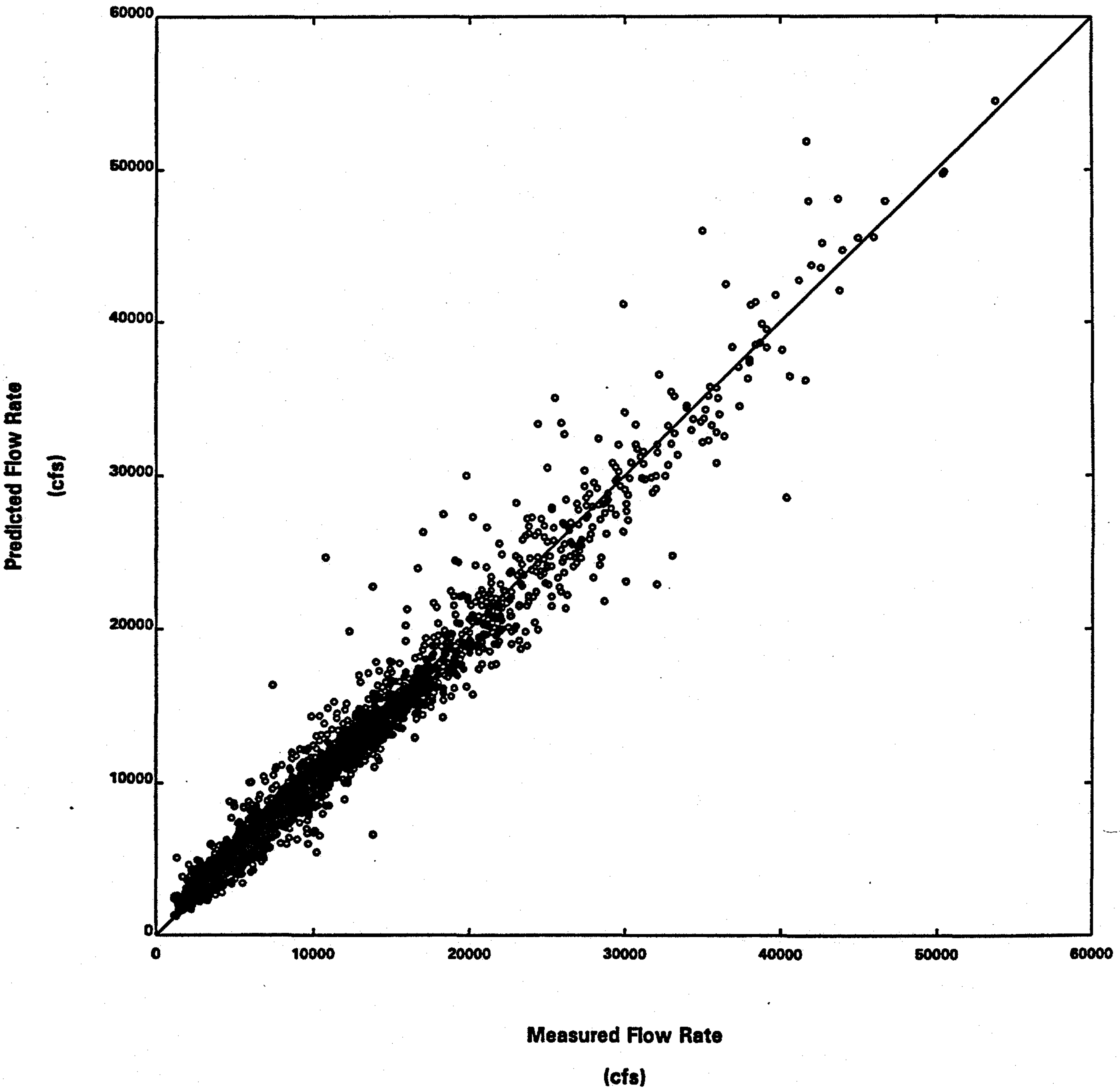

Figure 2-12. Comparison between measured and predicted daily average flow rates at Waterford during 1977 to 1992 period.

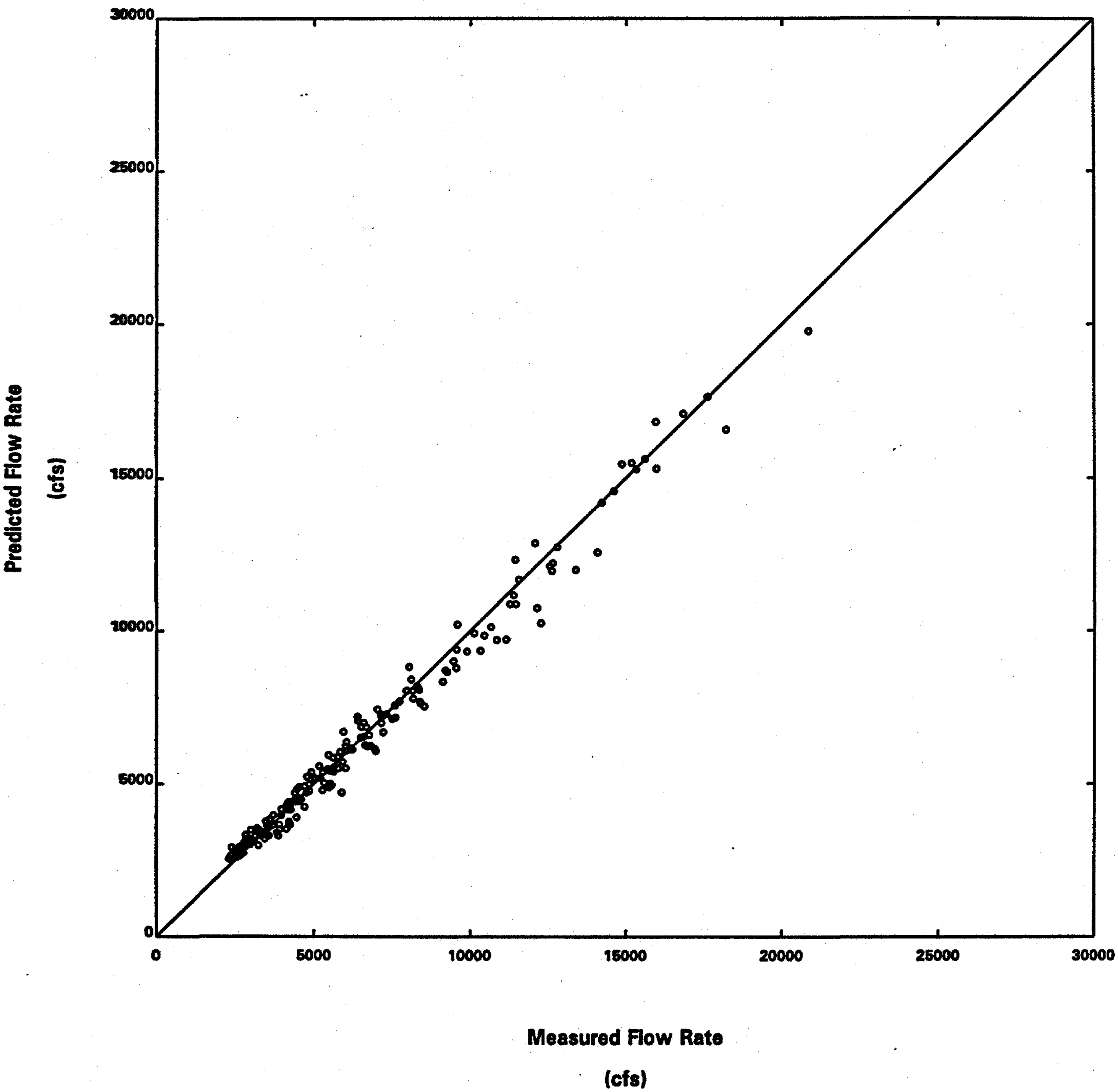

Figure 2-13. Comparison between measured and predicted 30-day average flow rates at Stillwater during 1977 to 1992 period.

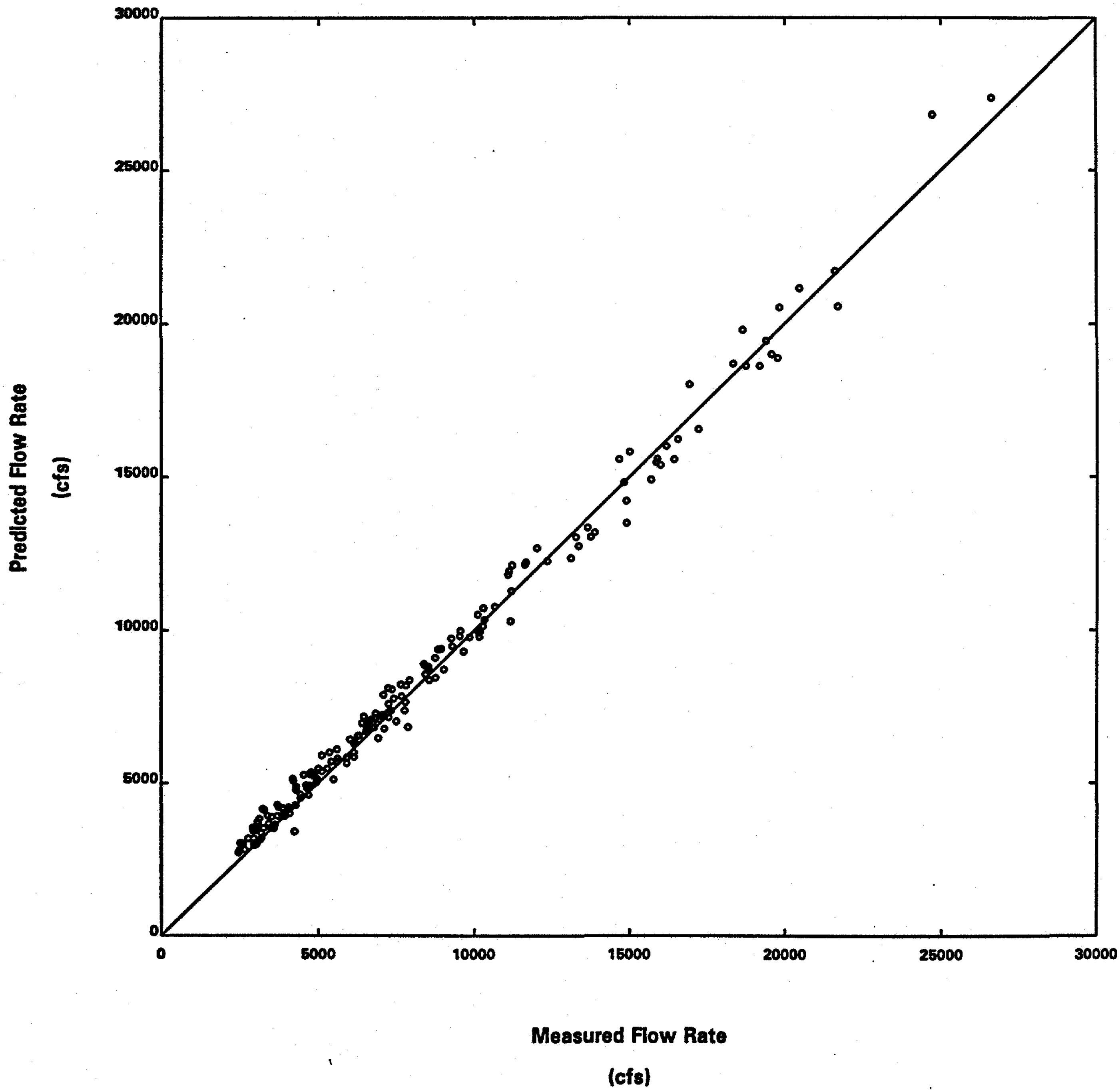

Figure 2-14. Comparison between measured and predicted 30-day average flow rates at Waterford during 1977 to 1992 period.

2.2 1994 FLOW BALANCE

The estimation methods discussed in the previous sub-section were used to determine tributary flow rates for the 30-day period in 1994 that was considered in this analysis. Measured flow rates at Fort Edward were used to specify discharges at that upstream location. Hourly flow rates measured at the three gauging stations (i.e., Fort Edward, Kayaderosseras Creek and Hoosic River near Eagle Bridge) were used to specify discharge in the Upper Hudson River during this period. Tributary flows included were: Snook Kill, Moses Kill, Batten Kill, ungauged tributaries between Schuylerville and Stillwater, Hoosic River and ungauged tributaries between Stillwater and Waterford. Discharge information for locations along the main stem of the Hudson River were calculated by summing the Fort Edward flow rate and the estimated discharges of all tributaries upstream of a particular location; flow balances were constructed to determine flow rates at locations on the Upper Hudson River that are downstream of Fort Edward. Figures 2-15 and 2-16 present the measured and estimated flow rates for the locations corresponding to the ten TSS sampling stations shown in Figures 2-1 and 2-2.

Average flow rates for the 30-day period (9 AM on March 30 through 9 AM April 29) were calculated at each location and are presented in Table 2-2. A flow balance for this 30-day period, based upon average flow rates, is shown on Figure 2-17. The flow balance for a particular reach was determined using conservation of mass

$$Q_{down} - Q_{up} - \Sigma Q_{trib} = 0 \tag{2-5}$$

where Q_{down} = downstream flow rate, Q_{up} = upstream flow rate and Q_{trib} = tributary flow rate.

To investigate the accuracy of the estimated tributary flows during this high flow period in 1994, predicted flow rates at Stillwater and Waterford were compared to USGS estimates of discharge. As noted earlier, the Stillwater and Waterford gauges were inoperative during this period. Daily average flow rates at these two locations are thus reported as estimates based upon data obtained at the Fort Edward gauge and also from historical data at the Battenville gauge on Batten Kill, which has not been in operation since 1968. Flow records at the Stillwater and Waterford gauges are described as poor for estimated values, which means that 95% of the daily discharges have an accuracy of less than 15% (USGS, 1994). Bearing these limitations

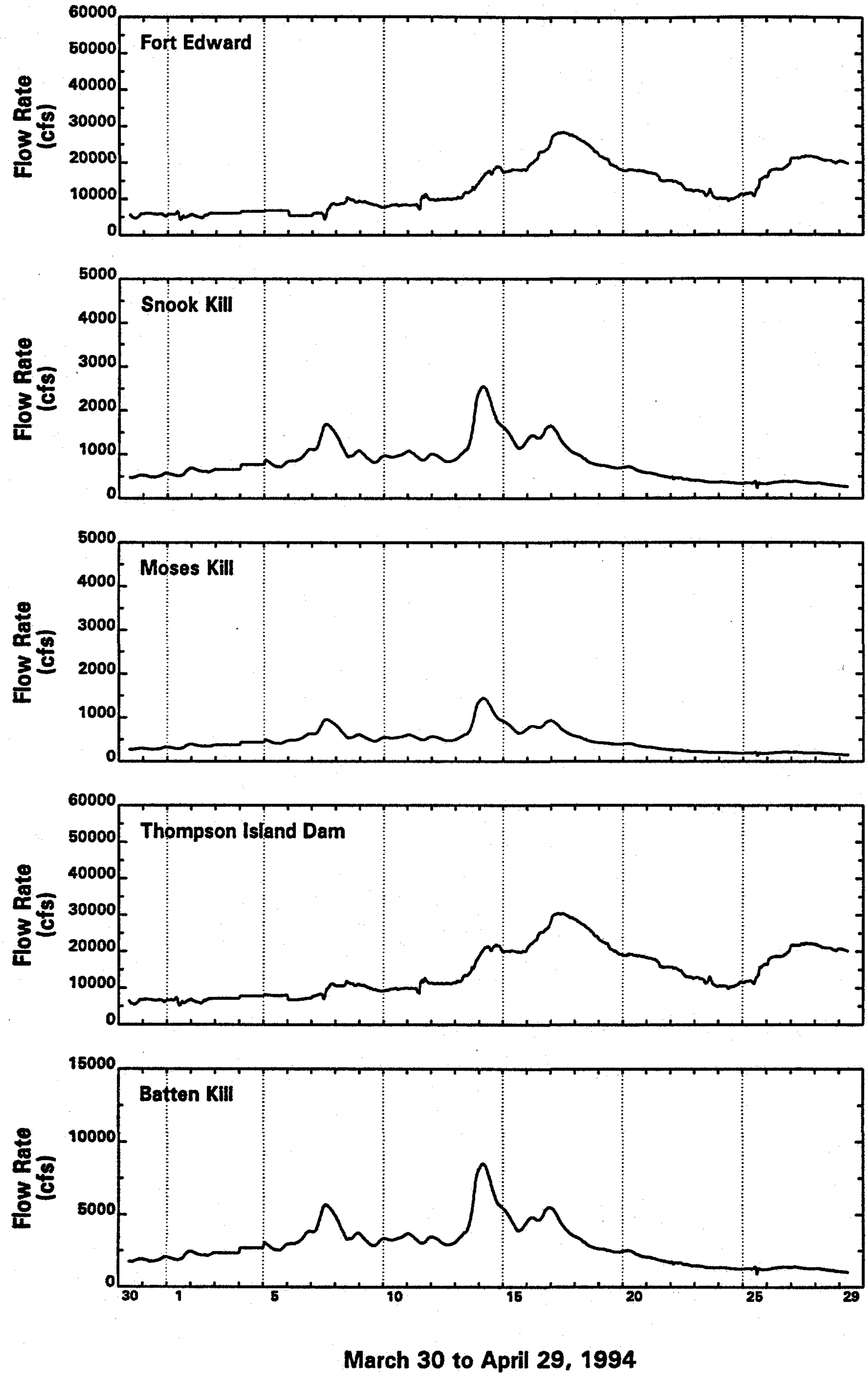

Figure 2-15. Hourly flow rates at Fort Edward, Snook Kill, Moses Kill, Thompson Island Dam and Batten Kill for March 30 to April 29, 1994. Note change in flow rate scales at the various locations.

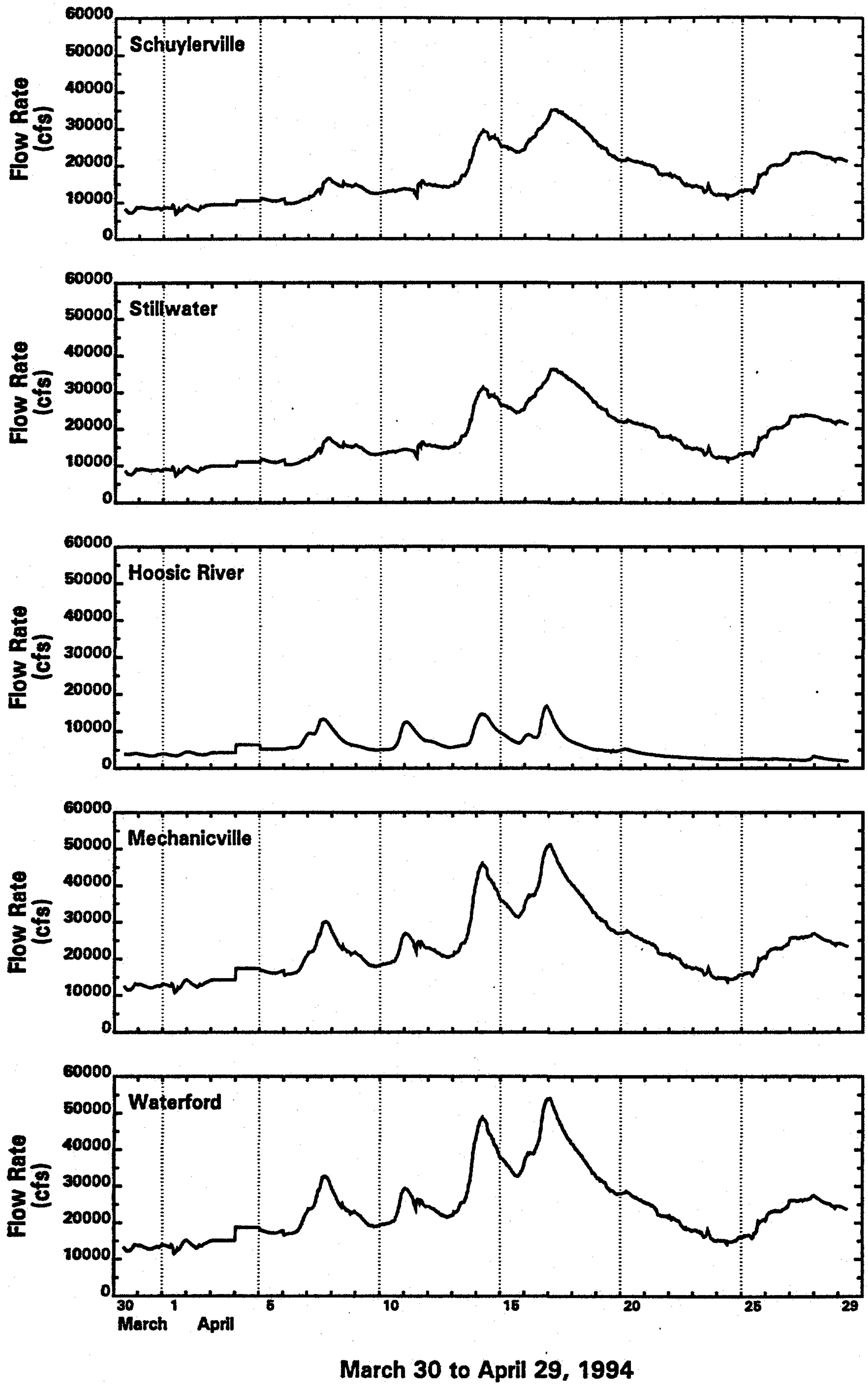

Figure 2-16. Hourly flow rates at Schuylerville, Stillwater, Hoosic River, Mechanicville and Waterford for March 30 to April 29, 1994.

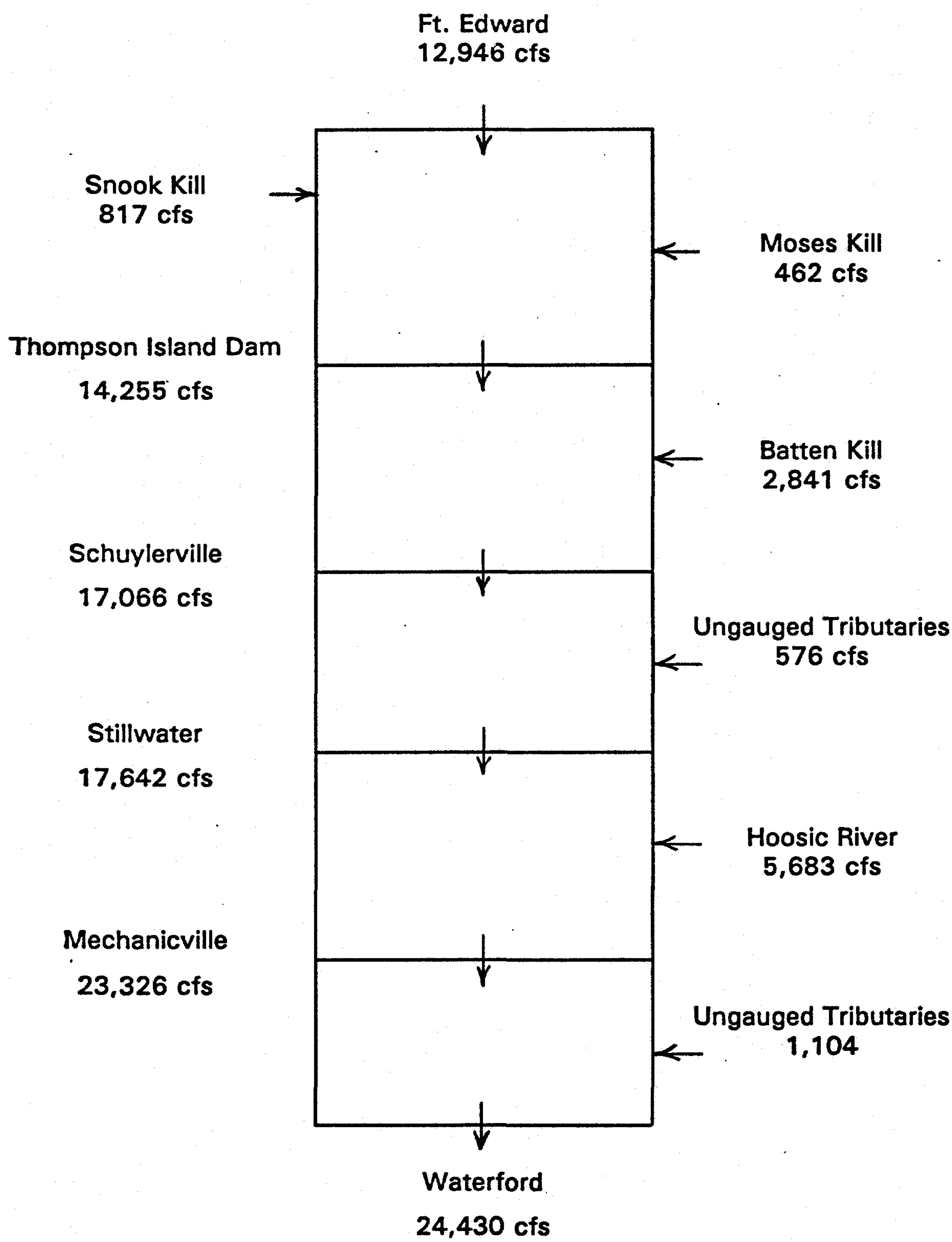

Figure 2-17. Mean flow balance in the Upper Hudson River for March 30 to April 29, 1994.

in mind, the mean flow rates, based upon USGS estimates, for this period at Stillwater and Waterford are 16,946 and 23,816 cfs, respectively. The predicted mean flow rates at Stillwater and Waterford are 4.1 and 2.6% higher, respectively, than the values estimated by USGS. Thus, the predicted flow rates are within the error range of the USGS estimation methods. These results indicate that the procedures used in this analysis to predict tributary flow rates are credible and yield reasonably accurate values.

Table 2-2. Average Hourly Flow Rates and Total Sediment Loadings for March 30 through April 29, 1994

Location	Average Flow Rate (cfs)	Total Sediment Load (metric tons)
Hudson River at Ft. Edward	12,946	8,362
Snook Kill	817	6,448
Moses Kill	462	2,987
Thompson Island Dam	14,225	14,793
Batten Kill	2,841	6,580
Hudson River at Schuylerville	17,066	24,944
Hudson River at Stillwater	17,642	33,748
Hoosic River	5,683	37,196
Hudson River at Mechanicville	23,326	56,174
Hudson River at Waterford	24,430	64,104

2.3 1994 SEDIMENT LOAD CALCULATIONS

The TSS and flow rate data discussed in the previous sub-sections were used to calculate sediment loads in the Upper Hudson River for the 30-day period from 9 AM on March 30 through 9 AM on April 29, 1994. Hourly sediment loads were calculated using the available data in the integral defined in Equation (2-1). The assumption was made that flow rates and TSS concentrations varied linearly between each hourly data point

$$C(t) = \frac{t - t^n}{t^{n+1} - t^n} (C^{n+1} - C^n) + C^n \quad , t^n \leq t \leq t^{n+1} \tag{2-6}$$

and

$$Q(t) = \frac{t - t^n}{t^{n+1} - t^n} (Q^{n+1} - Q^n) + Q^n \quad , t^n \le t \le t^{n+1} \qquad \text{(2-7)}$$

where C^n = TSS concentration at hour n (t^n) and Q^n = flow rate at hour n. Thus, the hourly sediment load for hour n+1 (i.e., $t^n \le t \le t^{n+1}$) is given by

$$L^{n+1} = \int_n^{n+1} Q(t)\, C(t)\, dt$$

$$= \tfrac{1}{3} (t^{n+1} - t^n) [Q^{n+1}C^{n+1} + Q^nC^n + \tfrac{1}{2} (Q^{n+1}C^n + Q^nC^{n+1})] \qquad \text{(2-8)}$$

The total sediment loadings, calculated from the sum of the hourly loads for the period March 30 through April 29, 1994, at the ten locations are presented in Table 2-2.

Sediment yields, which represent the total loading per square mile of drainage area for this 30-day period, are 53, 43, 15 and 52 metric tons/mi^2, respectively, for Snook Kill, Moses Kill, Batten Kill and Hoosic River. Note that the sediment yield for these four tributaries were all within a factor of four. Of particular interest are the sediment yields for the Thompson Island Pool tributaries (43 and 53 metric tons/mi^2) and Hoosic River (52 metric tons/mi^2), which are remarkably similar. The Batten Kill sediment yield for this 30-day period is considerably lower than the yields for the other three tributaries. It is unclear at this time whether this situation is typical or if this high flow event produced an anomalously low sediment load from Batten Kill. Estimates of soil erosion (Soil Conservation Service, 1974) and land use patterns in the Batten Kill drainage basin show that its sediment yield would probably not be significantly different from the Snook Kill and Moses Kill sediment yields. Additional tributary sediment loading data during high flow events would aid in clarifying this issue.

Completion of a sediment budget for the Upper Hudson River requires estimation of sediment loading from the ungauged tributaries. These estimates were made using sediment yield information from the gauged drainage areas. For the reach between Schuylerville and Stillwater, sediment yields from Snook Kill, Moses Kill and Batten Kill were used as follows. The area-weighted mean sediment yield from these three tributaries, which comprise reach 1, is 26 metric tons/mi^2. Note that this mean sediment yield may be biased low if the sediment yield for Batten Kill during the 30-day period considered in this analysis is anomalously low.

The ratio between reach 1 and 2 sediment yields was assumed to equal the ratio of runoff rates, i.e., $r = R_1 / R_2 = 3.9$. Applying this approximation results in a sediment yield for reach 2 that is 3.9 times smaller than the mean sediment yield for reach 1, i.e., reach 2 sediment yield is approximately 7 metric tons/mi^2. This sediment yield generates 2,330 metric tons of sediment from the ungauged tributaries between Schuylerville and Stillwater. The ungauged tributaries between Stillwater and Waterford can be estimated using the Hoosic River sediment yield of 52 metric tons/mi^2. Applying this yield to the 137 mi^2 of ungauged drainage area in this reach produces 7,124 metric tons of sediment added to the tributary sediment load.

Comparing the sediment loading from the upstream source at Fort Edward (8,362 metric tons) to the tributary loadings shows some interesting characteristics of this riverine system. The total load from all tributaries is estimated to be 62,665 metric tons, which is 7.5 times larger than the Fort Edward load, see Figure 2-18. Of particular interest is the loading to the Thompson Island Pool. Together, Snook Kill and Moses Kill contribute 9,435 metric tons, which is greater than the Fort Edward load and these tributaries contribute 53% of the total sediment load to this reach, see Figure 2-19.

2.4 SEDIMENT BUDGET FOR 1994 HIGH FLOW EVENT

Total sediment loadings (Table 2-2) were compared and sediment mass balances were performed, using Equations (1-1) and (1-2), for the various reaches between Ft. Edward and Waterford. The results of the mass balance analysis, which represents the 30-day sediment budget, are presented on Figure 2-20. A negative value for a reach indicates net deposition; a positive value indicates net erosion.

On a global basis, net sedimentation occurred between Fort Edward and Waterford during this 30-day period. Using the available tributary loading data from the four gauged tributaries, the sediment budget indicates that 6,923 metric tons of sediment were deposited in the Upper Hudson River. This amount of deposition corresponds to an overall trapping efficiency of 10%.

Examination of the sediment budget on a finer scale shows that net deposition occurred in two reaches: Thompson Island Pool and the reach between Stillwater and Mechanicville. The sediment budget for Thompson Island Pool indicates that 3,004 metric tons of sediment were deposited during this 30-day period, which corresponds to a trapping efficiency of 17%. Assuming a dry bulk density of 0.9 g/cm^3 for the deposited sediment, which is approximately

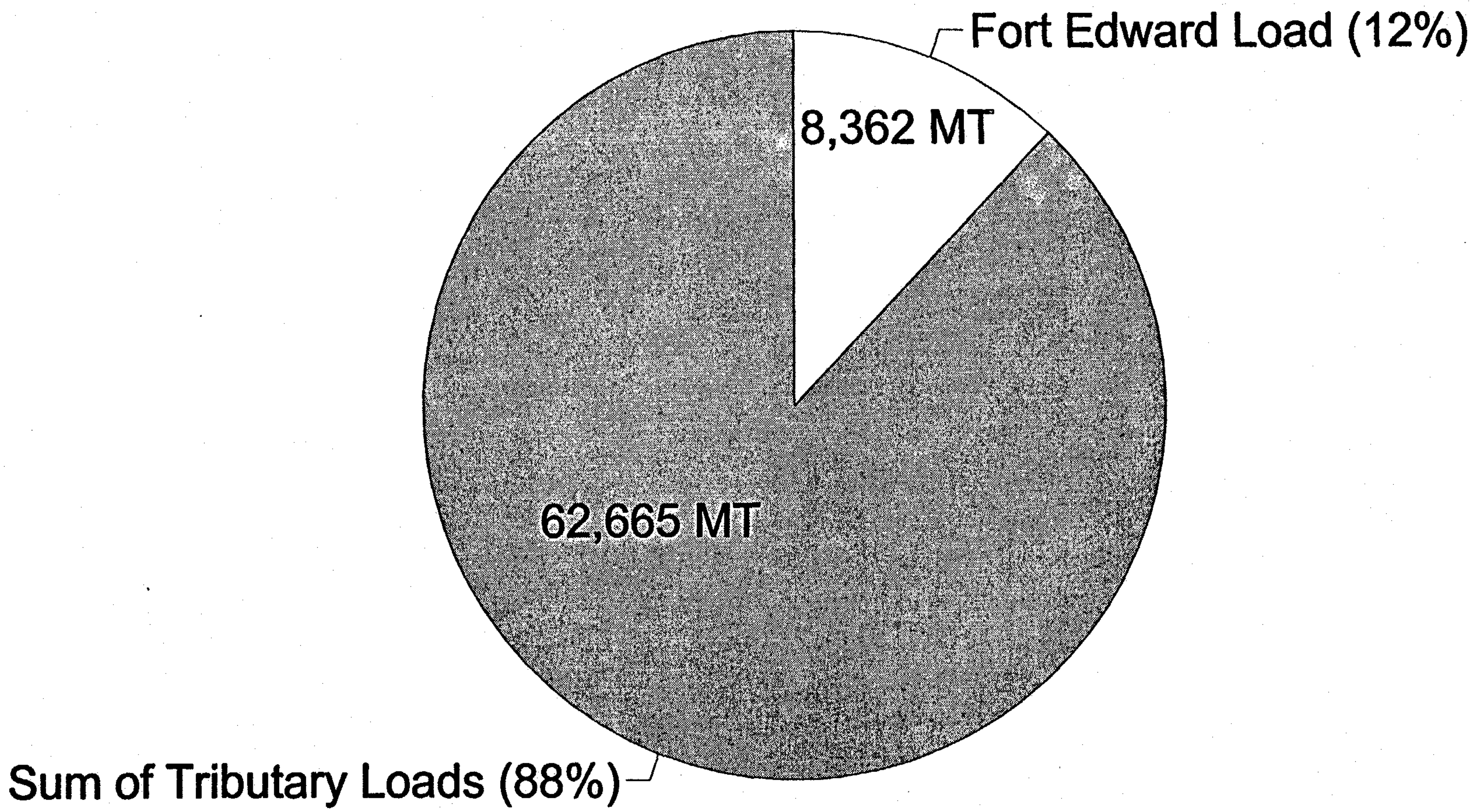

Figure 2-18. Comparison of total sediment load (metric tons) at Fort Edward to the sum of all tributary loads for March 30 to April 29, 1994.

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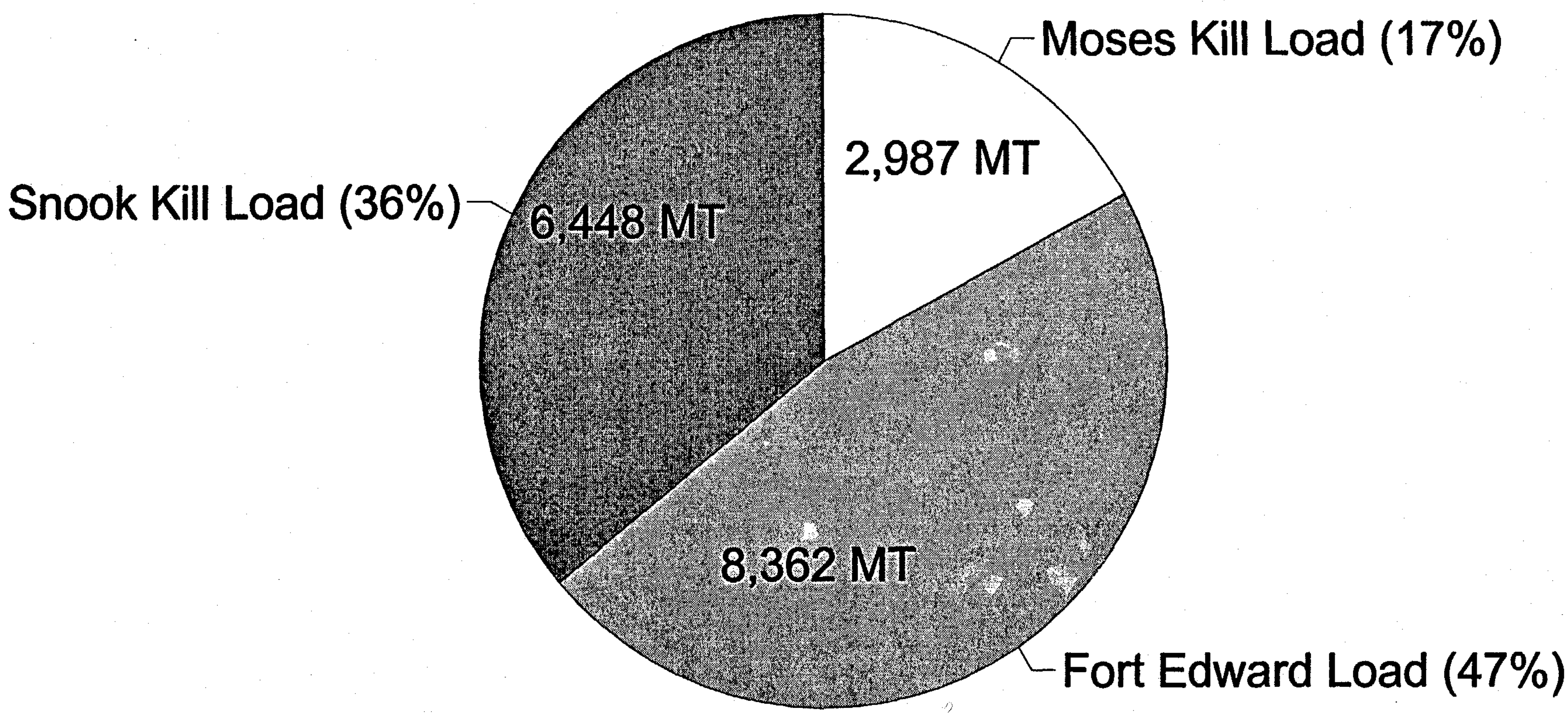

Figure 2-19. Comparison of total sediment loads (metric tons) at Fort Edward to sediment loads from Snook Kill and Moses Kill for March 30 to April 29, 1994.

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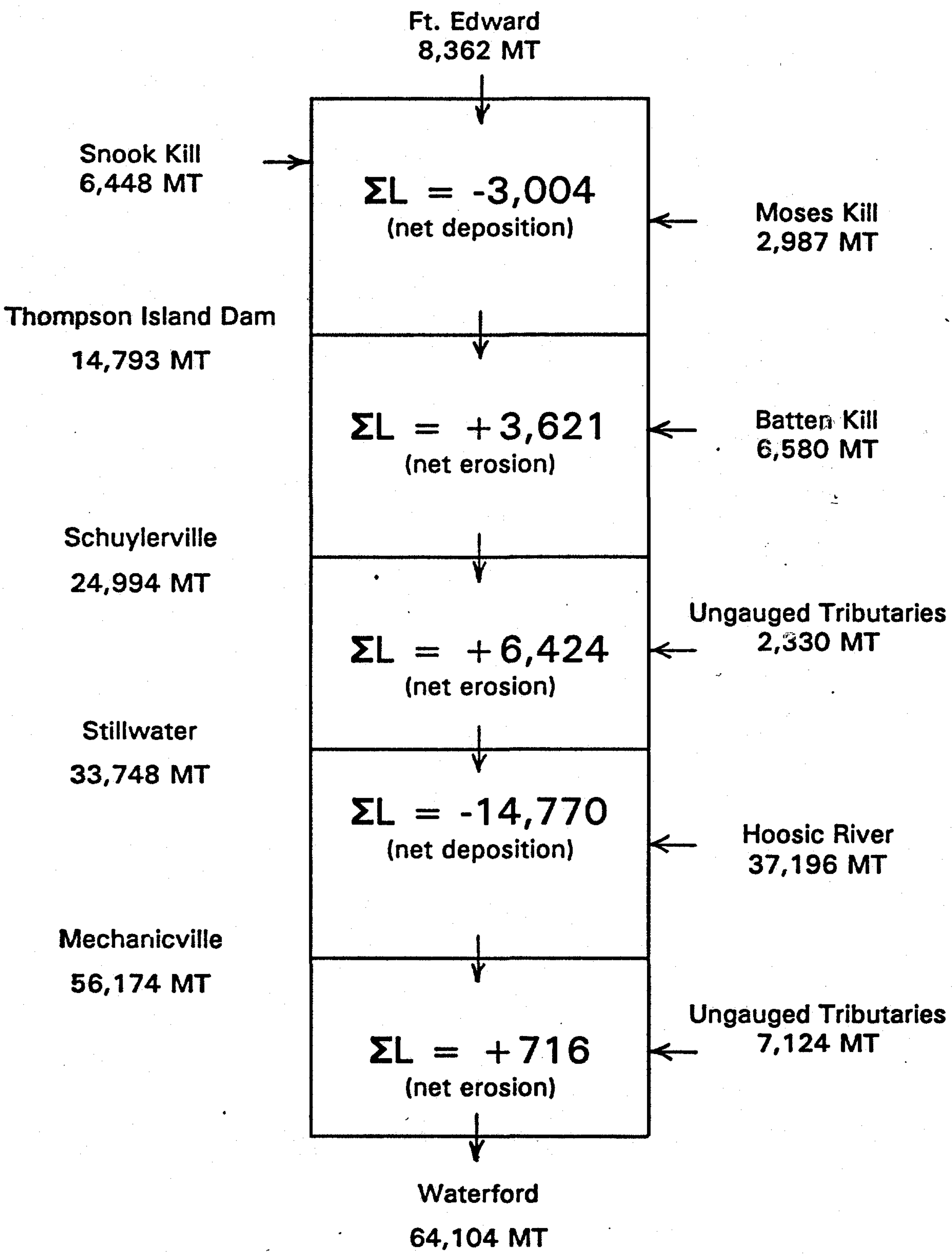

Figure 2-20. Sediment budget for the Upper Hudson River for March 30 to April 29, 1994. Units are metric tons.

equal to the average value for surficial sediments in this reach, the thickness of deposited sediments, averaged over the Thompson Island Pool, was 0.19 cm. A total of 14,770 metric tons were deposited in the Stillwater to Mechanicville reach, which represents a trapping efficiency of 24%. Net erosion was calculated in three reaches: Thompson Island Dam to Schuylerville (3,621 metric tons); Schuylerville to Stillwater (6,424 metric tons); and Mechanicville to Waterford (716 metric tons).

2.5 SEDIMENT DYNAMICS IN THE THOMPSON ISLAND POOL

The Thompson Island Pool sediment budget indicated that about 3,000 metric tons of sediment were deposited during the 1994 high flow period. This result suggests that long-term, net sedimentation is occurring in the Thompson Island Pool. Further examination of the temporal variation of sediment loading during the 30-day period analyzed here may provide important insights concerning the sediment dynamics in this reach.

Temporally variable sediment loads at Fort Edward, Snook Kill, Moses Kill and Thompson Island Dam were calculated using the procedures described in Section 2.3. The calculated loading rates, in metric tons/hour, for the 1994 high flow event are displayed on Figure 2-21. The loading at Fort Edward is related to the discharge at that location, with the highest incoming loads occurring on the rising limb of the flood hydrograph. Significant hysteresis in sediment loading at Fort Edward, i.e., high loading on rising limb and low loading on falling limb, is observed during the flood peak (~29,000 cfs) on April 16 to 19. The first peak in sediment loading from Snook Kill and Moses Kill happened on April 7, when flow rates in the Hudson River were relatively low (~5,000 cfs). A second peak in tributary loading occurred on April 14, which corresponded to increasing flow in the river (~15,000 to 18,000 cfs). Tributary sediment loading decreased significantly after April 14. This pattern in sediment loading, with most of the tributary loading occurring during a relatively low flow period prior to the flood peak in the Hudson River, will be shown to have an important effect on sedimentation processes in the Thompson Island Pool. The sediment load at the dam had two large peaks which correspond to different portions of the rising limb of the flood hydrograph between April 13 and 17. A minor loading peak at the dam occurred on April 7, when the tributary loading was high.

A temporally variable sediment budget, using Equations (1-1) and (1-2), can be constructed for the Thompson Island Pool using the loading rates discussed above. Net

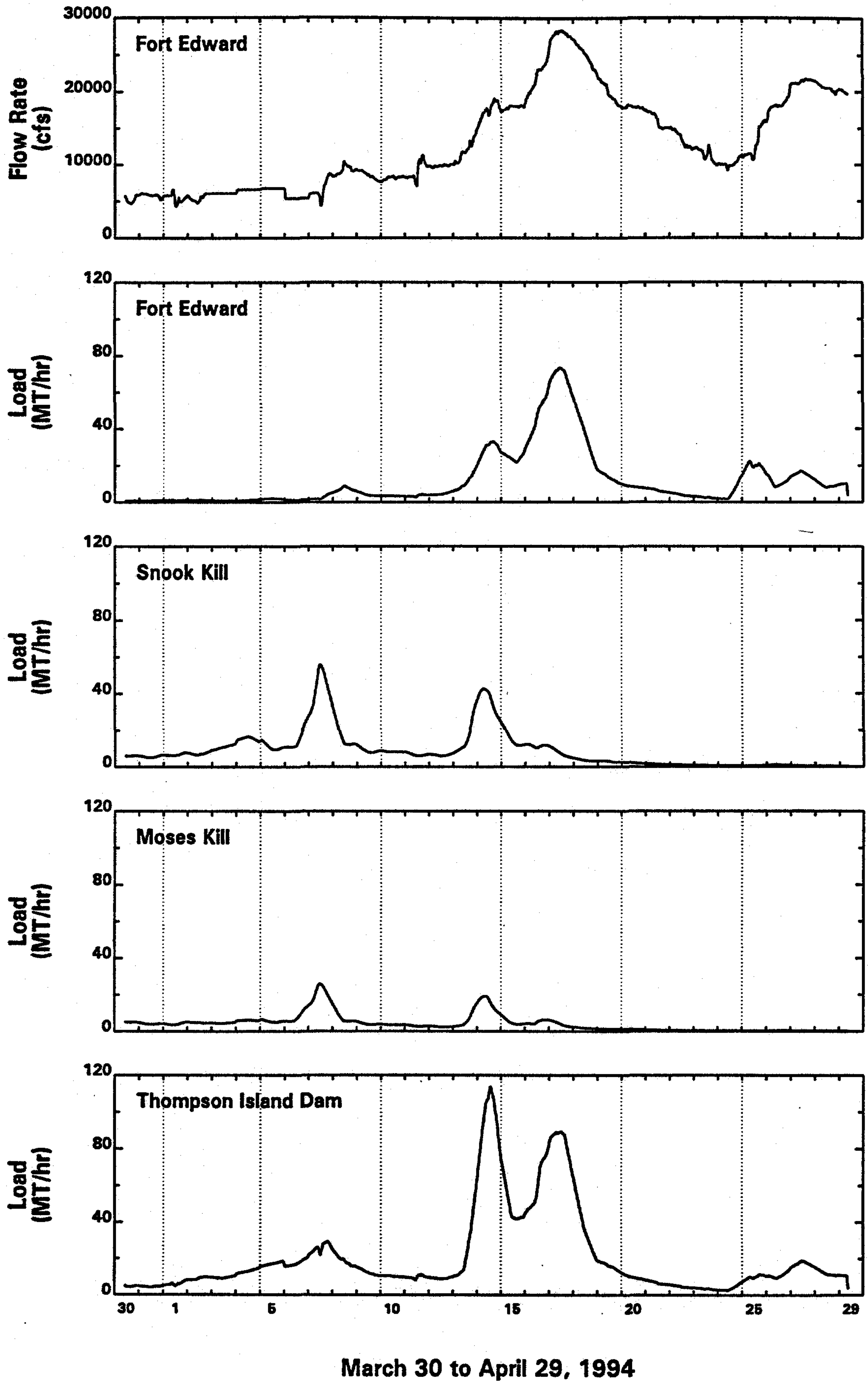

Figure 2-21. Sediment loading rates (metric tons/hour) in the Thompson Island Pool for March 30 to April 29, 1994.

deposition (negative load) occurs in this reach until April 14, with a large pulse of sediment from the tributaries being deposited on April 7, see the middle panel of Figure 2-22. In fact, nearly all of the sedimentation in the Thompson Island Pool happens during the 15 days before the Hudson River flood (see the bottom panel of Figure 2-22), which was a period when tributary sediment loading was much greater than loading at Fort Edward. High tributary loading occurred during a time when flow rates in the Hudson River were relatively low, which corresponds to low bottom shear stresses and an environment that is conducive to deposition. Thus, the timing and magnitude of tributary loading to the Thompson Island Pool is seen to be of major importance to sedimentation processes in this reach.

Two periods of net erosion occurred during the rising limb of the flood hydrograph, on April 14 and 17. The first erosion peak, on April 14, was the largest and it occurred as the flow rate in the Hudson River increased from about 15,000 to 18,000 cfs. The April 17 erosion peak was much smaller and it occurred near the flood peak (about 27,000 to 29,000 cfs). The erosion peaks were also very transient, with a sharp increase in erosion rate being followed by a dramatic decrease in erosion; the erosion events occurred over a 24-hour period, approximately. These results demonstrate the effects, and importance, of bed armoring on erosion processes in the Thompson Island Pool. In the absence of cohesive and non-cohesive bed armoring, the erosion rate would increase or remain constant during the rising limb of the hydrograph, it would not decrease to zero, as was observed during the erosion events on April 14 and 17. Another indication of bed armoring is that the erosion rate was significantly lower at the flood peak, about 29,000 cfs on April 17, than during the initial rising limb, about 15,000 to 18,000 cfs on April 14. Higher erosion rates will occur at higher flow rates, which generate higher bottom shear stresses, when bed armoring effects are negligible. Clearly, this situation did not happen during the April 1994 flood. Thus, this data analysis shows that bed armoring, in cohesive and non-cohesive bed areas, occurs during high flow events in the Thompson Island Pool.

It is also interesting to note that net deposition occurred in this reach after the erosion events on April 14 and 17, see bottom panel of Figure 2-22. Sedimentation occurred during the falling limb of the hydrograph, after April 17, but at a slower rate than during the relatively low flow period prior to April 14. One possible explanation for this effect, i.e., deposition during high flow (high bottom shear stress) conditions, is that the composition of the incoming sediment load has changed; the incoming load has a higher fraction of coarse sediment (i.e., sand) during the falling limb than during the lower flow period before April 14. Future sediment loading

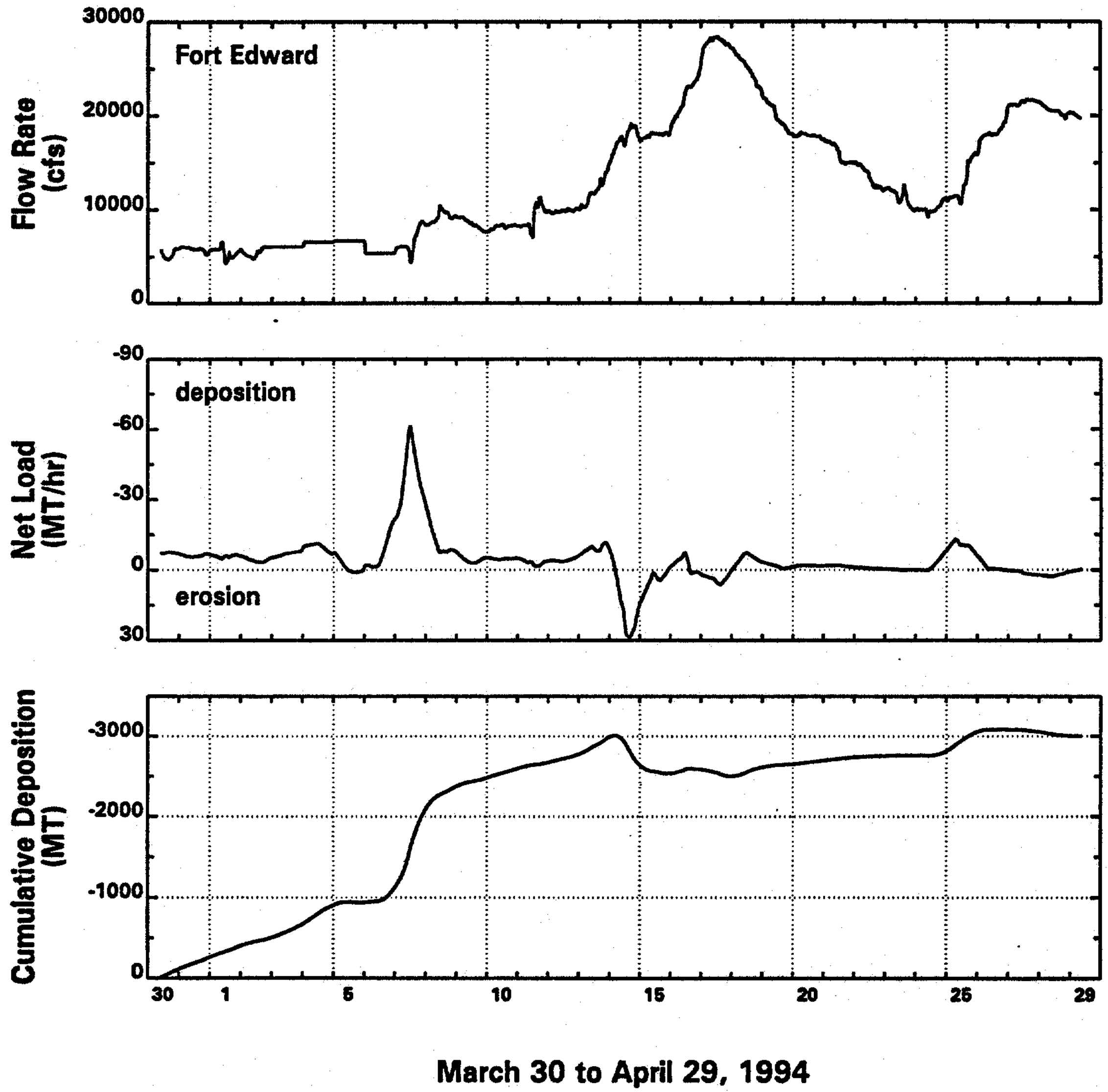

Figure 2-22. Net sediment load (metric tons/hour) and cumulative deposition (metric tons) in the Thompson Island Pool for March 30 to April 29, 1994.

studies should investigate this hypothesis by measuring the particle size distribution of all TSS samples.

2.6 UNCERTAINTY IN SEDIMENT BUDGET RESULTS

Various assumptions and approximations had to be made to construct the sediment budget for the 30-day period considered here. These approximations, due to incomplete data sets, result in some uncertainty in the analysis results. A discussion of this uncertainty, along with possible implications, is presented below.

The primary uncertainty in this analysis is the estimation of tributary flow rates, particularly the tributaries between Fort Edward and Stillwater. The tributaries in that reach of the Upper Hudson River are all based upon flow rates measured in Kayaderosseras Creek. The procedures used to estimate tributary flow rates using Kayaderosseras Creek gauge data have been shown to produce credible results. However, uncertainty is introduced into the analysis due to this approximate method for assigning tributary discharge. An attempt was made to quantify that uncertainty and determine its impact on the 1994 sediment budget.

Batten Kill flow rates were estimated using a correlation developed between discharge data collected at the Battenville and Kayaderosseras Creek gauging stations, i.e., Figure 2-7 and Equation (2-2). As can be seen on Figure 2-7, considerable variation in Battenville flow rates occurs for a particular flow in Kayaderosseras Creek. This variation is a source of uncertainty that was quantified as follows. First, the paired daily discharge values measured at the Battenville and Kayaderosseras Creek stations were sorted in ascending order of Kayaderosseras Creek discharge. The sorted flow rates were then binned into groups of 25 and the mean Kayaderosseras Creek flow rate and the standard deviation of the Battenville flow rate were calculated for each group. The standard deviation of each Battenville data group was then converted to a 95 % confidence interval limit. A plot of the 95% confidence interval limits for Battenville as a function of Kayaderosseras Creek flow rate is shown on Figure 2-23. The variation in Battenville flow increases approximately linearly with Kayaderosseras Creek flow, with a linear regression analysis yielding

$$K_{bat} = 0.81\ Q_{kay} + 18 \qquad \text{(2-9)}$$

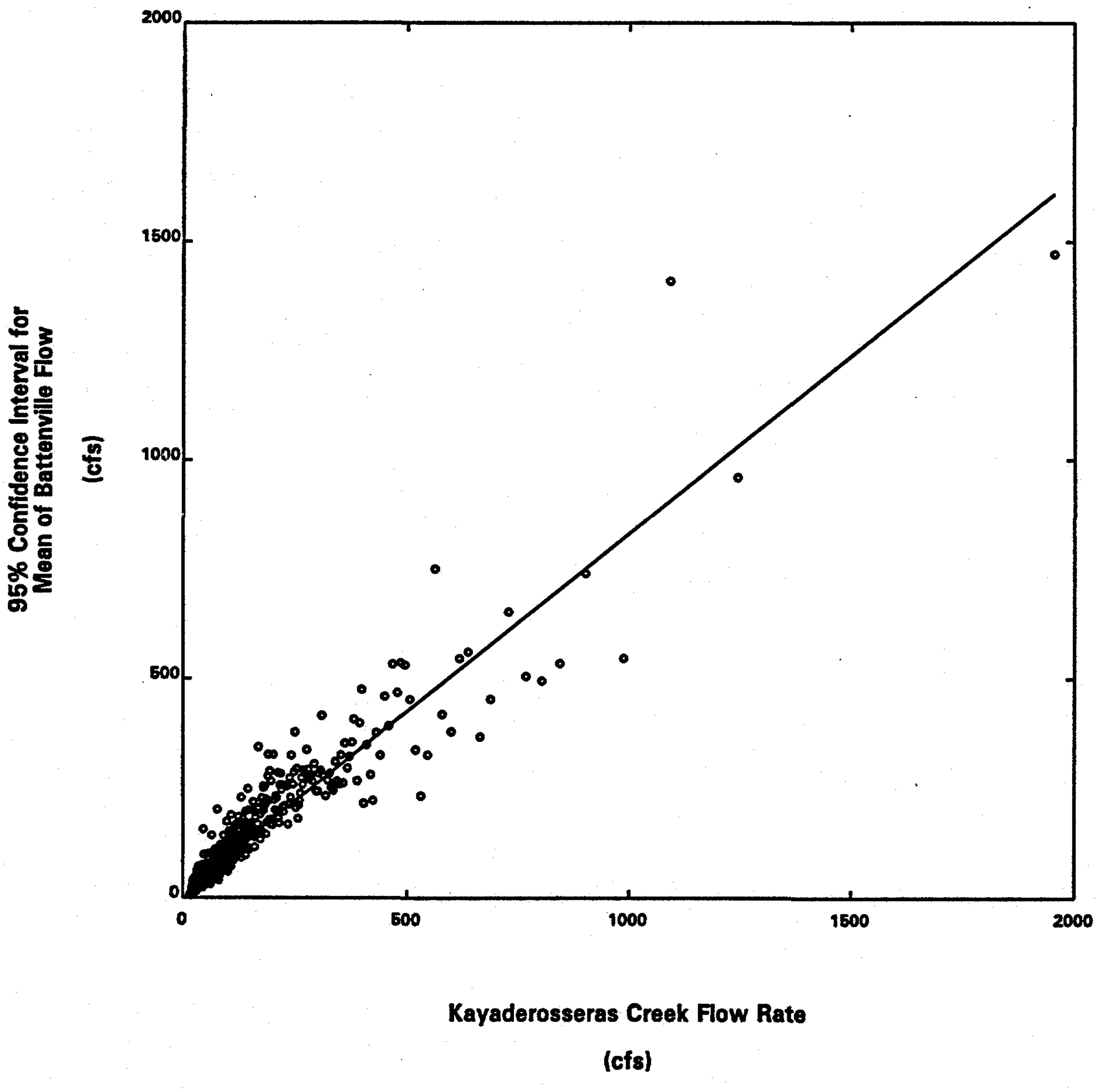

Figure 2-23. Correlation between standard deviation (converted to 95% confidence interval about the mean) of Batten Kill (at Battenville) flow rates and Kayaderosseras Creek flow rates.

where K_{bat} = 95% confidence interval limit on Battenville flow rates (cfs), Q_{kay} = Kayaderosseras Creek flow rate (cfs), and $R^2 = 0.89$ for this correlation. Confidence limits for Equation (2-2), i.e., correlation between Battenville and Kayaderosseras Creek flows, can be constructed using Equation (2-9)

$$\begin{aligned} Q_{bat} &= 4.03\ Q_{kay} + 163 \pm K_{bat} \\ &= (4.03 \pm 0.81)\ Q_{kay} + (163 \pm 18) \end{aligned} \tag{2-10}$$

The effect of the variable confidence limits on predicted Battenville flow rates is illustrated on Figure 2-24. Drainage area proration can then be used to convert Battenville flow rates to Batten Kill discharges, as discussed in Section 2.1.

Uncertainty in predicted Battenville flow rates, as expressed by Equation (2-9), can be extended to the other tributaries between Fort Edward and Stillwater because discharge in all of these tributaries is predicted using Kayaderosseras Creek flows. This transformation can be accomplished by normalizing Equation (2-9) with respect to the Battenville drainage area

$$\kappa_{bat} = 0.0021\ Q_{kay} + 0.046 \tag{2-11}$$

where κ_{bat} = normalized 95% confidence interval limit on Battenville flow rates (cfs/mi^2). Applying Equation (2-11) to Snook Kill, Moses Kill and the ungauged tributaries between Schuylerville and Stillwater results in the following 95% confidence limits for flow rate estimators

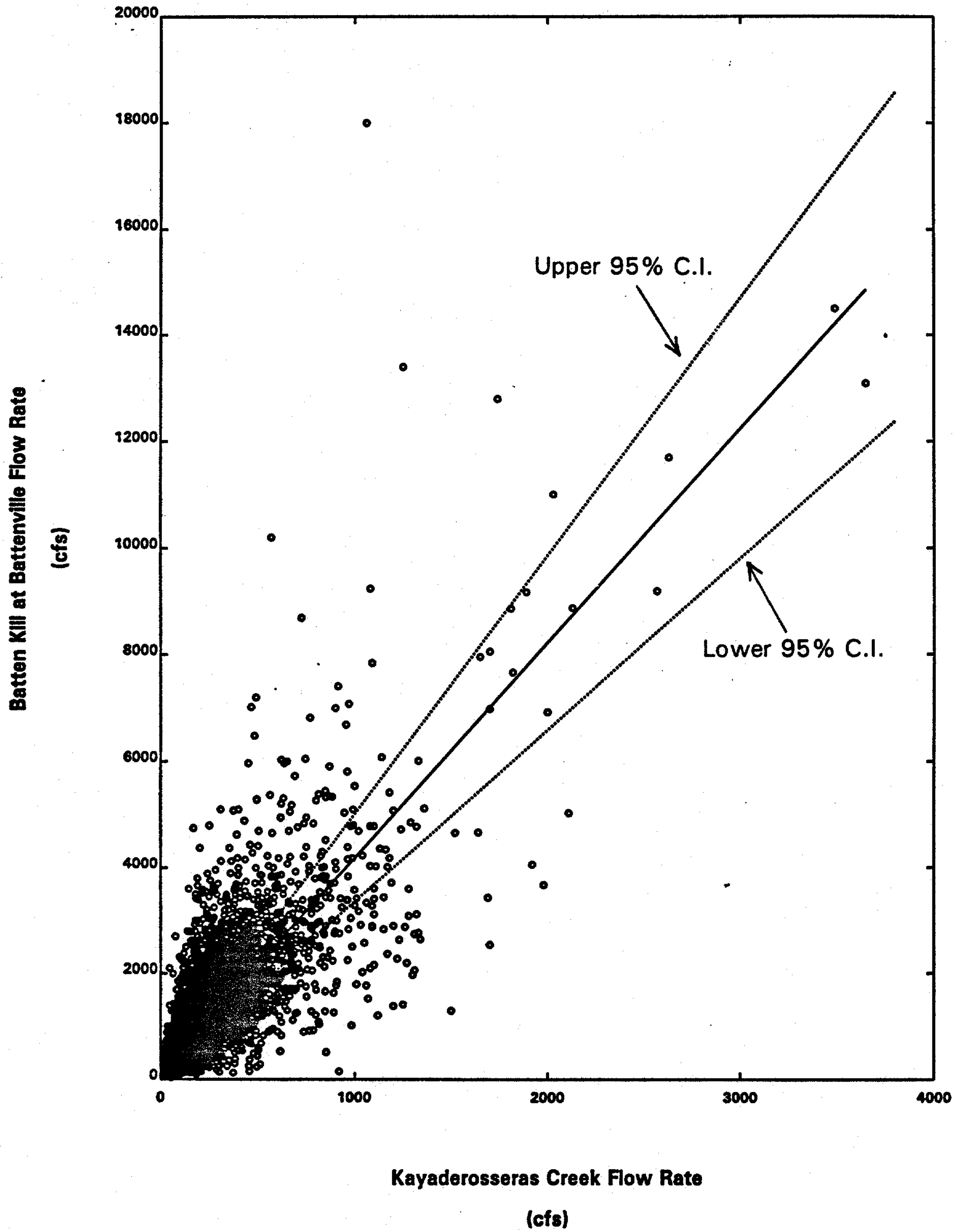

Figure 2-24. Correlation (with upper and lower 95% confidence limits) between daily average flow rates measured in Kayaderosseras Creek (at West Milton) and Batten Kill (at Battenville).

$$Q_{sno} = (1.36 \pm 0.26)\ Q_{kay} \pm 6 \tag{2-12}$$

$$Q_{mos} = (0.77 \pm 0.14)\ Q_{kay} \pm 3 \tag{2-13}$$

$$Q_{R2} = (0.96 \pm 0.70)\ Q_{kay} \pm 15 \tag{2-14}$$

where Q_{sno} = Snook Kill flow rate (cfs), Q_{mos} = Moses Kill flow rate (cfs) and Q_{R2} = flow rate for ungauged tributaries between Schuylerville and Stillwater (cfs). Examination of these three equations shows that the greatest relative uncertainty exists for the ungauged tributaries between Schuylerville and Stillwater, which is consistent with the approximations made to estimate flows in these tributaries.

The validity of applying the 95% confidence interval limits to the tributaries between Fort Edward and Stillwater can be tested by recalculating Upper Hudson River flow rates for the 1977-92 period as was done in Section 2.1. Comparisons of predicted and observed daily average flow rates at Stillwater during this 15-year period yielded means of the absolute relative error of 11.3 and 11.7% for the lower and upper 95% confidence limits, respectively. These errors are slightly higher than the error for the original calculation, which was 10.6%. The predicted mean flow rates at Stillwater for the 15-year period were 6,179 and 6,839 cfs for the lower and upper 95% confidence limits, respectively. The measured mean discharge was 6,604 cfs, which means that the predicted lower and upper limit values are 6.4% low and 3.6% high, respectively. For comparison, the original calculation produced an error of 1.5% low for the mean discharge. Thus, the predicted tributary flow rates at the 95% confidence interval limits produce less accurate results than the original calculation, as would be expected, but varying the tributary flows in this manner yields realistic predictions.

The 95% confidence intervals for the tributaries between Fort Edward and Stillwater were then applied to the 30-day period in 1994 that has been the focus of this analysis. The resulting flow balances, using the lower and upper limits, are shown on Figures 2-25 and 2-26. Comparing predicted mean flow rates at Stillwater and Waterford, for both lower and upper limits, with the USGS estimated mean discharges shows that all differences are less than 11%, which is within the measurement error. Thus, adjusting the tributary flow rates as described above produces credible flow balances.

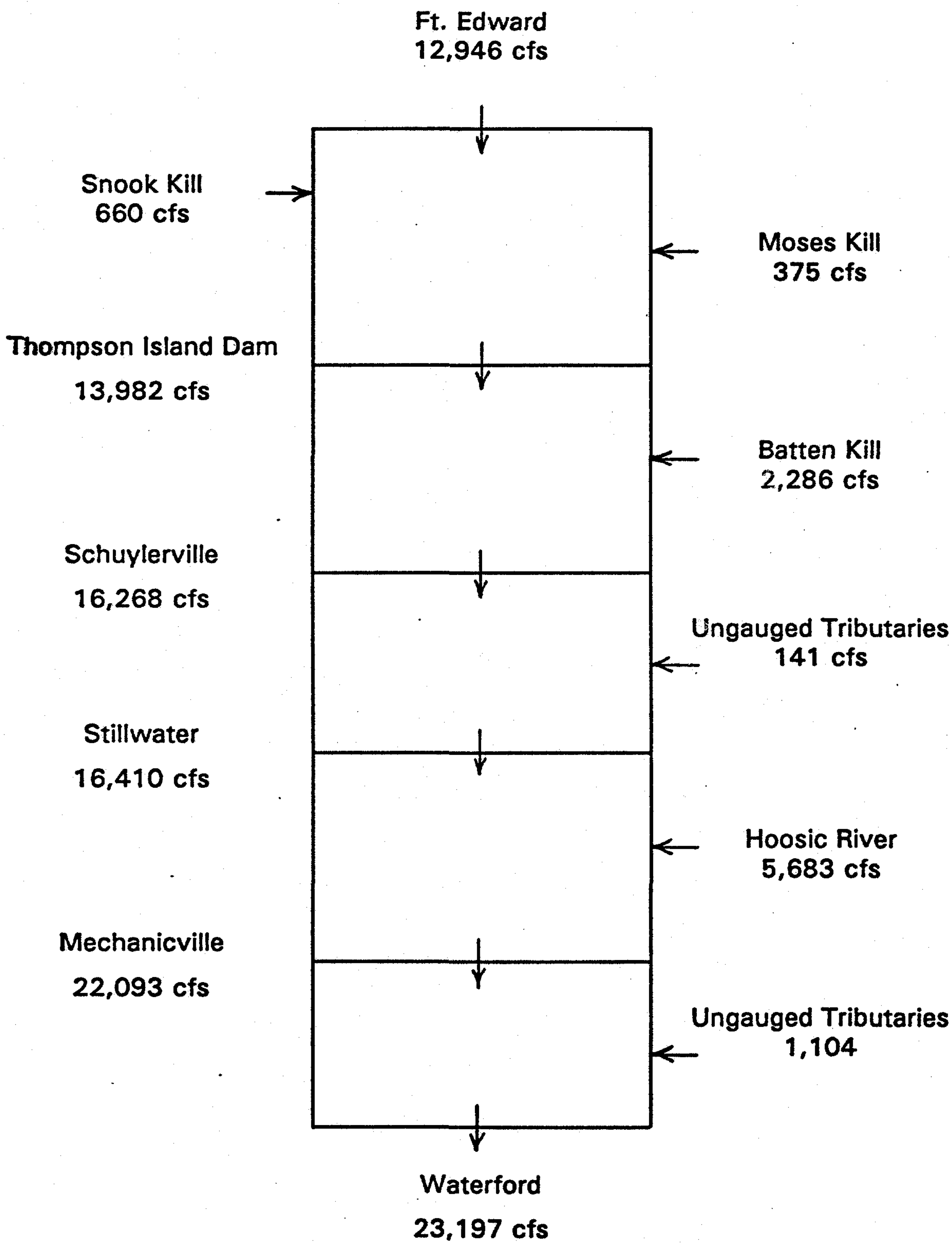

Figure 2-25. Mean flow balance in the Upper Hudson River for March 30 to April 29, 1994. Lower 95% confidence limit used for estimating tributary flow rates.

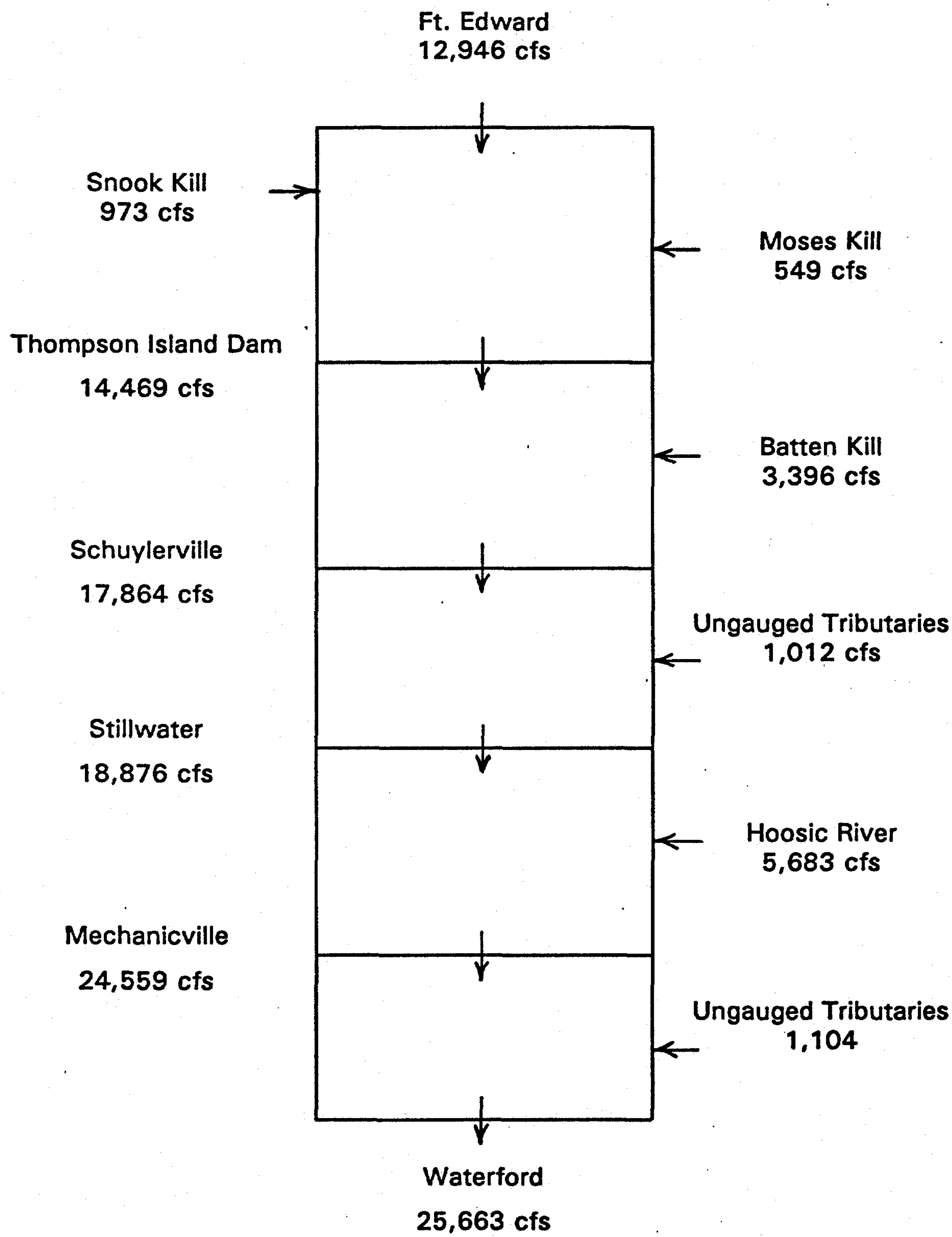

Figure 2-26. Mean flow balance in the Upper Hudson River for March 30 to April 29, 1994. Upper 95% confidence limit used for estimating tributary flow rates.

Sediment budgets for the 30-day period in 1994, developed using the lower and upper tributary flow limits, are presented on Figures 2-27 and 2-28. Net deposition occurs for the Upper Hudson River system in both cases, with 7,021 and 6,642 metric tons of sediment deposited for the lower and higher confidence limits, respectively. These estimates are within 4% of the original estimate of 6,923 metric tons of deposited sediment. The overall trapping efficiency for the Upper Hudson River ranges from 9 to 10% for the three sediment budgets. Patterns of net deposition and erosion in the five reaches delineated in this analysis were unaffected by the adjustments in tributary flow. In the Thompson Island Pool, net sedimentation occurred, with a variation of approximately $\pm 50\%$ when compared to the original calculation, which corresponds to a range in trapping efficiencies of 10 to 23%. This variation in net sedimentation would produce a range in average depositional thickness of 0.10 to 0.28 cm, where a dry bulk density of 0.9 g/cm^3 has been assumed for Thompson Island Pool sediments.

A final uncertainty in this analysis lies in the TSS data. These data were collected on a daily basis, making it possible that peaks in sediment loading during the flood, especially in the tributaries, were not observed. Measuring sediment loadings in rivers during high flow events typically requires TSS measurement frequencies of at least once every 4 hours, with higher collection frequencies being preferable (Thomas, 1985; Walling et al., 1992; Ziegler and Connolly, 1995). The impact of the daily TSS measurement frequency on the sediment budget cannot be ascertained but, based upon sediment loading studies on other river systems (Walling et al., 1992), it is likely that the tributary loadings have been underestimated.

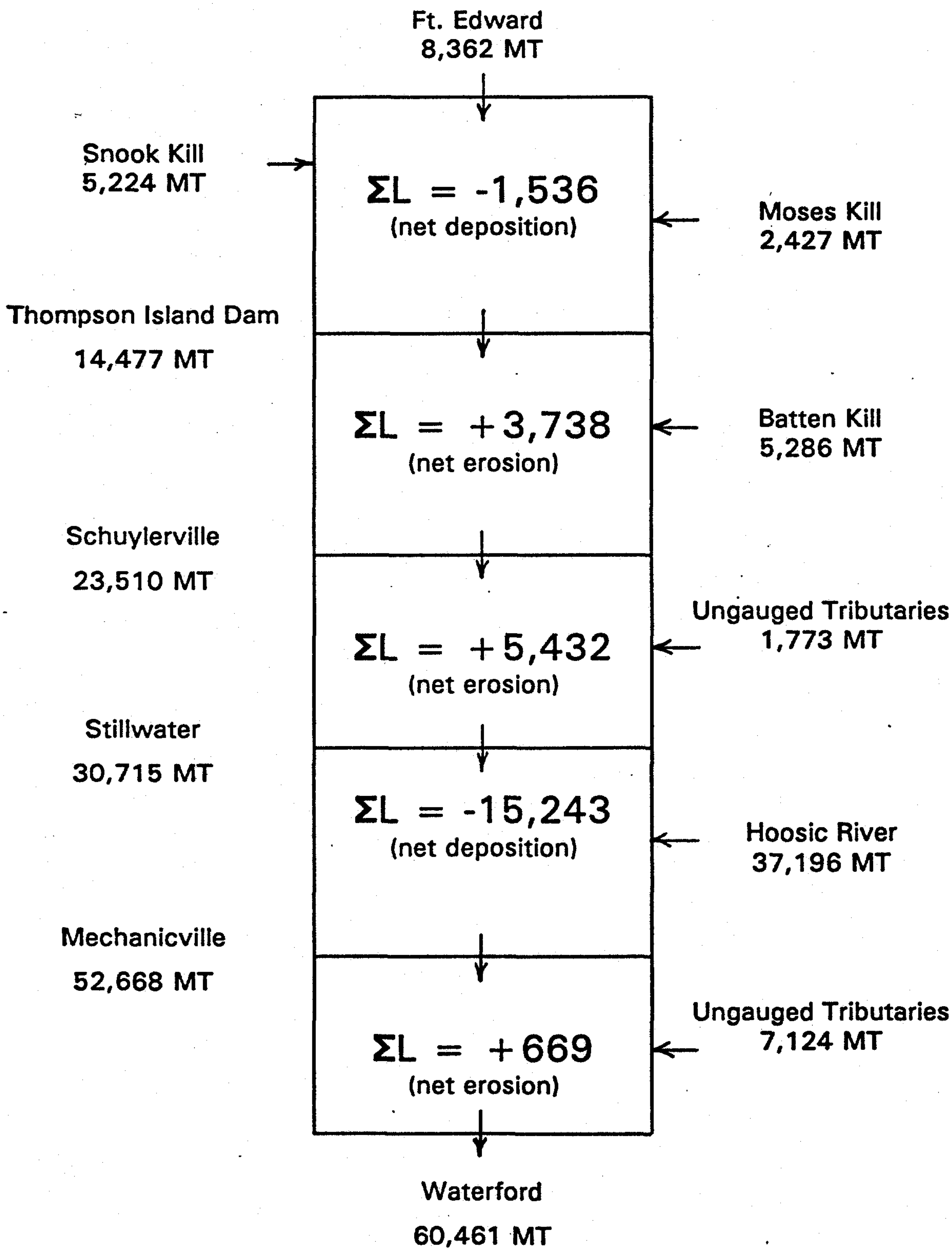

Figure 2-27. Sediment budget for the Upper Hudson River for March 30 to April 29, 1994. Units are metric tons. Lower 95% confidence limit used for estimating tributary flow rates.

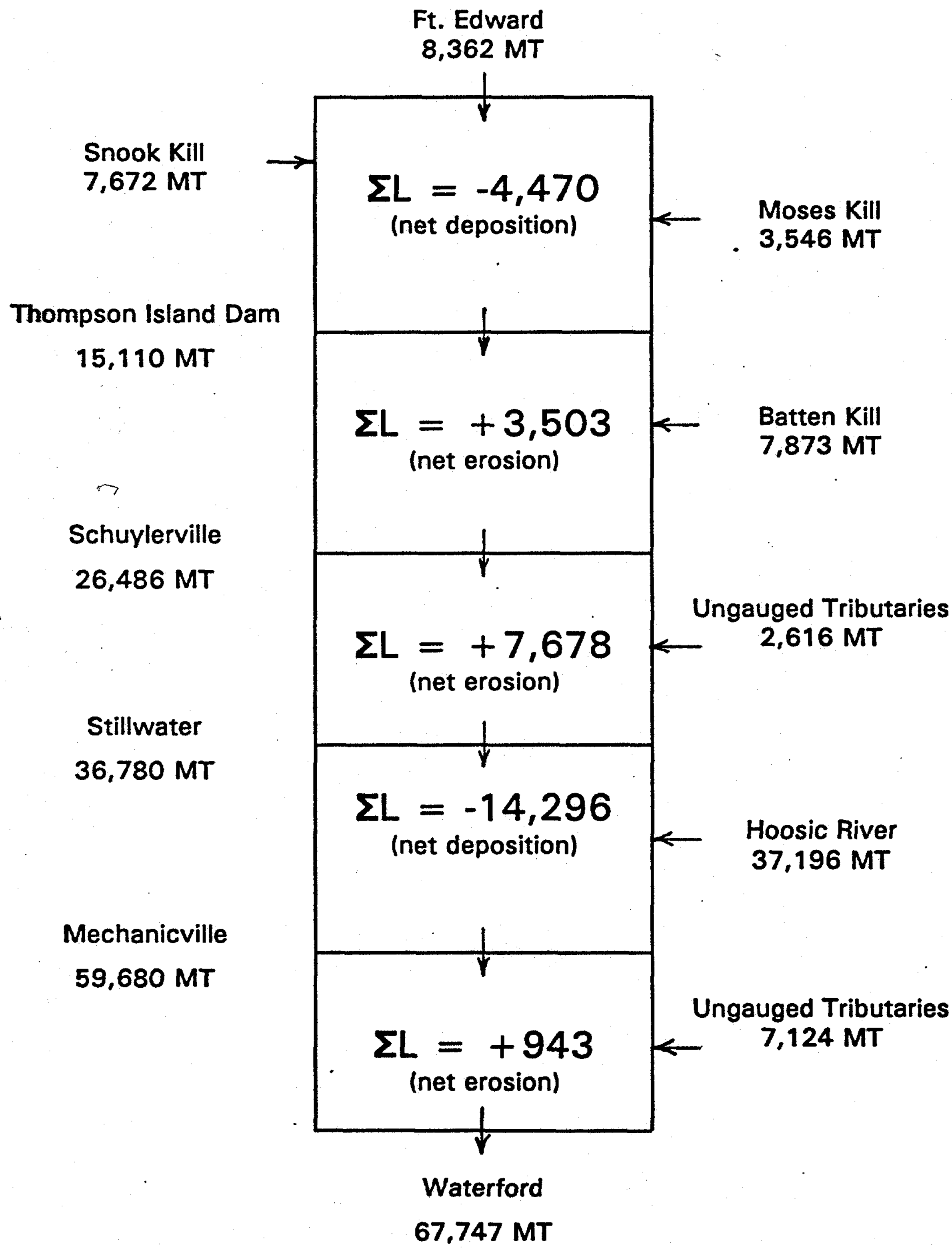

Figure 2-28. Sediment budget for the Upper Hudson River for March 30 to April 29, 1994. Units are metric tons. Upper 95% confidence limit used for estimating tributary flow rates.

SECTION 3

CONCLUSIONS AND RECOMMENDATIONS

Flow rate and TSS data collected during a 30-day period in 1994 have been used to estimate sediment loading to the Upper Hudson River and construct a sediment budget for this riverine system. The data analysis showed that net sedimentation occurred during this period between Fort Edward and Waterford, with an overall trapping efficiency of about 10%. Uncertainty in the quantity of sediment deposited in the system exists due to incomplete data sets and the need to make various assumptions in the analysis. However, accounting for variation in tributary flow rates between Fort Edward and Stillwater produces a global sediment budget with net deposition that ranges between approximately 6,600 and 7,000 metric tons. This uncertainty range is relatively small, about ±3%, which strongly suggests that the present analysis is valid, despite the various assumptions and approximations used to fill in data gaps.

Approximately 3,000 metric tons of sediment were deposited in the Thompson Island Pool during the 30-day high flow period, with an uncertainty range of about ±50% associated with this value. This amount of deposition represents a trapping efficiency range of 10 to 23% in this reach. The average thickness of deposited sediments in the Thompson Island Pool was estimated to range between 0.10 and 0.28 cm. Based upon analysis of various sedimentation data for Thompson Island Pool (HydroQual, 1995), the predicted depositional thickness appears to be realistic, which further supports the validity of the present analysis. Note that these ranges are based on uncertainty in estimated flows for Moses Kill and Snook Kill.

The importance of tributary loading and bed armoring on sediment dynamics in the Thompson Island Pool was demonstrated by this data analysis. Sedimentation in this reach was shown to be strongly affected by sediment loading from Snook Kill and Moses Kill. The sediment loads from these two tributaries must be accurately estimated in any sediment transport analysis. Bed armoring effects on erosion were clearly evident during the flood, indicating that any sediment transport model applied to the Thompson Island Pool must account for bed armoring, in both cohesive and non-cohesive bed areas.

The flow rate and TSS data used in this analysis are the best data available for estimating tributary sediment loading to the Upper Hudson River during a flood period. However, as discussed in the previous section, uncertainty exists in the sediment budget results due to data limitations. This uncertainty could be reduced in two ways. First, couple the data analysis with a mass balance model of the Upper Hudson River. This approach provides a powerful tool that can be used to quantitatively examine sediment transport processes in the river and that also maximizes the effectiveness of available data. Second, additional TSS and discharge data should be collected during at least one high flow event in 1997. Tributaries to the Thompson Island Pool should be the focus of this study. Flow gauges need to be established on Snook Kill and Moses Kill so that flow rates from those tributaries can be accurately determined. In addition to being used in sediment loading calculations, these data could be used to validate the accuracy of estimating Thompson Island Pool tributary flow rates using Kayaderosseras Creek gauge data. A method for measuring flow rates at Thompson Island Dam should also be established. TSS data need to be collected at Fort Edward, Snook Kill, Moses Kill and Thompson Island Dam during this study. Automated samplers need to be used so that TSS measurements can be made at least once every 4 hours, with a higher sampling rate being preferable. This flow and TSS data could then be used to construct a sediment budget for the Thompson Island Pool for the high flow period in 1997 that would be monitored. Comparisons with the results of the 1994 analysis would help to validate the results of the analysis presented in this report. In addition, the 1997 data set could prove to be very useful in validating a sediment transport model of the Thompson Island Pool.

SECTION 4

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