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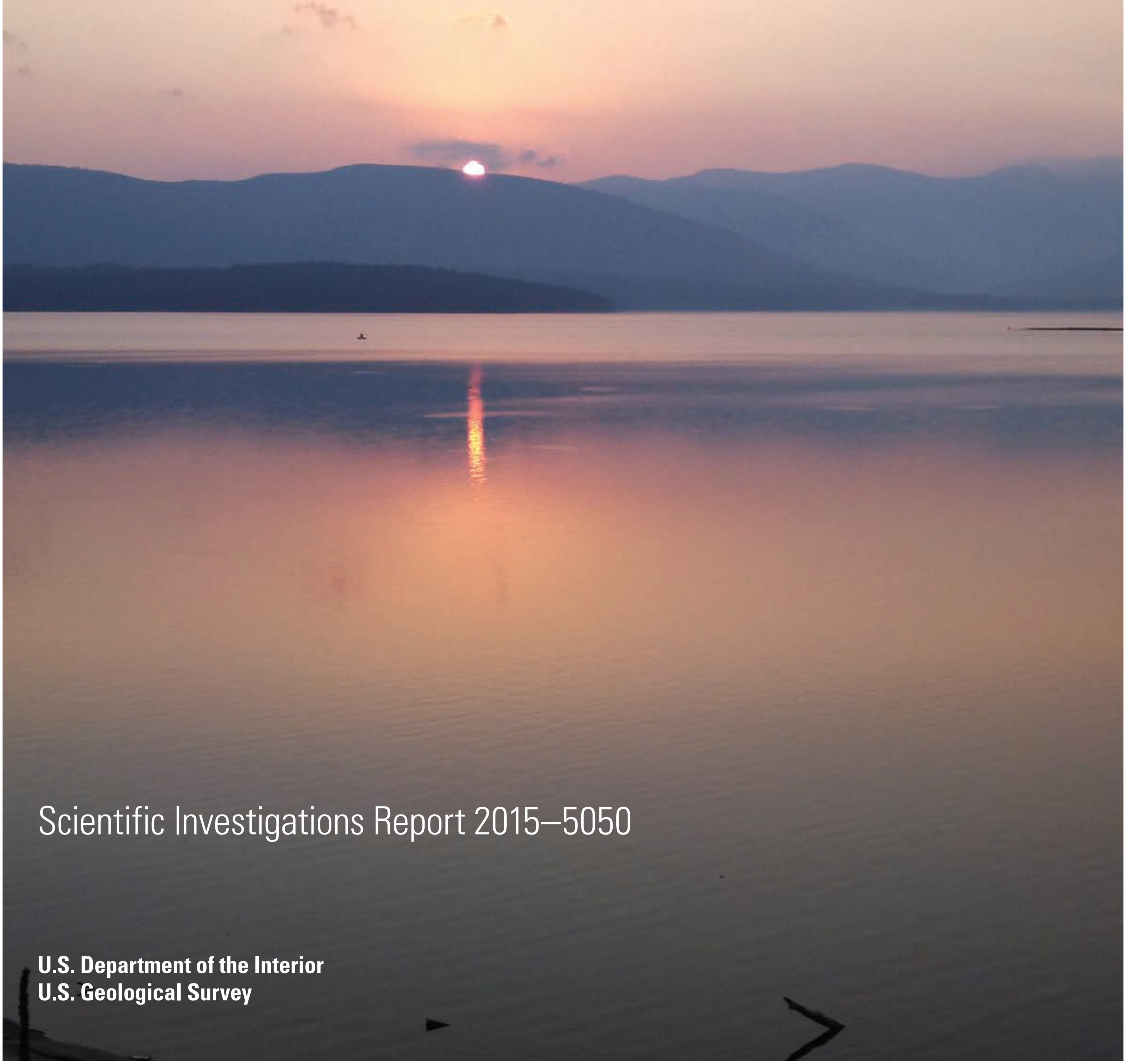
Estimates of Natural Streamflow at Two Streamgages on the Esopus Creek, New York, Water Years 1932 to 2012



Scientific Investigations Report 2015–5050

U.S. Department of the Interior
U.S. Geological Survey

Cover. The West Basin of Ashokan Reservoir at sunset. Photograph by Elizabeth Nystrom, 2013.

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U.S. Geological Survey
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Conversion Factors

Inch/Pound to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)

Datum

Vertical coordinate information is referenced to North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

Abbreviations

IHA	Indicators of Hydrologic Alteration software
NYSET	New York Streamflow Estimation Tool
USGS	U.S. Geological Survey
WY	water year

Estimates of Natural Streamflow at Two Streamgages on the Esopus Creek, New York, Water Years 1932 to 2012

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Abstract

Streamflow in the Esopus Creek watershed is altered by two major watershed management activities carried out by the New York City Department of Environmental Protection as part of its responsibility to maintain a water supply for New York City: (1) diversion of water from the Schoharie Creek watershed to the Esopus Creek through the Shandaken Tunnel, and (2) impoundment of the Esopus Creek by a dam that forms the Ashokan Reservoir and subsequent release through the Catskill Aqueduct. Stakeholders in the Catskill region are interested and concerned about the extent to which these watershed management activities have altered streamflow, especially low and high flows, in the Esopus Creek. To address these concerns, natural (in the absence of diversion and impoundment) daily discharge from October 1, 1931, to September 30, 2012, was estimated for the U.S. Geological Survey streamgages at Coldbrook (station number 01362500), downstream of the Shandaken Tunnel discharge, and at Mount Marion (01364500), downstream of the Ashokan Reservoir.

A multiple linear regression approach, using nearby discharge records from unimpounded streams as predictive variables, was applied to estimate natural discharge at the Coldbrook streamgage. Estimated values of natural daily discharge at the Coldbrook streamgage were lower than values of gaged daily discharge throughout the flow range at this site. At moderate- and low-flow conditions, gaged daily-discharge values were about two to three times greater than natural daily-discharge estimates, whereas the difference between the two records was less than 5 percent for the highest 1 percent of daily-discharge values. These results indicate that Shandaken Tunnel discharge has a minor effect on flooding in the Esopus Creek Basin. However, a difference of 5 percent is within the uncertainty of the regression-based natural discharge estimates for Coldbrook; thus, it cannot be stated with certainty that the Tunnel has on average any effect on flow for the highest 1 percent of daily discharge values.

Natural discharge at the Mount Marion streamgage was estimated by summing the natural discharge estimated for the Coldbrook streamgage and the discharge estimated for the intervening basin area through application of the New York Streamflow Estimation Tool, recently developed for estimating unaltered streamflow at ungaged locations in the State. Estimates of natural daily discharge at the Mount Marion streamgage were about three times greater than gaged daily discharge throughout the moderate- to low-flow range from October 1, 1970, to September 30, 2012, the period of record for full water years at this streamgage. The relative difference between the two discharge time series declined as flow increased beyond the moderate range, but gaged daily discharge was still 25 to 43 percent less than estimated natural daily discharge for the high-flow metrics calculated in this analysis, and the mean relative difference was 43 percent for the annual 1-day maximum discharge. Overall, these estimates of natural discharge reflect the absence of effects of the Shandaken Tunnel and Ashokan Reservoir on flows in the Esopus Creek over broad time frames. However, caution is warranted if one is attempting to apply the natural estimates at short time scales because the regression prediction intervals indicate that uncertainty at a daily time step ranges from about 40 to 80 percent.

Introduction

The natural flow regimes of Earth's streams and rivers are greatly altered by human activities such as withdrawals for water supply and irrigation, discharges from point sources, and impoundment (Vörösmarty and Sahagian, 2000; Eng and others, 2013). As examples of the extent of this alteration, about 20 percent of global continental runoff is stored behind registered dams (Vörösmarty and Sahagian, 2000), and more than half of global runoff accessible to humans is withdrawn or maintained for instream uses (Postel and others, 1996). Human exploitation of rivers has wide ranging implications, including changes in the following: the flow and thermal regimes of rivers, aquatic and riparian ecological communities, the geomorphology of channel networks and flood plains, water quality, and land-use patterns (Rosenberg and others, 2000; Magilligan and Nislow, 2005). Temporal patterns in population growth and per capita water use indicate that human alteration of the global water cycle and river flow regimes is increasing and suggest that further increases are likely in the future (Wada and others, 2013). Although many of the effects of human water use have deleterious environmental consequences, the benefits of water use are numerous and include food production, electricity generation, recreation, flood reduction, and improved health outcomes (Gleick, 1996). This complex mix of benefits and adverse effects often creates water management conflicts among interest groups with divergent priorities. Successful resolution of water-use conflicts presents a challenge and forms the basis of good water management (Wolf and others, 2005).

The Catskill Mountain region of southeastern New York is valued for its water resources, and its water has long been used for human activities such as recreation, industry, and water supply (Francis, 1988; Swaney and others, 2006). Streamflow and water quality in the region have been altered by human activities that date to at least the 19th century, when leather tanneries diverted flow and severely polluted waterways (Swaney and others, 2006). New York City began to play a large role in the use and management of water resources in the Catskills in the early 20th century. The city's water-supply needs were forecast to exceed the available Croton water supply, and the newly established Bureau of Water Supply then began to acquire land in the Catskills to build dams, reservoirs, and aqueducts for what would become the City's West of Hudson water supply (Iwan, 1987).

The first reservoir completed, the Ashokan, began delivering water to the city through the Catskill Aqueduct in 1915 (Galusha, 1999). Development of the West of Hudson water supply continued through the mid-1960s until the sixth reservoir, the Cannonsville, was completed and began to deliver water downstate through the Delaware Aqueduct. The extensive use of water from the Catskills by New York City has often pitted the interests of the city in protecting its water supply against those of governmental agencies at the municipal, county, and state levels, as well as those of regional citizen and interest groups (Soll, 2013). These conflicts have played out against a backdrop of regulatory enforcement that has driven watershed and water-supply management requirements that New York City must meet under laws such as the Safe Drinking Water Act (42 U.S.C. §300f et seq.) and Clean Water Act (33 U.S.C. §1251 et seq.; McClure, 2007; Smith and Porter, 2010).

The six reservoirs in the Catskills that form the New York West of Hudson water-supply system, along with smaller reservoirs and impoundments, have altered the natural flow regime in the region. Although the City's reservoirs were not designed for flood control, impoundment has diminished and attenuated flood peaks and decreased base flow (Zembrzuski and Evans, 1989; Suro and Firda, 2006; Milone and MacBroom, Inc., 2009). The New York City Department of Environmental Protection manages the City's water-supply system in accordance with several regulations that dictate releases from the reservoirs. This mix of mandatory and voluntary regulations is carried out under the guidance of the New York State Department of Environmental Conservation (2014a), the U.S. Environmental Protection Agency (2014), and the Delaware River Basin Commission (http://www.state.nj.us/drbc/). Some of these regulations are designed to minimize downstream flood effects by increasing releases in advance of periods when flood risk is high and when refilling of reservoirs in the near future is likely.

The Esopus Creek is an example of a watershed in which diversions for New York City's water supply have altered the natural flow regime. Water is transferred from the Schoharie Reservoir to the Esopus Creek through the 18-mile (mi) Shandaken Tunnel. This diversion increases the flow of the Esopus Creek, and businesses that offer float trips on inner tubes and other watercraft are dependent on this enhanced discharge during summer low-flow periods. Regulations govern releases from the tunnel to serve these recreational needs (New York State Department of Environmental Conservation, 2014b). Because the Shandaken Tunnel provides up to 600 million gallons per day (Mgal/d; about 930 cubic feet per second [ft^3/s]) to the Esopus Creek, the issue of whether the tunnel increases the magnitude of floods in the Creek has long been controversial. Reports as far back as the mid-20th century blame Shandaken Tunnel discharges for increased flood damage (Van Burkalow, 1959).

Downstream of the U.S. Geological Survey (USGS) streamgage at Coldbrook (station number 01362500), the Esopus Creek is impounded by a dam that forms the Ashokan Reservoir. About 350 to 400 Mgal/d of water is diverted downstate from this reservoir through the Catskill Aqueduct to serve New York City's water-supply needs. A spillway discharges back into the Esopus Creek (upstream of the USGS streamgage at Mount Marion [01364500]) when the Reservoir is full or when gated releases are occurring to serve objectives such as minimizing downstream floods. Lowered base flow and decreased high flow in the Esopus Creek downstream of the dam have been noted previously (Suro and Firda, 2007; Milone and MacBroom, Inc., 2009). In addition to the Ashokan Reservoir, there are three other impoundments in the Esopus Creek Basin, the largest of which is Cooper Lake, a water supply for the city of Kingston (http://www.kingston-ny.gov/content/76/78/1005/default.aspx). However, this lake is quite small, with a storage volume equivalent to about 1 percent of the Ashokan Reservoir volume.

The Esopus Creek is also an example of a Catskill watershed about which the water management interests of New York City have often conflicted with the interests of various stakeholders, such as governmental organizations and citizen groups (Postel and Thompson, 2005; Kane and Erickson, 2007). A variety of issues have arisen about the management of flow and water quality in the Esopus Creek that include protecting fish habitat, supporting water recreation businesses, minimizing flooding and flood damage, and managing excessive turbidity. Turbidity in the Esopus Creek Basin has been a prominent issue, and a successful lawsuit in which the Shandaken Tunnel was determined to be a point source of sediment pollution under the Clean Water Act (McClure, 2007) has resulted in considerable effort by the New York City Department of Environmental Protection to minimize tunnel diversions during periods of high turbidity.

The focus of the current study by the U.S. Geological Survey, in cooperation with the New York City Department of Environmental Protection, is to determine the natural flow conditions in the Esopus Creek at two key locations, represented by USGS streamgages at (1) Coldbrook, N.Y. (01362500), and (2) Mount Marion, N.Y. (01364500). The Coldbrook streamgage is 10.5 mi downstream of the Shandaken Tunnel and therefore receives additional discharge on days when flow is exiting the tunnel. The Mount Marion streamgage is 31.6 mi downstream of the Ashokan Reservoir and therefore receives less discharge than would naturally be received from upstream sources.

Purpose and Scope

This report describes the development and application of a method that provides estimates of natural discharge in the Esopus Creek at two streamgages (Coldbrook and Mount Marion) for water years (WYs) 1932 through 2012 (a water year begins on October 1 of the preceding calendar year and ends on September 30). Flow at these streamgages is affected by the water management activities of the New York City Department of Environmental Protection. The purpose of this report is to provide broad multiyear comparisons of the natural daily-discharge estimates with the gaged daily-discharge record across a range of flow conditions at these sites to describe the extent to which the Shandaken Tunnel and Ashokan Reservoir affect streamflow in the Esopus Creek Basin. The report evaluates the validity of the estimates of natural daily discharge by (1) comparing estimated natural discharge at the Coldbrook streamgage with gaged discharge for days when water management effects were negligible and (2) comparing natural runoff at these two streamgages with natural runoff from six streamgages in the region that are not affected by diversion or impoundment.

"Natural" in this instance indicates Esopus Creek flow that is affected neither by discharge from the Shandaken Tunnel nor by impoundment in the Ashokan Reservoir and subsequent diversion of flow to New York City through the Catskill Aqueduct. The term "gaged discharge" at these two streamgages refers to values that are influenced by discharge from the Shandaken Tunnel and by impoundment and consequent diversion downstate from the Ashokan Reservoir. Other human development, including roads, residences, and towns in the Esopus Creek Basin, likely has some effect on streamflow. Furthermore, the effect of human development on streamflow in the basin likely increased over the study period. This report assumes that the effect of human development in the Esopus Creek Basin, which is minor compared with the heavy development of urbanized watersheds, is likely affecting streamflow much less than that of New York City's water-supply management activities. Specifically, the report is predicated on the assumption that the Shandaken Tunnel and the Ashokan Reservoir and Catskill Aqueduct are the two major human influences on streamflow in the Esopus Creek Basin. There are other small impoundments in the Esopus Creek Basin, but the scale of these structures is much smaller than that of the Ashokan Reservoir. The results of this study should provide an improved understanding of the effects of flow management on low flows and floods in this basin.

Study Site

The Esopus Creek, a tributary of the Hudson River with headwaters in the Catskill Mountains, drains a watershed area of 424 square miles (mi^2) at the point of discharge to the river (fig. 1). The Esopus Creek at the Mount Marion streamgage, downstream of the Ashokan Reservoir, drains a watershed area of 419 mi^2, and the Esopus Creek at Coldbrook streamgage, upstream of the Reservoir but downstream of the Shandaken Tunnel discharge, drains a smaller watershed area of 192 mi^2 (fig. 1). A watershed area of 256 mi^2 is regulated by the Ashokan Reservoir, and when the influence of the reservoir is combined with that of three additional impoundments in the Esopus watershed, the effective drainage area of the Mount Marion streamgage is 112 mi^2, about 27 percent of the true drainage area. However, a spillway and gates release excess water from the reservoir that re-enters the Esopus Creek downstream of the dam but upstream of the Mount Marion streamgage. These releases occur primarily during high flow, but water can be released for other purposes. During WYs 1971 through 2012, the daily mean discharge in the spillway channel was 158.3 ft^3/s, but there was no flow release on 80.1 percent of the days (J. Porter, New York City Department of Environmental Protection, written commun., 2014). For the 19.9 percent of days when discharge was noted, the effective drainage area of the reservoir is uncertain.

The headwaters of the Esopus Creek watershed originate on Slide Mountain, which has the highest elevation in the Catskills. These headwaters receive mean annual precipitation of 63.6 inches (in.; Northeast Regional Climate Center, 2014), a value among the highest in New York and all of the northeastern United States. The Esopus Creek watershed drains steeply from the westernmost headwaters to the USGS streamgage at Allaben, N.Y. (01362200), a basin of 63.7 mi^2. At the Coldbrook streamgage, downstream of the Shandaken Tunnel, the watershed remains steep, with a mean slope of 31.0 percent (table 1), and is mainly forested (97.8 percent of basin), with only minor influence from urban land use (0.61 percent of basin). Downstream of the reservoir at the Mount Marion streamgage, the basin is, on average, less steep than at the Coldbrook streamgage, with less forest cover and more urban land, but mean annual precipitation remains quite high for New York at 48.1 in. (table 1).

Methods

The approach described in the project proposal was changed after an initial exploration of the data showed that

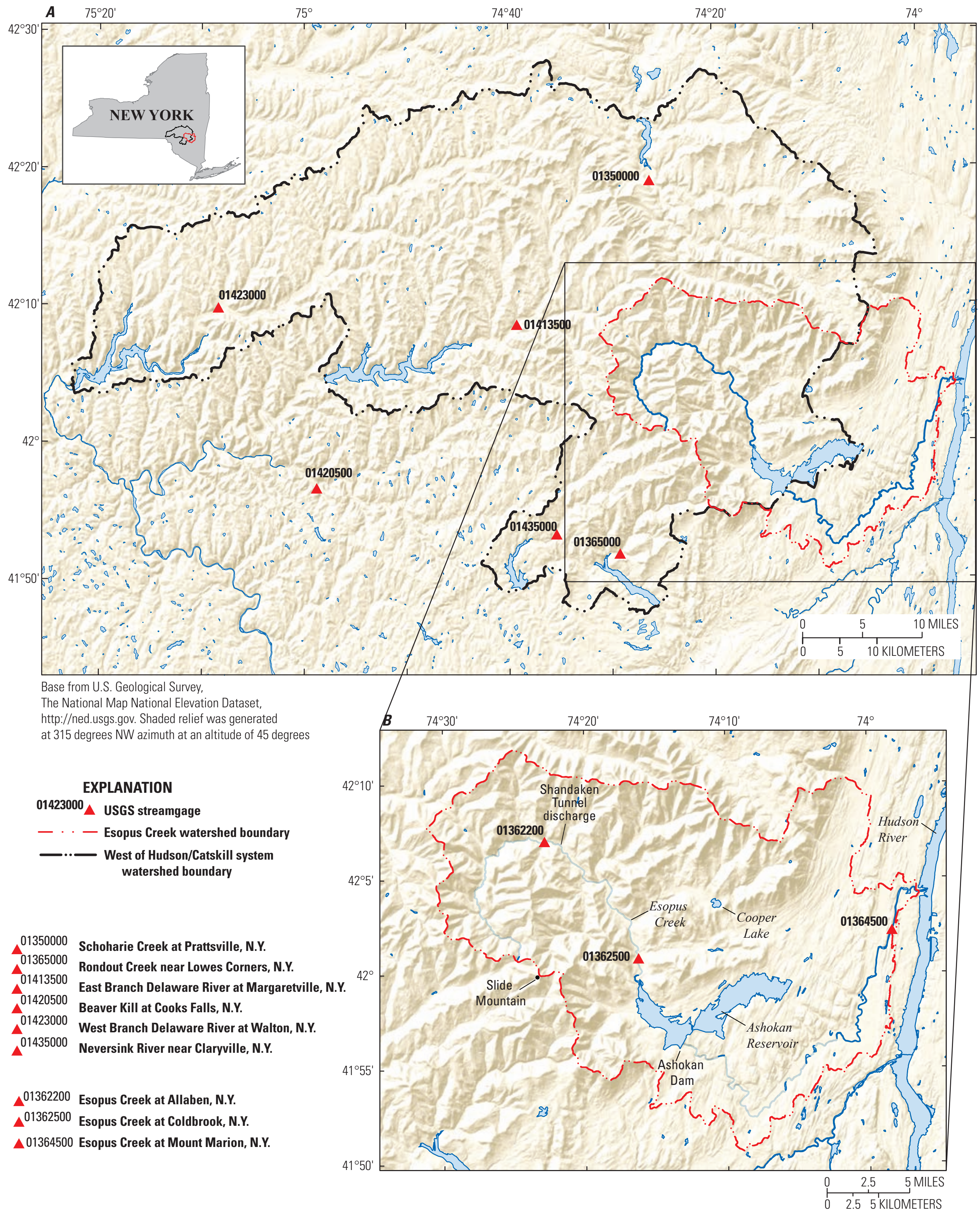

Figure 1. Esopus Creek and West of Hudson/Catskill and Delaware System watersheds, New York. *A*, watershed boundaries and six U.S. Geological Survey (USGS) streamgages located outside of the Esopus Creek and used in this study. *B*, Esopus Creek watershed with USGS streamgages at Allaben, Coldbrook, and Mount Marion; Slide Mountain, the outflow of the Shandaken Tunnel, the Ashokan Reservoir with dam, Cooper Lake, and the Hudson River are also shown. N.Y., New York.

Table 1. Basin characteristics of the Esopus Creek watershed at the Coldbrook, New York, streamgage (01362500), at the Mount Marion, N.Y., streamgage (01364500), and at the point of discharge to the Hudson River.

[Data are from U.S. Geological Survey (2014a). N.Y., New York; Mt., Mount; mean annual values are for the period 1951–1980]

Basin characteristics	Streamgage		
	Esopus Creek at Coldbrook, N.Y.	Esopus Creek at Mt. Marion, N.Y.	Esopus Creek at Hudson River
Drainage area, in square miles	192	419	424
Mean basin slope, in percent	31.0	22.3	22.2
Basin storage[1], in percent	0.26	3.42	3.45
Forested area, in percent	97.8	88.7	88.3
Urban area, in percent	0.61	2.85	3.03
Mean annual runoff, in inches	31.6	28.6	28.4
Mean annual precipitation, in inches	50.9	48.1	47.9

[1]Percentage of total area in lakes, ponds, and wetlands.

the assumptions of the proposed methodology were not met. This originally proposed approach was to subtract the Shandaken Tunnel discharge from that of the Coldbrook streamgage to estimate natural discharge at Coldbrook. This proposed approach failed to provide discharge estimates that could confidently be assumed to represent natural flow conditions. The results of this originally proposed approach are briefly described in a later section of this report. The alternative approach that was applied to obtain natural streamflow estimates is described in this section.

Study Approach

Natural discharge at the Coldbrook streamgage was estimated through a multiple linear regression approach for days when the Shandaken Tunnel had little effect on discharge in the Esopus Creek, which were assumed to be days when Shandaken Tunnel discharge did not exceed 1 percent of the discharge at the Coldbrook streamgage. A subset of Coldbrook daily-discharge data was selected for days when this condition was met: 6,874 daily-discharge values from October 1, 1931, to September 30, 2012. Natural discharge on these 6,874 days was calculated by subtracting the gaged daily discharge of the Shandaken Tunnel from the gaged daily discharge at Coldbrook. Natural discharge for the other 22,712 days during the 81-year period was estimated by applying a multiple regression approach as described in the following paragraphs.

Two multiple regression models were fit to Coldbrook discharge for the 6,874 days assumed to represent natural discharge. These regressions were then applied to estimate natural discharge on the 22,712 days on which Shandaken Tunnel discharge exceeded 1 percent of discharge at the streamgage. Daily-discharge values at nearby streamgages that are not greatly affected by either diversions or impoundment were selected as potential independent variables in the regression models. For the period from October 1, 1931, to February 3, 1937, discharge data were available for two nearby streamgages, Schoharie Creek at Prattsville, N.Y. (01350000), and Beaver Kill at Cooks Falls, N.Y. (01420500). For the period from February 4, 1937, to September 30, 2012, discharge data for two additional gages were available for potential inclusion in the second multiple regression model: East Branch Delaware River at Margaretville, N.Y. (01413500), and Rondout Creek near Lowes Corners, N.Y. (01365000). Discharge values for the day before and the day after each day for which natural discharge was estimated were also explored as potential predictive variables in the regression. A few other streamgages in the region were explored for possible inclusion in models as well, but these sites showed weak relations to the daily discharge at the Coldbrook streamgage and were not considered further.

Multiple linear regression models were developed through use of a best subsets approach that explored all possible models for predicting natural flow at the Coldbrook streamgage with the combination of variables available for each of the two time periods. The final “best” models were chosen by examining fit metrics, including the standard error of estimate and the coefficient of determination (R^2). Parsimony was achieved by adding an additional independent variable to a model only if the adjusted R^2 (Theil, 1961) increased by at least 0.02. Independent variables were included in regression models only if the significance level (p value) was less than 0.05 and the variance inflation factor (a measure of multicollinearity) was less than 10. Models with comparable fit were then explored graphically for bias. Independent variables and the dependent variable were log (base 10) transformed, new regression models were calculated, and these models were compared with models developed with untransformed variables for improvement of fit and bias. Values derived from a regression model in which the dependent variable was log transformed were bias corrected by using a smearing estimator (Duan, 1983) before analysis and presentation.

The New York Streamflow Estimation Tool (NYSET) was used to estimate natural daily discharge for the watershed area between the Mount Marion and Coldbrook streamgages. This estimation was done by subtracting the daily discharge estimated by NYSET for the Coldbrook streamgage from the daily discharge estimated by NYSET for the Mount Marion streamgage. This difference was then added to the regression-estimated daily-discharge values that were derived for the Coldbrook streamgage (as described previously) to represent natural flow at the Mount Marion streamgage. This approach was considered superior to simply using the NYSET-estimated discharge at the Mount Marion streamgage because the multiple regression approach provided a better fit than NYSET to natural flow days at the Coldbrook streamgage.

NYSET was recently developed to estimate unaltered daily discharge at ungaged sites on streams and rivers in New York for the period from October 1, 1960, to September 30, 2010 (Gazoorian, 2015). NYSET can also be used to estimate natural discharge at gaged streams and rivers where discharge is affected by human water management activities. NYSET uses data from existing streamgages in New York to predict natural flow at an ungaged location or, as in this case, at a streamgage affected by water management (impoundment and withdrawal). Briefly, a reference gage is identified for the ungaged site through a geostatistical approach termed "map correlation" (Archfield and Vogel, 2010), and the flow-duration value from the reference gage is assigned to each day for which an estimated flow is sought for the ungaged site. "Flow duration" refers to the number of days on which the daily flow is exceeded within a period of record (Foster, 1934); the period of WYs 1961 through 2010 was used in the development of NYSET. For example, a day whose flow was exceeded on 40 percent of the days during the period of record would have a flow-duration exceedance value of 40 percent; this is equivalent to a 60-percentile value. The daily discharge was then estimated for 17 points along this hypothetical flow-duration curve on the basis of regression equations derived from 90 reference gages in New York, for which various basin characteristics, such as measures of slope, basin area, elevation, and precipitation, serve as dependent variables; the full suite of variables used in these regressions is described by Gazoorian (2015). In a final step, the full daily-flow record was filled between these 17 values through log-log interpolation. This approach, termed the QPPQ method, was specifically developed to estimate natural flow conditions in a river, and has been applied in Massachusetts and other states surrounding New York. Additional details of the method are described by Archfield and Vogel (2010) and Archfield and others (2010).

In this study, the Schoharie Creek at Prattsville streamgage was used as the reference gage to determine flow-duration values for the Esopus Creek because discharge at this site was the most strongly correlated with the Coldbrook streamgage over the entire study period for days when Shandaken Tunnel discharge was minimal. An additional modification to the NYSET approach here was to extend the estimates back to October 1, 1931, and forward to September 30, 2012. This modification was consistent with the originally proposed study approach of providing an estimated natural flow record at the Mount Marion streamgage that extends from WY 1932 to WY 2012.

Sources of Discharge Data

Stream discharge data were obtained from the USGS New York Water Science Center Web site (U.S. Geological Survey, 2014b) for the entire periods of record at the Esopus Creek at Coldbrook (WYs 1932 through 2012) and the Esopus Creek at Mount Marion (WYs 1971 through 2012). Stream discharge data were obtained for the Schoharie Creek at Prattsville and the Beaver Kill at Cooks Falls streamgages for the period of WYs 1932 through 2012 and from the East Branch Delaware River at Margaretville and the Rondout Creek near Lowes Corners streamgages for the period from February 4, 1937, to September 30, 2012 (table 2). Additional data were obtained from the West Branch Delaware River at Walton (01423000), Neversink River near Claryville (01435000), and Esopus Creek at Allaben streamgages for WYs 1971 through 2012 to provide a comparison of gaged and natural annual runoff (discharge per unit basin area, reported in inches per year) at the Coldbrook and Mount Marion streamgages with the runoff of other regional streams (table 2). Finally, a dataset was assembled for the Shandaken Tunnel discharge to the Esopus Creek (diversion from Schoharie Reservoir, 01362230). Data before December 18, 1996 were obtained from records compiled by the New York City Department of Environmental Protection (J. Porter, New York City Department of Environmental Protection, written commun., 2014), and data for subsequent dates were obtained from USGS streamgage records.

Stream discharge was calculated from a stage-discharge rating curve according to methods described by Rantz and others (1982a,b). The USGS provides a general assessment of the accuracy of discharge data from a streamgage largely on the basis of the judgment of the hydrographer who processes the flow record each year. The accuracy categories are "excellent" (95 percent of daily values within 5 percent of actual discharge), "good" (95 percent of daily values within 10 percent of actual discharge), "fair" (95 percent of daily values within 15 percent of actual discharge) and "poor" (lower than "fair" quality). The flow records at the Esopus Creek streamgages at Coldbrook and Mount Marion are generally rated as "good," as are those of the Beaver Kill at Cooks Falls, East Branch Delaware River at Margaretville, West Branch Delaware River at Walton, and Neversink River near Claryville streamgages. In contrast, the streamgages at Schoharie Creek at Prattsville, Rondout Creek near Lowes Corners, and Esopus Creek at Allaben are generally rated as "fair."

Table 2. Basin characteristics of seven streamgages that were used either as predictive variables in the estimation of natural discharge in the Esopus Creek at the Coldbrook, New York, streamgage or in calculations of annual runoff for comparison with gaged and natural runoff in the Esopus Creek at Coldbrook and Mount Marion, N.Y., streamgages.

[Data from U.S. Geological Survey (2014a). Ck., Creek; N.Y., New York; E., East; R., River; W., West; USGS, U.S. Geological Survey; ID, identification number]

Basin characteristics	Streamgage						
	Schoharie Ck. at Prattsville, N.Y.	Beaver Kill at Cooks Falls, N.Y.	E. Branch Delaware R. at Margaretville, N.Y.	Rondout Ck. near Lowes Corners, N.Y.	W. Branch Delaware R. at Walton, N.Y.	Neversink R. near Claryville, N.Y.	Esopus Ck. at Allaben, N.Y.
USGS streamgage ID	01350000	01420500	01413500	01365000	01423000	01435000	01362200
Drainage area, in square miles	237	241	163	38.3	332	66.6	63.7
Mean basin slope, in percent	20.7	17.8	23.1	27.9	18.1	22.7	31.5
Basin storage[1], in percent	0.54	1.3	0.17	0.08	0.30	0.09	0.03
Forested area, in percent	91.8	94.7	90.3	99.0	75.4	99.3	98.7
Urban area, in percent	0.55	0.50	0.45	0.02	0.56	0.08	0.21
Mean annual runoff, in inches, 1951–1980	27.5	30.5	27.6	34.0	24.6	37.5	33.5
Mean annual precipitation, in inches, 1951–1980	46.8	49.1	46.3	51.7	44.0	55.4	52.4

[1]Percentage of total area in lakes, ponds, and wetlands.

Analyses of Discharge Data

The estimated records of natural daily discharge at the Esopus Creek at Coldbrook and Mount Marion streamgages were compared to the daily gage records affected by tunnel discharge and impoundment, respectively. First, the cumulative percentage of days throughout the study period on which the flow was exceeded was calculated for each record as a basis for comparing natural and gaged flow-duration or exceedance values. Second, the Indicators of Hydrologic Alteration (IHA) software was applied to calculate several high-flow and low-flow metrics (table 3) as a basis for further comparisons between the natural and gaged discharge records (Richter and others, 1996). Comparisons of estimated natural and human-influenced daily discharge were made for the Coldbrook streamgage for WYs 1932 through 2012, whereas comparisons for the Mount Marion streamgage were for WYs 1971 through 2012 to encompass the maximum number of full water years available (the Mount Marion record began March 1, 1970). Flow metrics were also calculated by using IHA for the estimated natural daily discharge at the Mount Marion streamgage for WYs from 1932 through 2012 to facilitate comparisons with the estimated natural discharge record at the Coldbrook streamgage. Finally, annual runoff was calculated for seven streamgage sites in the Catskills that were not affected by impoundment during WYs 1932 through 2012 and WYs 1971 through 2012 for comparing to the gaged and natural annual runoff at the Coldbrook and Mount Marion streamgages.

Estimated Natural Discharge Results

Results for two multiple linear regression equations developed to estimate natural discharge at the Coldbrook streamgage are described along with the ability of these regressions to predict natural flow in the Esopus Creek. The resulting natural discharge estimates for the Coldbrook streamgage are then compared with gaged discharge throughout the range of flow at this site, including several low-flow and high-flow metrics. A similar comparison is then made between natural discharge estimates and gaged discharge for the Esopus Creek at Mount Marion streamgage. Finally, the natural estimates of discharge and gaged discharge at the two Esopus Creek sites are compared with discharge at several nearby Catskill region streamgages through calculation of mean annual runoff..

Table 3. Description of flow metrics calculated by the Indicators of Hydrologic Alteration software for each discharge record analyzed in this study.

[Mean values were calculated for each period of record analyzed]

Flow metric	Description
1-day minimum flow	Annual 1-day minimum daily discharge
3-day minimum flow	Annual consecutive 3-day minimum daily discharge
7-day minimum flow	Annual consecutive 7-day minimum daily discharge
30-day minimum flow	Annual consecutive 30-day minimum daily discharge
90-day minimum flow	Annual consecutive 90-day minimum daily discharge
1-day maximum flow	Annual 1-day maximum daily discharge
3-day maximum flow	Annual consecutive 3-day maximum daily discharge
7-day maximum flow	Annual consecutive 7-day maximum daily discharge
30-day maximum flow	Annual consecutive 30-day maximum daily discharge
90-day maximum flow	Annual consecutive 90-day maximum daily discharge

Regression Models for Estimating Natural Discharge at the Coldbrook Streamgage

Two different multiple regression models were developed to predict natural discharge at the Coldbrook streamgage. From October 1, 1931, through February 3, 1937, the beginning of the period for which estimations were made, only two nearby discharge records were available as independent variables in a regression: Schoharie Creek at Prattsville and Beaver Kill at Cooks Falls. A regression model with two independent variables was selected as having the best fit and least predictive bias while meeting the conditions of acceptability as described in the methods section. Log transformation of the variables improved the fit and bias, and therefore, a model with log-transformed variables was selected.

The equation for this regression model is

$$\log \text{Coldbrook} = 0.0568 + (0.418 \times \log \text{Cooks}) + (0.553 \times \log \text{Prat}), \quad (1)$$

where

log Coldbrook is the log base 10 of the predicted natural discharge at the Coldbrook streamgage (equation was fit to Coldbrook discharge minus Shandaken Tunnel discharge),

log Cooks is the log base 10 of discharge at the Beaver Kill at Cooks Falls streamgage, and

log Prat is the log base 10 of discharge at the Schoharie Creek at Prattsville streamgage.

All discharge values are in units of cubic feet per second. This regression model was based on 6,874 days during WYs 1932 through 2012 on which discharge at the Coldbrook streamgage minus the Shandaken Tunnel discharge was less than 1 percent of the Coldbrook streamgage discharge. The adjusted R^2 value of this model is 0.931, and both independent variables are highly significant ($p<0.001$). The predicted discharge values of this regression are shown relative to the Coldbrook streamgage minus Shandaken Tunnel discharge values in figure 2*A*. Because this regression was developed with log-transformed data, the uncertainty as reflected by the 95-percent prediction intervals is not symmetrical about the regression line and varies in untransformed discharge units throughout the full range of flow at this site. However, the prediction intervals are approximately constant relative to the predicted discharge, and vary by about +79 percent and –44 percent throughout the flow range at the Coldbrook streamgage. These results highlight the limitations of using the regression model developed to predict natural discharge on any individual day. Although the multiple regression model to estimate natural flow at the Coldbrook streamgage is highly significant and can account for about 93 percent of the variation in the full set of days when the tunnel did not impact streamflow, the model cannot predict discharge with high accuracy on any particular day, and these results should be applied on a daily basis with caution.

The second multiple regression model to represent natural flow at the Coldbrook streamgage was developed for the period from February 4, 1937, through September 30, 2012, when in addition to the Schoharie Creek at Prattsville and the Beaver Kill at Cooks Falls streamgages, two additional nearby flow records were available for the Rondout Creek near Lowes Corners and the East Branch Delaware River at Margaretville (not used in final predictive regressions). A multiple regression model with three independent variables was selected as having the best fit and least predictive bias while meeting the conditions of acceptability (as described in the methods section).

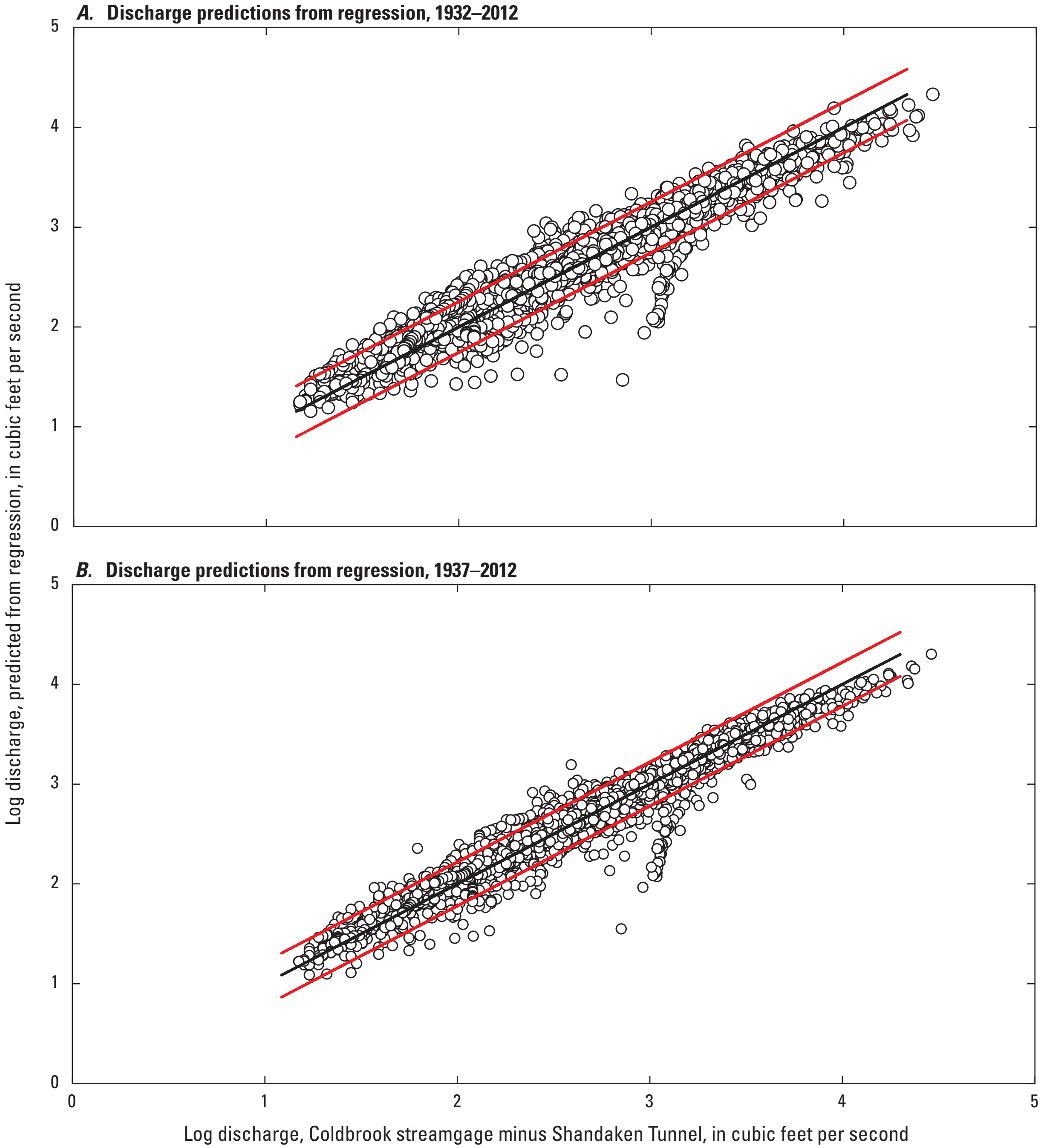

Figure 2. Daily-discharge values predicted by two multiple regression models applied to estimate natural daily discharge at the Esopus Creek at Coldbrook streamgage (01362500) from October 1, 1931, to September 30, 2012. Discharge values predicted by the regressions are shown relative to the difference of Coldbrook streamgage discharge and Shandaken Tunnel discharge for days when Tunnel discharge was less than 1 percent of Coldbrook streamgage discharge. The solid black line represents the regression relation, and the two red lines indicate the upper and lower limits for the 95-percent prediction intervals of the regression relation. *A*, Gaged and regression-derived values for the period from October 1, 1931, to September 30, 2012, shown for 6,874 days when the discharge at the Coldbrook streamgage was assumed to represent natural flow conditions. This regression was applied to estimate natural discharge at the Coldbrook streamgage for days from October 1, 1931, to February 3, 1937, when gaged discharge did not represent natural flow conditions. *B*, Gaged and regression-derived values from February 4, 1937, to September 30, 2012, shown for 6,298 days when the discharge at the Coldbrook streamgage was assumed to represent natural flow conditions. This regression was applied to estimate natural discharge at the Coldbrook streamgage for days from February 4, 1937, to September 30, 2012, when gaged discharge did not represent natural flow conditions.

Improved fit and bias were achieved by log-transforming the dependent and independent variables.

The equation for this regression model is

$$\log \text{Coldbrook} = 0.263 + (0.430 \times \log \text{Prat}) + (0.525 \times \log \text{Rondout}) + (0.0744 \times \log \text{Cooks} - 1), \quad (2)$$

where

log Coldbrook is the log base 10 of the predicted natural discharge at the Coldbrook streamgage (equation was fit to Coldbrook discharge minus Shandaken Tunnel discharge),

log Prat is the log base 10 of the discharge at the Schoharie Creek at Prattsville streamgage,

log Rondout is the log base 10 of the discharge at the Rondout Creek near Lowes Corners streamgage, and

log Cooks-1 is log base 10 of the discharge at the Beaver Kill at Cooks Falls streamgage on the day preceding the day for which predictions were made.

All discharge values are in units of cubic feet per second. This regression model was based on 6,298 days during the period on which the discharge at the Coldbrook streamgage minus the Shandaken Tunnel discharge was less than 1 percent of the Coldbrook streamgage discharge. The adjusted R^2 value of this model was 0.946, and all three independent variables were highly significant ($p<0.001$). The predicted discharge values of this regression are shown relative to the difference of the Coldbrook streamgage discharge and the Shandaken Tunnel discharge in figure 2*B*. Because this regression was developed with log-transformed data, the uncertainty in predictions is not symmetrical about the regression line and varies in untransformed discharge units throughout the full range of flow at this site. However, the prediction intervals are approximately constant relative to the predicted flow, and vary by about +66 percent and –40 percent throughout the flow range at the Coldbrook streamgage.

Comparison of Estimated Natural Discharge and Gaged Discharge at the Coldbrook Streamgage

Daily-discharge values at the Coldbrook streamgage were used directly to represent natural daily discharge in the Esopus Creek on days when the Shandaken Tunnel discharge was less than 1 percent of the discharge at the streamgage, which occurred on 6,874 days, or 23.2 percent of the days throughout the full study period. To estimate natural discharge for the remaining 76.8 percent of the daily record, the two regression models discussed in the previous section were applied to predict daily-discharge values: the first regression for the period from October 1, 1931, to February 3, 1937, and the second regression for the period from February 4, 1937, to September 30, 2012. The complete record of estimated natural daily discharge was then compared with the Coldbrook streamgage daily-discharge record through flow-duration curves and several high-flow and low-flow statistics computed by using IHA.

The estimated natural daily discharge at the Coldbrook streamgage was less than the gaged daily discharge throughout the flow range, and the mean difference peaked in the 10- to 20-percent flow-exceedance range (fig. 3; table 4). The mean difference declined gradually through the 80- to 90-percent flow-exceedance range before dropping off sharply thereafter. The mean difference also declined fairly sharply and by nearly half from the 10- to 20-percent flow-exceedance range to the 0- to 1-percent flow-exceedance range. The mean relative difference between the Coldbrook gaged discharge and estimated natural discharge shows a different pattern of change than that of the mean difference, with the mean relative difference peaking in the 80- to 90-percent flow-exceedance range and sharply declining to the 99- to 100-percent flow-exceedance range. The mean relative difference also decreased gradually and successively from the 80- to 90-percent flow-exceedance range to the 10- to 20-percent flow-exceedance range and then decreased sharply to the 0- to 1-percent flow-exceedance range. The gaged discharge exceeded the estimated natural discharge for Coldbrook streamgage by a mean of 4.3 percent for the highest 1 percent of flows. The low-flow metrics calculated by IHA indicate that the Coldbrook gaged discharge was 66.8 ft^3/s greater than the estimated natural discharge for the 1-day annual minimum flow, and this value increased successively and by more than threefold to 227.9 ft^3/s for the 90-day annual minimum flow (table 5). Gaged discharge at the Coldbrook streamgage was consistently about three times greater than natural flow estimates throughout the low-flow range shown in table 5. The relative differences between these two records for the high-flow metrics are much smaller than those calculated for the low-flow metrics, indicating that the relative influence of the Shandaken Tunnel on Esopus Creek discharge

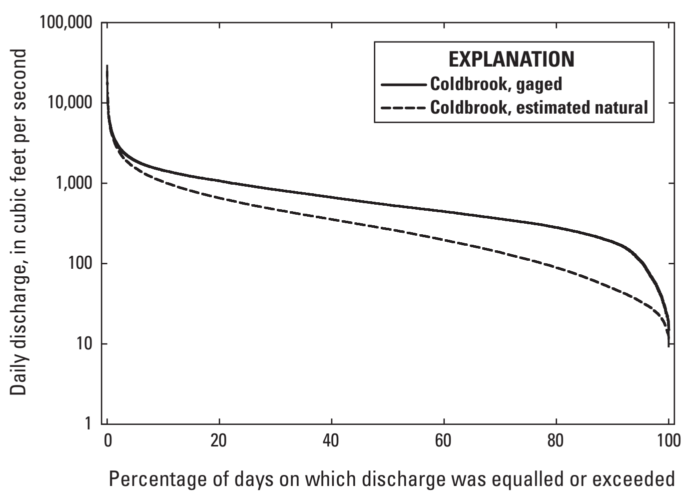

Figure 3. Flow-duration curves based on gaged daily discharge and natural daily-discharge estimates for the Coldbrook streamgage (01362500) from October 1, 1931, to September 30, 2012.

Table 4. Range of gaged daily discharge and natural daily-discharge estimates as well as mean relative difference between these values as a function of flow exceedance range for the Coldbrook, New York, streamgage (01362500) from October 1, 1931, to September 30, 2012.

[ft^3/s, cubic feet per second]

Flow-exceedance range, in percent	Gaged daily discharge across exceedance range, in ft^3/s	Natural daily-discharge estimates across exceedance range, in ft^3/s	Mean Discharge Difference (ft^3/s)	Mean relative difference, as percentage of natural discharge
99–100	32–9.3	19.4–11.6	+8.8	+53.4
90–100	185–9.3	49.1–11.6	+71.6	+193.7
80–90	280–185	88.9–49.1	+166.3	+246.9
70–80	360–280	138–88.9	+208.6	+187.6
60–70	444–360	196–138	+234.4	+142.3
50–60	538–444	269–196	+257.3	+111.9
40–50	665–538	354–269	+288.6	+93.6
30–40	830–665	468–354	+336.6	+82.7
20–30	1,070–830	653–468	+385.9	+70.2
10–20	1,440–1,070	1,040–653	+413.6	+51.6
0–10	29,030–1,440	29,015–1,040	+339.5	+22.1
0–1	29,030–3,901	29,015–3,750	+228.7	+4.3

Table 5. Gaged daily discharge and estimated natural daily discharge as well as the difference and relative differences between these values as a function of mean annual flow metrics for consecutive-day low-flow and high-flow days for the Coldbrook, New York, streamgage (01362500) from October 1, 1931, to September 30, 2012.

[ft^3/s, cubic feet per second]

Annual flow metric	Gaged daily discharge, in ft^3/s	Estimated natural daily discharge, in ft^3/s	Discharge difference, in ft^3/s	Relative difference, as percentage of natural discharge
1-day minimum flow	100.8	34.0	66.8	196.5
3-day minimum flow	107.6	35.5	72.1	203.1
7-day minimum flow	122.5	39.4	83.1	210.9
30-day minimum flow	196.8	59.4	137.4	231.3
90-day minimum flow	362.4	134.5	227.9	169.4
1-day maximum flow	8,898	8,602	296	3.4
3-day maximum flow	5,541	5,253	288	5.5
7-day maximum flow	3,518	3,235	283	8.7
30-day maximum flow	1,919	1,561	358	11.1
90-day maximum flow	1,291	954.1	336.9	35.3

is substantially less at high flow. Although the differences in discharge between these two records are greater at high flow, the relative differences in discharge are much greater at low flow.

Comparison of Estimated Natural Discharge and Historical Discharge at the Mount Marion Streamgage

The estimated natural daily discharge at the Mount Marion streamgage, developed by summing the estimated natural daily discharge at the Coldbrook streamgage and the NYSET-estimated natural daily discharge for the intervening area between Coldbrook and Mount Marion streamgages, was compared with the gaged daily discharge at the Mount Marion streamgage for the period from October 1, 1970, to September 30, 2012. The gaged discharge at the Mount Marion streamgage was less than the estimated discharge throughout the full range of flow conditions during WYs 1971 through 2012 (fig. 4). The mean difference in discharge between these two flow records increased with increasing flow and decreasing flow exceedance value (table 6). The mean difference in discharge ranged from 21.5 ft^3/s in the 99- to 100-percent flow-exceedance range and increased successively to a value of 3,221 ft^3/s in the 0- to 1-percent flow-exceedance range.

The gaged discharge at Mount Marion streamgage was about two-thirds less than that of the estimated natural discharge throughout the 40- to 100-percent flow-exceedance range, and this difference narrowed successively to 27.7 percent less in the flow-exceedance range of 0 to 1 percent. These high-flow results are consistent with previous observations that the Ashokan Reservoir and other reservoirs in the Catskills operated by the New York City Department of

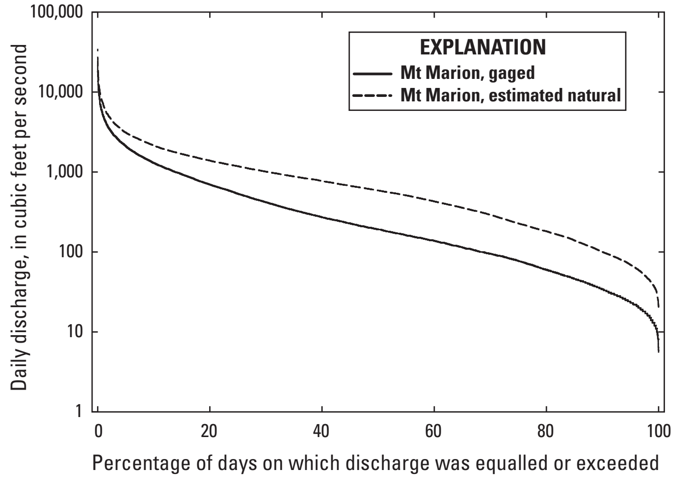

Figure 4. Flow-duration curves based on gaged daily discharge and natural daily-discharge estimates for the Mount Marion streamgage (01364500) from October 1, 1970, to September 30, 2012.

Table 6. Range of gaged daily discharge and natural daily-discharge estimates as well as mean relative difference of these values as a function of flow exceedance values for the Mount Marion, New York, streamgage (01364500) from October 1, 1970, to September 30, 2012.

[ft^3/s, cubic feet per second]

Flow exceedance range, in percent	Gaged daily discharge across exceedance range, in ft^3/s	Natural daily discharge estimates across exceedance range, in ft^3/s	Mean Discharge Difference (ft^3/sec)	Mean relative difference, as percentage of natural discharge
99–100	13–5.6	30–17	-21.5	-66.5
90–100	34–5.6	75–17	-44.6	-66.0
80–90	60–34	129–75	-93.3	-66.7
70–80	95–60	212–129	-153.4	-66.5
60–70	138–95	316–212	-243.3	-68.0
50–60	191–138	437–316	-345.2	-68.0
40–50	270–191	588–437	-445.6	-66.2
30–40	418–270	808–588	-546.6	-62.0
20–30	696–418	1,149–808	-640.7	-54.4
10–20	1,290–696	1,821–1,149	-752.4	-44.6
0–10	24,200–1,290	46,237–1,821	-1,310	-33.2
0–1	24,200–4,979	46,237–6,173	-3,221	-27.7

Table 7. Gaged daily discharge and estimated natural daily discharge as well as the difference and relative difference of these values as a function of mean annual flow metrics for consecutive-day low-flow and high-flow days for the Mount Marion streamgage (01364500) from October 1, 1970, to September 30, 2012.

[ft^3/s, cubic feet per second]

Annual flow metric	Gaged daily discharge, in ft^3/s	Estimated natural daily discharge, in ft^3/s	Discharge difference, in ft^3/s	Relative difference, as percentage of natural discharge
1-day minimum flow	22.4	67.8	45.4	-67.0
3-day minimum flow	23.3	71.0	47.7	-67.2
7-day minimum flow	25.9	80.4	54.5	-67.8
30-day minimum flow	41.8	122.2	80.4	-65.8
90-day minimum flow	114.8	277.4	162.6	-58.6
1-day maximum flow	8,307	14,540	6,233	-42.9
3-day maximum flow	6,393	8,938	2,545	-28.5
7-day maximum flow	4,193	5,624	1,431	-25.4
30-day maximum flow	1,974	2,916	942	-32.3
90-day maximum flow	1,166	1,880	714	-38.0

Environmental Protection, though not designed as flood-control reservoirs, decrease downstream flood peaks substantially (Zembrzuski and Evans, 1989; Suro and Firda, 2007; Milone and MacBroom, Inc., 2009). The analysis by Milone and MacBrook, Inc. (2009) indicated that instantaneous flood peaks are reduced by about 60 percent as a result of the emplacement of the Ashokan Reservoir. In contrast, the current analysis indicates that the 1-day annual maximum daily discharge was diminished by a lower mean value of about 43 percent during WYs 1971 through 2012. The higher diminishment value from the analysis in Milone and MacBrook, Inc.(2009) may reflect the report's basis on only 5 instantaneous peaks, whereas the analysis in this report reflects 1-day annual values based on 43 peak-flow days. Streamgage remarks from the National Water Information System (U.S. Geological Survey, 2014c) as well as the analysis of Milone and MacBroom, Inc. (2009) describe the natural discharge at the Mount Marion streamgage as representative of an effective watershed area of 112 mi^2 during nonflood conditions, whereas the analysis in this report indicates a value of about one-third of the drainage area, or 140 mi^2.

The annual low-flow metrics showed a similar pattern to those of the flow-exceedance values (table 7). The Mount Marion streamgage discharge was about two-thirds less than

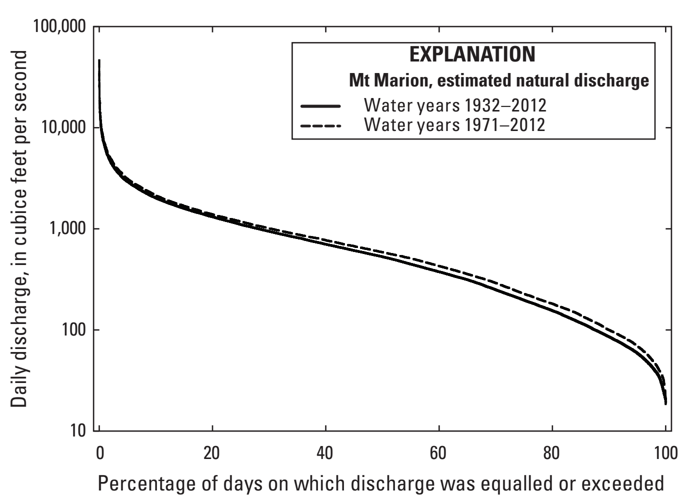

Figure 5. Flow-duration curves based on natural daily-discharge estimates for the Mount Marion streamgage (01364500) from October 1, 1931, to September 30, 2012, and from October 1, 1970, to September 30, 2012.

the estimated natural discharge for the 1-day, 3-day, 7-day, and 30-day annual minimum flows and decreased slightly to 58.6 percent less for the 90-day annual minimum flow. At high flow, the relative differences in flow were less than those at low flow; relative differences at high flow ranged from 25.4 to 42.9 percent less than the estimated natural discharge for the five metrics for annual maximum flow, and the greatest relative difference was for the annual 1-day maximum flow.

Natural discharge was also estimated for the period of WYs 1932 through 2012 for the Mount Marion streamgage. The estimated natural discharge values for this period were lower than the exceedance values for the previously computed period of WYs 1971 through 2012 (fig. 5). The differences between these estimates, however, were smaller than the differences previously described for comparisons of the effects of Shandaken Tunnel discharge on Coldbrook streamgage discharge and the effects of impoundment of the Ashokan Reservoir on the Mount Marion streamgage discharge. For example, the estimated natural discharge at the Mount Marion streamgage for WYs 1971 through 2012 was 17.0 percent greater than the estimated natural discharge for WYs 1932 through 2012 at 90-percent flow exceedance, 11.1 percent greater at 50-percent flow exceedance, and 6.3 percent greater at 10-percent flow exceedance.

Comparison of Natural Annual Runoff Estimates for the Coldbrook and Mount Marion Streamgages with Annual Runoff at Nearby Catskill Streamgages

Mean annual runoff values from several streamgages operated by the USGS in the Catskill Mountain region were compared with values computed from the gaged and natural daily discharge at the Coldbrook and Mount Marion streamgages. Only streamgages upstream of the New York City water-supply reservoirs were chosen for this analysis to minimize the effects of impoundment and therefore provide a stronger basis for comparison. The comparisons were made for two periods—from October 1, 1931, to September 30, 2012, and from October 1, 1970, to September 30, 2012—to include as many complete water years as possible within the full periods of record for the Coldbrook and Mount Marion streamgages, respectively. The data indicate a wide range of natural variation in annual runoff in streams of this region. Across both time periods examined, mean annual runoff at the regional streamgages ranged from 26.3 in at the West Branch Delaware River at Walton streamgage to 42.3 in at the Neversink River near Claryville streamgage (table 8). Mean annual runoff values at the two streamgages affected by flow alteration that resulted from New York City's water-supply activities were outside this range of natural variation. Mean annual runoff was 53.5 in at the Esopus Creek at Coldbrook streamgage during WYs 1932 through 2012 (and 53.0 in during WYs 1971 through 2012), whereas mean annual runoff at the Esopus Creek at Mount Marion streamgage was 17.2 in during WYs 1971 through 2012. In contrast, the estimated annual natural runoff during the same two periods was 34.4 in. and 37.1 in., respectively, at the Coldbrook streamgage and 29.6 and 32.0 in, respectively, at the Mount Marion streamgage. These results show that estimation of natural flow in the Esopus Creek shifted annual runoff values from being the highest (Coldbrook) and lowest (Mount Marion) in the region to being well within the range of natural variation observed for Catskill region streams. These natural runoff estimates are greater than those provided in table 1, which are based on the analysis of Randall (1996) for the period of 1951 through 1980.

The difference between mean annual runoff and the mean annual estimated natural runoff for the Coldbrook streamgage provides an estimate of the extent to which Shandaken Tunnel discharge increases natural flow in the Esopus Creek. During WYs 1932 through 2012, the difference was 19.1 in., compared with a mean annual runoff value of 20.7 in. based on the gaged discharge of the Shandaken Tunnel for the same period (table 8). During WYs 1971 through 2012, the calculated difference was 15.9 in., whereas the value based on gaged Shandaken Tunnel discharge was 18.2 in.

Effects of Discharge Through the Shandaken Tunnel on the Interaction of Esopus Creek With Alluvial Groundwater

The originally proposed study approach was to estimate natural discharge at the Coldbrook streamgage by subtracting the daily Shandaken Tunnel discharge from the daily discharge at the streamgage. This approach did not provide accurate estimates of natural daily discharge at Coldbrook. This proposed calculation would be appropriate if the Esopus Creek behaved like a pipe, transferring all of the discharge from the Shandaken Tunnel in one day to the streamgage at Coldbrook, but the data show that the creek did not consistently behave like a pipe along the approximately 10.5-mi reach between the two measurement sites (fig. 6). Additionally, a lag is likely between the time when water is discharged from the Shandaken Tunnel and when this discharge is detected at the Coldbrook streamgage, 10.5 mi downstream. This lag is expected to vary according to stream velocity and resulting traveltimes, but a value as high as half a day to 2 days is likely based on typical stream velocities measured at the Coldbrook streamgage.

Figure 6 provides examples of two periods in which the daily discharge of the Shandaken Tunnel exceeded that at the Coldbrook streamgage, resulting in negative values of natural daily discharge when calculated by the subtraction approach, an unrealistic situation. Negative discharge values resulted for 12 days during July 1966 (fig. 6*A*) and 3 days during August 1965 (fig. 6*B*). Negative daily discharge during these two periods reached values of –114.5 ft^3/s on July 18, 1966, and –85.5 ft^3/s on August 14, 1965. The magnitude of these calculated negative discharge values suggest that they did not likely result solely from uncertainty in the two discharge measures.

Table 8. Mean annual runoff based on gaged and estimated natural daily discharge at the Coldbrook, New York (01362500), and Mount Marion, N.Y. (01364500), streamgage sites along with mean annual runoff for three other gaged sites in the Catskill Mountain region from October 1, 1931, to September 30, 2012, and seven other gaged sites from October 1, 1970, to September 30, 2012. Annual runoff values are expressed in inches.

[--, no data]

Streamgage site or flow record	Mean annual runoff, in inches	
	October 1, 1931–September 30, 2012	October 1, 1970–September 30, 2012
Esopus Creek at Coldbrook gaged discharge	53.5	53.0
Esopus Creek at Coldbrook natural discharge	34.4	37.1
Esopus Creek at Mount Marion gaged discharge	--	17.2
Esopus Creek at Mount Marion natural discharge	29.6	32.0
Esopus Creek at Allaben (01362200) gaged discharge	--	34.3
Schoharie Creek at Prattsville (01350000) gaged discharge[1]	27.8	30.6
Beaver Kill at Cooks Falls (01420500) gaged discharge	32.4	34.8
Rondout Creek near Lowes Corners (01365000) gaged discharge	--	39.1
East Branch Delaware River at Margaretville (01413500) gaged discharge	--	28.3
West Branch Delaware River at Walton (01423000) gaged discharge	--	26.3
Neversink River near Claryville (01435000) gaged discharge	--	42.3
Shandaken Tunnel[2]	20.7	18.2

[1]Discharge was affected by withdrawals for snowmaking during winter.

[2]Runoff was calculated by dividing tunnel discharge by the drainage area of the Esopus Creek at Coldbrook streamgage.

Shandaken Tunnel discharge exceeded that at the Coldbrook streamgage on 1,503 days during water years (WYs) 1932 through 2012, about 5.1 percent of the total days.

On many days, this difference calculation did not yield negative values but still provided unrealistically low estimates of natural discharge for the Esopus Creek at Coldbrook. For example, between August 13, 1965, and August 15, 1965, the estimated difference was less than the discharge measured at the upstream Esopus Creek at Allaben, N.Y., streamgage (01362200), a site that drains a watershed only one-third the size of the watershed at Coldbrook (fig. 6*B*). An additional consideration is that the drainage area of the Esopus Creek where the Shadaken Tunnel enters is 67.2 mi^2, much smaller than the drainage area of 192 mi^2 at the Coldbrook streamgage, and many tributaries enter the Creek along the 10.5-mi reach between the two sites. If the contributions of all inflows to Esopus Creek are considered, then many additional days are likely for which subtraction of these two flow records would yield unrealistically low values.

The calculated difference between the Shandaken Tunnel discharge and that of the Coldbrook streamgage also seemed to be unrealistically high for many days. For example, during August 14–18, 1965, this calculated difference increased during a period when flows on the Esopus Creek (as shown by the Allaben streamgage) were generally receding (fig. 6*B*).

The evidence of unrealistically low and high daily discharge values when calculated by the originally proposed subtraction approach suggest that the Esopus Creek channel does not behave like a pipe and that, instead, streamflow likely reflects dynamic interaction between stream water and the streambanks and flood plain, which in the Esopus valley generally consist of permeable sand and gravel deposits (Rich, 1935). Dynamic interaction of streamflow with adjacent alluvial groundwater has been well known in hydrology for decades (Cooper and Rorabaugh, 1963; Pinder and others, 1969). This interaction is heightened during floods and is further amplified when stream channels receive artificial floods such as those derived by release from an irrigation canal or discharged from a tunnel, aqueduct, or pipe (Hancock, 2002) as occurs in the Esopus Creek. Gaged annual runoff of the Shandaken Tunnel exceeded the difference between the annual runoff at the Coldbrook streamgage and the estimated natural mean annual runoff at Coldbrook, which is consistent with small net annualized losses caused by induced infiltration along the reach. But these differences were small on an annual basis, averaging 8.4 percent of the difference between Coldbrook streamgage flow and natural estimates during WYs 1932 through 2012 and 14.5 percent of the difference during WYs 1971 through 2012. Factors such as increased evaporative losses from artificially elevated levels of shallow

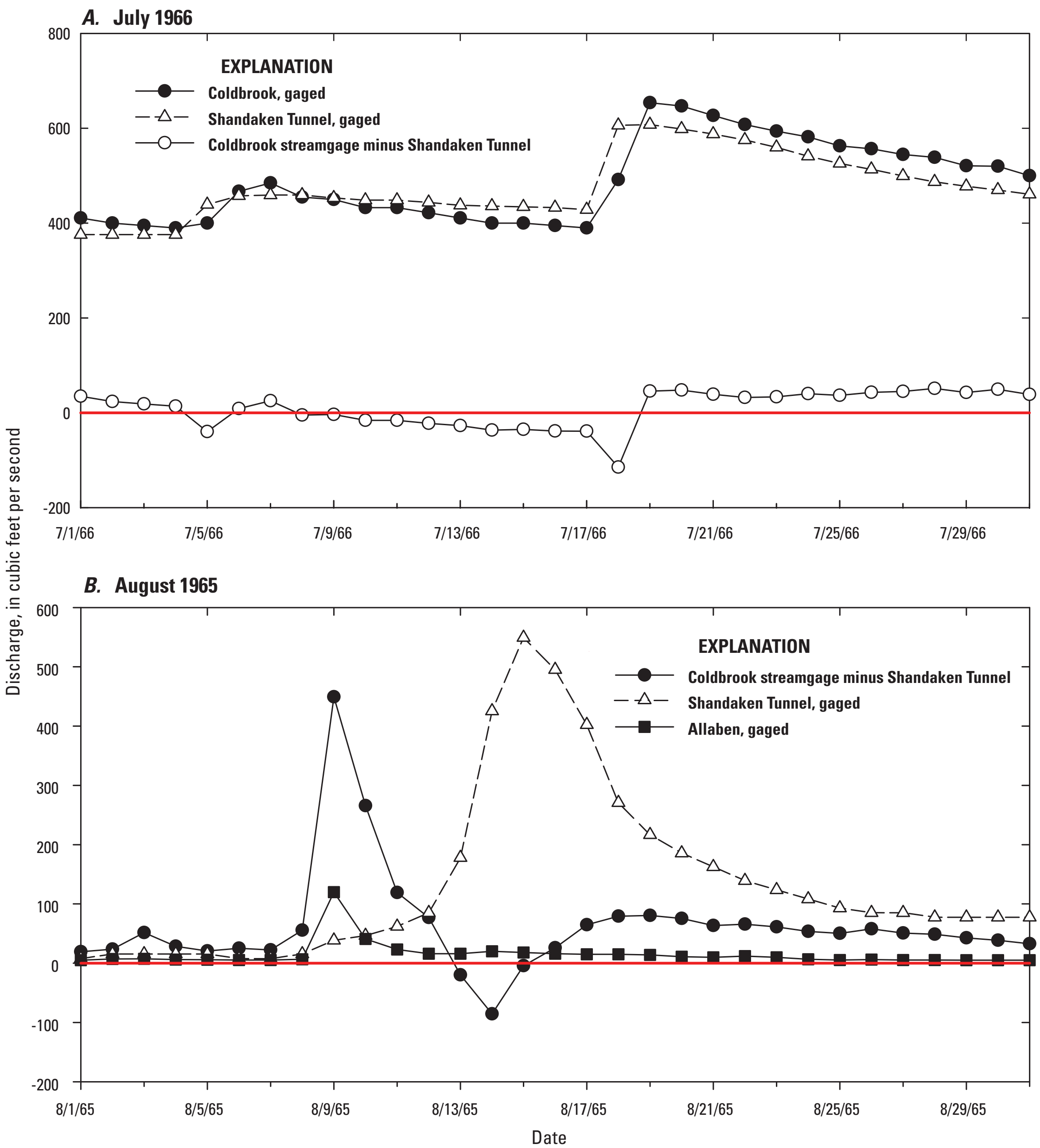

Figure 6. Discharge measures from streamgages on the Esopus Creek and the Shandaken Tunnel, New York. *A*. Coldbrook streamgage (01362500), Shandaken Tunnel, and Coldbrook streamgage minus Shandaken Tunnel discharge during July 1966, and *B*. Coldbrook streamgage minus Shandaken Tunnel, Shandaken Tunnel, and Allaben streamgage (01362200) discharge during August 1965. Red horizontal line on each plot indicates discharge of zero.

groundwater may have played a role in the apparent long-term loss of tunnel discharge.

These imbalances in long-term runoff, when considered along with the day-by-day analysis presented in this section, might be interpreted to indicate that induced infiltration resulting from Shandaken Tunnel discharge causes long-term losses of stream water to groundwater. This interpretation, however, may be unwarranted because measured discharge values have uncertainty of about 10 percent, and the uncertainty of natural flow estimates is even greater. Consideration of uncertainty indicates that the combined runoff values cannot be viewed conclusively as exceeding those of natural runoff. For some days, comparisons of the Shandaken Tunnel and Coldbrook discharge records also show exfiltration of excess flow from adjacent alluvial groundwater into the Esopus Creek (the opposite effect of induced infiltration), which is consistent with the idea that induced infiltration results in only temporary losses of streamflow. Regardless of what causes Shandaken Tunnel discharge to exceed that measured at the Coldbrook streamgage on many days throughout the record, the existence of this phenomenon resulted in a change from the originally proposed study approach (subtracting the tunnel flow from Coldbrook discharge to yield a natural discharge record) to the use of a regression-based statistical approach with nearby streams as predictive variables.

Summary

This report summarizes the results of a study by the U.S. Geological Survey (USGS) in cooperation with the New York City Department of Environmental Protection to estimate natural discharge in the Esopus Creek at two USGS streamgages on the Esopus Creek at Coldbrook (10362500) and Mount Marion (01364500), New York. The Coldbrook streamgage is affected by out-of-basin discharge from the Shandaken Tunnel, and the Mount Marion streamgage is affected by impoundment in the Ashokan Reservoir and subsequent release through the Catskill Aqueduct. Natural daily discharge values for water years (WYs) 1932 to 2012 were estimated at the Coldbrook streamgage by multiple linear regression using nearby daily discharge values from streamgages that are not greatly affected by human activities. These natural discharge estimates for the Coldbrook streamgage were then added to those estimated by the New York Streamflow Estimation Tool for the basin area from Coldbrook downstream to the Mount Marion to estimate natural daily discharge at the Mount Marion streamgage for WYs 1932 through 2012. These estimated natural daily discharge values were compared with those of the measured daily discharge at the two streamgages for consecutive-day low- and high-flow metrics and for the full range of flow exceedance values. Annual runoff values derived from these natural estimates and gaged discharge values were compared with each other and with those derived from nearby streamgages with little impact from human activities.

Gaged discharge in the Esopus Creek at two USGS streamgage sites produced mean annual runoff values that fell outside the current range observed in unimpounded streams in the Catskill region of New York. However, natural discharge estimates produced runoff values well within this range that are consistent with natural runoff patterns in this region. Natural discharge estimates at the Coldbrook streamgage (01362500) were lower than gaged discharge values, which is consistent with the expected effects of inflow from the Shandaken Tunnel to the Esopus Creek. Gaged daily-discharge values varied from two to more than three times greater than natural discharge estimates in the low- to moderate-flow range (50- to 99-percent flow exceedance), but the relative difference between gaged and natural discharge declined sharply at the lowest 1 percent of daily-discharge values.

One plausible explanation for this lower relative difference is that tunnel inflow is most likely to induce infiltration into the adjacent alluvial aquifer at the lowest flow conditions. The presence of streamflow losses that were likely due to infiltration induced by Shandaken Tunnel discharge was identified in an analysis according to which daily tunnel discharge exceeded daily discharge at the Coldbrook streamgage on about 5 percent of the days during WYs 1932 through 2012. The infiltration losses are probably not of long duration, and exfiltration back to the stream is likely following a rapid increase in tunnel discharge. Long-term runoff patterns suggest the possibility of slight permanent losses of tunnel discharge, which could also be caused in part by increased evaporation from shallow groundwater. However, the sum of tunnel discharge and Coldbrook discharge exceeded the estimated natural discharge at the Coldbrook streamgage by only 8.4 percent during WYs 1932 through 2012 and by 14.5 percent during WYs 1971 through 2012 (values that are close to the 10-percent uncertainty of gaged discharge values at the Coldbrook streamgage). Additionally, with consideration of the uncertainty of these natural flow estimates, which is substantially greater than 10 percent of Coldbrook discharge, permanent losses over long periods of time caused by induced infiltration cannot be confirmed on the basis of this analysis.

Flow-exceedance values and annual consecutive-day high-flow metrics indicate that the relative difference between gaged daily discharge and estimated natural daily discharge at the Coldbrook streamgage narrows at the highest flows. For example, 1-day, 3-day, and 7-day maximum annual gaged discharge differed by less than 10 percent from natural discharge, within the 10-percent uncertainty range of gaged daily discharge values at this site. In contrast to previous reports of greatly increased flooding induced by Shandaken Tunnel discharges, these results indicate that the tunnel has only a minor effect on streamflow in the Esopus Creek during floods.

Impoundment of the Esopus Creek in the Ashokan Reservoir sharply diminishes discharge at the downstream Mount Marion streamgage (01364500) relative to natural flow estimates for this site. Estimated natural discharge is about three times greater than gaged discharge throughout the moderate- to low-flow range (50- to 90-percent flow exceedance). These natural discharge values are lower than would be expected considering that the true watershed area (419 square miles [mi^2]) is about 3.7 times greater than the effective watershed area (112 mi^2) when water is not being diverted from the reservoir. This diversion of flow into the Esopus Creek, which is reflected in the gaged discharge at the Mount Marion streamgage, may explain in part why the gaged discharge is greater than would be expected from the effective watershed area. The results described in this report indicate an effective watershed area of about 140 mi^2 at low to moderate flow conditions based on the Mount Marion streamgage record.

These relative differences between the Mount Marion gaged discharge and estimated natural discharge decrease at high flow, but gaged daily discharge is still 25 to 43 percent less than estimated natural daily discharge for all calculated annual high-flow metrics, and this mean relative difference is 27.7 percent for the 1 percent of highest flows from October 1, 1970, to September 30, 2012. These high-flow results are consistent with previous observations that the Ashokan Reservoir and other Catskill reservoirs operated by the New York City Department of Environmental Protection, though not designed as flood-control reservoirs, decrease downstream flood peaks. The analysis in this report indicates that the highest daily discharge values are diminished by a mean of 43 percent during WYs 1971 through 2012, whereas a previous analysis indicated a 60 percent diminishment of flood peaks. The previous analysis was based on 5 instantaneous flood peaks, whereas the current analysis is based on 43 daily peaks, which may account for this difference.

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