Fluvial Geomorphology of the Upper Esopus Creek Watershed and Implications for Stream Management

Dan Davis[1], Peter L.K. Knuepfer[2], Nicolas Miller[3] and Mark Vian[1]

[1]Stream Management Program, New York City Department of Environmental Protection,
71 Smith Avenue, Kingston, NY 12401
[2]Department of Geological Sciences and Environmental Studies,
Binghamton University, Binghamton, NY 13902-6000
[3]Binghamton University and Field Geology Services, P.O. Box 985, Farmington, ME 04938

INTRODUCTION

The New York City water supply system depends on the maintenance of natural high water quality in the watersheds that drain into the reservoirs that store water for the system. Accordingly, concentrations of suspended sediment in both streams and reservoirs are major concerns, and the identification and remediation of sites that are concentrated sources of high suspended load/turbidity are essential to water quality management.

The concern about water quality by New York City's Department of Environmental Protection (DEP) is further motivated by a Filtration Avoidance Determination (FAD), which was renewed by the U.S. Environmental Protection Agency in 2007 and currently runs through 2017. This determination allows New York City to avoid the high capital cost that would be associated with building and maintaining a filtration system to treat the New York City water supply originating west of the Hudson River (~90% of the total supply). The FAD requires DEP to maintain high water quality through, among other practices, the development of stream management protocols and funding additional stream restoration projects (US EPA, 2007).

The DEP established a Stream Management Program to oversee the assessment of stream corridor condition and the development of management strategies for the watersheds that comprise the West-of-Hudson water supply system (Figure 1), including the Ashokan Reservoir/Upper Esopus Creek watershed (Figure 2). The DEP has worked with municipal, county, state and federal partners to develop Stream Management Plans (SMP) for many of the principal streams supplying the Ashokan, Schoharie, Cannonsville, and Pepacton Reservoirs. The work in the Upper Esopus Creek watershed that will be summarized in this field trip has been part of this overall effort (see www.catskillstreams.org).

The purpose of this field trip, then, is to explore the Upper Esopus Creek watershed, highlighting historic changes to the creek channel (Miller, 2009) and strategies that have been implemented or are being considered to alleviate or manage suspended sediment yield. We will examine sites where lateral migration or change in base elevation of the channel is degrading water quality or threatening property damage, where bank erosion has created a source of turbidity, and where stream restoration/remediation strategies have been applied and will be applied in the future in efforts to remediate "hot-spots" of erosion and sources of high suspended sediment loading.

BACKGROUND

The watershed of Upper Esopus Creek occupies an area of approximately 500 km^2 (Figure 2) from headwaters on the south side of Panther Mountain to the upper end of Ashokan Reservoir downstream of Boiceville. The watershed streams drain the most rugged part of the Catskills, including the north slope of 4142 ft (1255 m) high Slide Mountain, and accordingly the main basin and its tributary basins have high relief. The base level controlled by Ashokan Reservoir is at an elevation of 633 ft (193 m). Nine main tributaries enter the Upper Esopus, including Broadstreet Hollow (Stops 5a and 5b), Stony Clove (Stops 6 and 7), and Beaver Kill (Optional Stops Bk1 and Bk2), which will be part of the field trip.

Figure 1. DEM of Catskill watersheds of the New York City water supply system. From Czekanski, 2005.

The watershed is subject to high precipitation levels, in large part due to the orographic effect of the surrounding high peaks. Annual precipitation increases from 36-42 inches (915-1065 mm) in the northwest to a high of 45-60 inches (1145-1525 mm) annually in the vicinity of the high peaks, based on regional maps from Thaler (1996) and records from the Slide Mountain, Phoenicia, and Shokan weather stations. Some 20% of the precipitation falls as snow, at least at the higher elevations, with an average of 100 inches (~2500 mm) of snow recorded at Slide Mountain from 1971 to 2000 (NYCDEP et al., 2007). However, often the precipitation falls as short-lived, high-intensity rainfall events that can produce significant flash flooding. For example, a widespread heavy storm June 26-28, 2006, dropped substantial rainfall (up to 14 inches—355 mm) across much of the western Catskills and produced extensive flooding in the upper Delaware and Susquehanna watersheds. Although much less rain fell over most of the Upper Esopus watershed, a persistent cell centered over the Beaver Kill on June 26, 2006, dropped an estimated 8-10 inches (200-255 mm) of rain, triggering extensive flooding in this tributary. And a flash flood was triggered in a tributary of the East Branch Delaware River on June 17, 2007, by a severe thunderstorm that dropped as much as 11 inches (280 mm) of rain mostly within a 3-hour period (Schaffner et al., 2008).

Historical land-use changes also have been significant in the Upper Esopus watershed. The watershed today is largely forested, but widespread logging and agricultural development in the middle to late 19th century likely had a strong impact on sediment yield in the basin. Tanneries and furniture factories (including one at Chichester, Stop 7) were developed in the watershed, and there were a number of sawmills that employed selective logging (Kudish, 2000). Clear-cut logging to supply charcoal kilns that supported the tanning and manufacturing industries (Evers, 1972) probably had an even greater impact. By the late 1800s, much of the watershed was deforested; high sediment yields certainly followed. The extent of legacy sediments that might be associated with these disturbances is largely unknown. The 20th century was marked by forest recovery, and slopes today are densely forested. Agriculture and housing occupies many of the larger stream terraces within the trunk valley and its tributaries. Streams likely were adjusting to changing sediment loads through at least part of the last century.

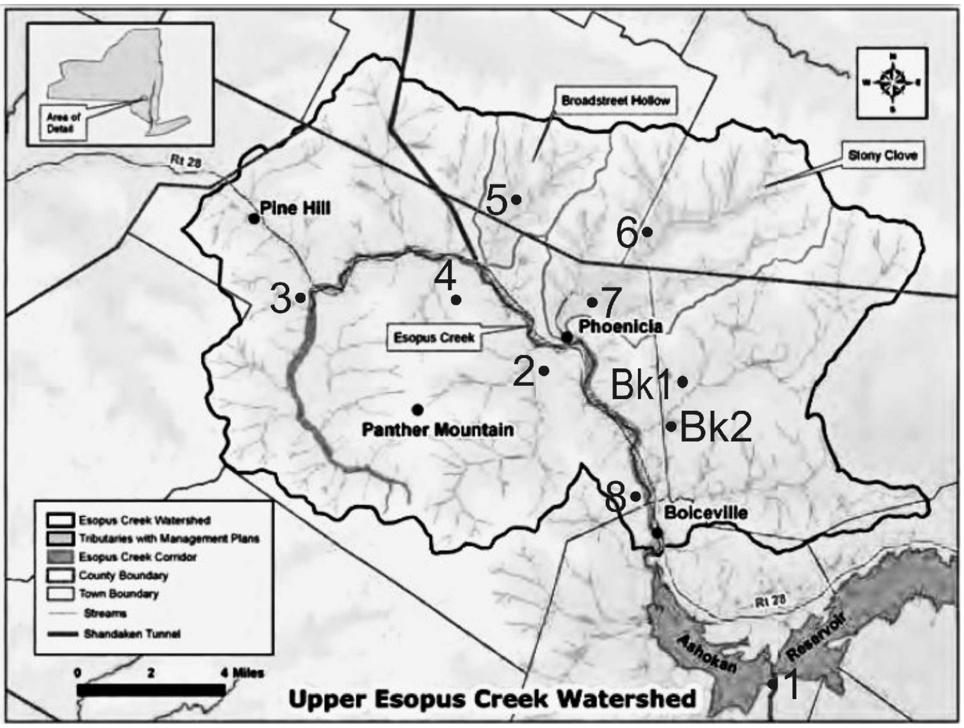


Figure 2. Map of Upper Esopus Creek watershed showing approximate locations of field trip stops. Modified from Cornell Cooperative Extension Ulster County et al., 2007.

Water quality and sedimentation in Catskill streams is largely controlled by the underlying geology (Schneiderman, 2000). Most of the Upper Esopus watershed is underlain by Devonian sandstones and shales of the Oneonta and Walton formations (Fisher et al., 1970). However, the valley bottoms and many of the slopes are underlain by weakly to moderately consolidated glacial sediments that date from the Last Glacial Maximum. Ice from the LGM covered the Catskills, scouring bedrock and deepening many of the valleys. The ice retreat phase likely was characterized by lobes of the ice sheet from the Hudson Valley that remained in main stream valleys like the Esopus, even after most of the Catskills had been deglaciated (Cadwell, 1986; Dineen, 1986). Some of these lobes likely impounded lakes in the trunk and tributary valleys as ice blocked drainage of meltwater and surface runoff (Figure 3a; Rich, 1935). These pro-glacial lakes deposited laminated silt and clay units that locally exceed 30 m in thickness (NYCDEP et al., 2007). Local readvances of glacial lobes led to interbedding of till and other diamicts with glaciolacustrine sediments, resulting in very complex relationships like those exposed at stop Bk1. These interbedded tills and glaciolacustrine sediments can strongly affect subsurface water flow, leading to slope instabilities (particularly

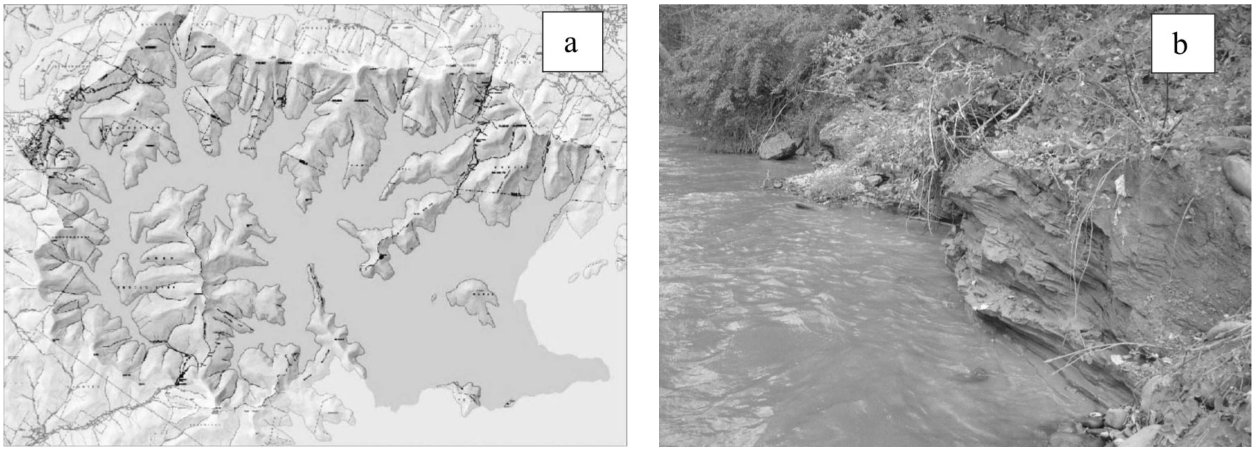


Figure 3. Glaciolacustrine conditions in Esopus Creek. a. Map of hypothetical Lake Peekamoose, from NYCDEP et al. (2007) based on Rich (1935). b. Exposure of laminated glaciolacustrine silt and clay in Esopus Creek.

where slopes are undermined by stream undercutting). Many of these glaciolacustrine deposits are overlain by post-glacial fluvial sediments, which can act as conduits for groundwater flow that can then pond on the finer deposits, as has apparently occurred at Stop 3. Bank erosion into the glaciolacustrine deposits produces the most significant sources of turbidity into Esopus Creek and its tributaries (Figure 3b).

HISTORIC CHANNEL CHANGES

Miller (2009) has investigated the extent of historic channel migration and changes in the main-stem Upper Esopus Creek using repeat aerial photographs and historic maps. He georeferenced aerial photographs and early topographic maps published in 1903 in order to quantify changes in channel position with time (Table 1). The 1903 maps provide some generalized indicators of changes in the center-line of the Esopus Creek channel, but because of a large RMS error, these were not used for quantitative comparisons with the later aerial photographs. However, the old maps are still useful in identifying locations along the valley where large changes have occurred in the channel configuration (Figure 4). These and other changes along the main-stem Esopus Creek are referenced to study reaches that were identified in Erwin et al. (2005) (Figure 5).

Channel changes have been imposed historically by construction of the railroad along the valley, the initial construction of Hwy. 28, and the more recent realignment of the state highway. The channel has been migrating along many reaches—in some cases due to meander migration (e.g. Reaches 16 and 2, Stops 3 and 8), in others due Channel changes have been imposed historically by construction of the railroad along the valley, the initial construction of Hwy. 28, and the more recent realignment of the state highway. The channel has been migrating along many reaches—in some cases due to meander migration (e.g. Reaches 16 and 2, Stops 3 and 8), in others due to abandonment and re-occupation of secondary channels and/or avulsions of the primary channel (e.g. Reach 7, Stop 2). Miller and Knuepfer (2009) reported that channel changes such as bank erosion, bar deposition, vegetation encroachment on bar surfaces and the establishment and abandonment of secondary channels are correlated with the timing, frequency and duration of peak and bankfull discharge events. Interestingly, however, the impact of individual large flows isn't necessarily as dramatic as the impact of repeated moderate to large flow events. The largest flow of record at the

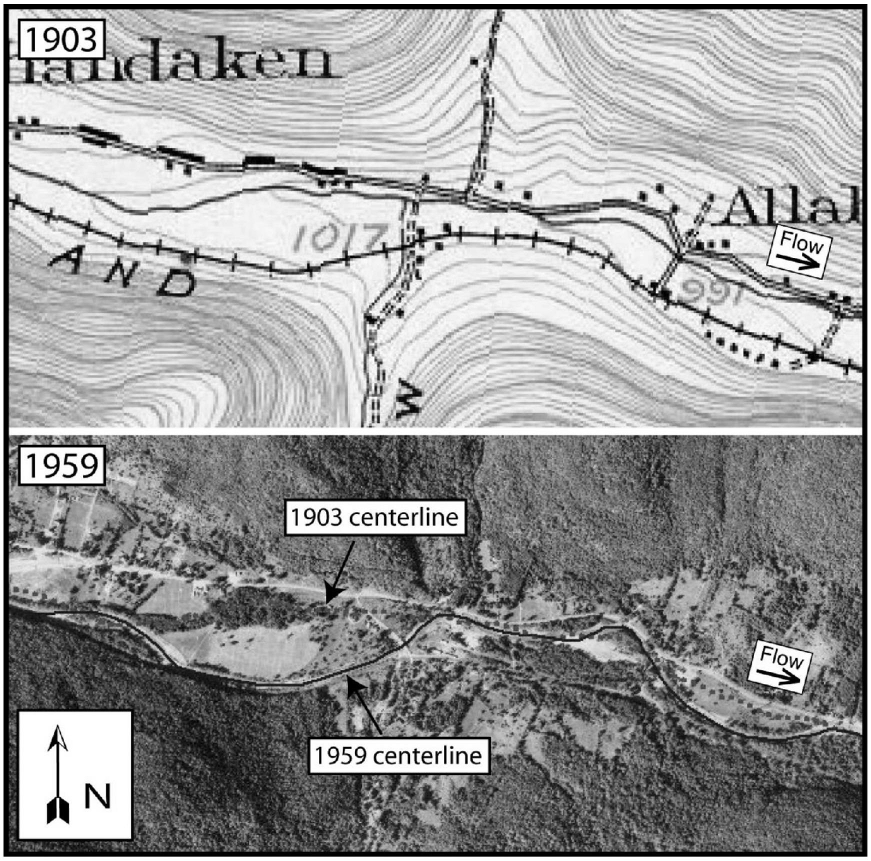


Figure 4. Comparison of 1903 map and 1959 aerial photograph of Esopus Creek near Allaben, NY, from Miller (2009). This is the vicinity of Stop 4 on the field trip. Note the abandonment of the 1903 channel where it is marked on the lower image. Reoccupation of this channel during the April 2005 flood led to washout of Fox Hollow Road and the destruction of several homes. The 1959 meanders right of the 1959 centerline label were cut off during realignment of Hwy. 28.

Format	**Series**	**Date acquired**	**Scale**	**Number of images rectified**	**Maximum RMS error*(m)**
Topographic map	1903	Aug. 1903	1:62500	2	26.8
Aerial photo	1959	9/5/1959	1:15840	9	2.3
Aerial photo	1967	4/30/1967	1:20000	7	1.3
Aerial photo	1968	6/5/1968	1:24000	2	1.0
Aerial photo	1980	9/11/1980	1:40000	2	0.5
Aerial photo	1980	10/23/1980	1:40000	5	2.3
DOQQ	1994-99	4/30/1997	NA	mosaic	NA
DOQ	2001	4/29/2001	NA	mosaic	NA
* Max RMS error refers to the highest RMS error among rectified images utilized in this study.					

Table 1. Source imagery used in this study (from Miller, 2009).

Coldbrook gage just upstream of Ashokan Reservoir occurred on March 21, 1980, after a period of relatively low flows (Figure 6). The 1980 aerial photographs, taken later that year, show relatively little channel adjustment. However, by the time the 2001 imagery was taken, considerably greater changes had occurred at many locations along the channel, following several large flow events in the 1980s and 1990s (Figure 7). Miller(2009) argues that it is the *repetition* of large flow events over short recurrence periods that has the most significant impact on channel changes. Given that climate changes in upcoming decades are predicted to increase the frequency and magnitude of high-intensity storms in the Catskills (Frumhoff et al., 2007), this historic pattern implies that channel migration and bank erosion may be continuing and even increasing problems in the future.

CHALLENGES FOR STREAM MANAGEMENT

Geologic Controls on Erosion

Channel migration, realignment, avulsion, and cutoff have combined with the underlying surficial geology to produce areas of enhanced bank erosion and landslide development at numerous locations along Esopus Creek and its tributaries (NYCDEP et al., 2007). The Watershed and Stream Characterization section of the Upper Esopus Creek Management Plan (NYCDEP et al., 2007) describes the controls on bank erosion exerted by different types of unconsolidated sediments:

- Once exposed, glaciolacustrine sediment typically erodes readily during storm events. However, where the silt and clay unit is overlain by coarser fluvial sediment, exposure is typically short-lived, and the bank tends to get armored by the collapse and draping of the coarser sediment (Figure 8a). Some glaciolacustrine deposits are more resistant to erosion where clays are stiffer or where they have not been disturbed by older hillslope failures.
- The till tends to erode either as (a) mass slumping from saturated conditions or by (b) translational fracture-bound failures forming high steep banks (Figure 8b). In general, till exposures yield coarser bedload (such as at optional stop Bk2).
- The coarse-grained, non-cohesive fluvial sediment can erode easily if not protected by dense roots or revetment (Figure 8c).

Thus, mapping bank materials in detail is an important tool in identifying existing and potential sources of suspended sediment/turbidity. This work is ongoing in the main-stem Esopus Creek and in tributary watersheds

Stream Restoration

Water quality management can best be achieved by remediating sites where bank erosion and/or channel migration and avulsion has created a "hot spot" of suspended sediment input. While eroding banks are often "solved" by hard engineering structures (often out of short-term necessity where infrastructure is at risk), the DEP Stream Management Program team has focused on using natural channel design approaches of Rosgen (1996) as modified for the flashy Catskills streams. The underlying principle is to use some approximation of the "natural" fluvial system—including stream hydraulic geometry, planform, and riparian vegetation—to create channel geometries that are more appropriate for the stream type than hard engineering approaches tend to produce. The advantages of using natural channel design approaches include flood hazard mitigation (particularly by reconnecting the stream with its floodplain), improvement of instream and riparian habitat conditions, improvement in water quality and fisheries, and property protection (Baldigo et al., 2008). Such an approach to channel restoration ideally will yield self-sustaining

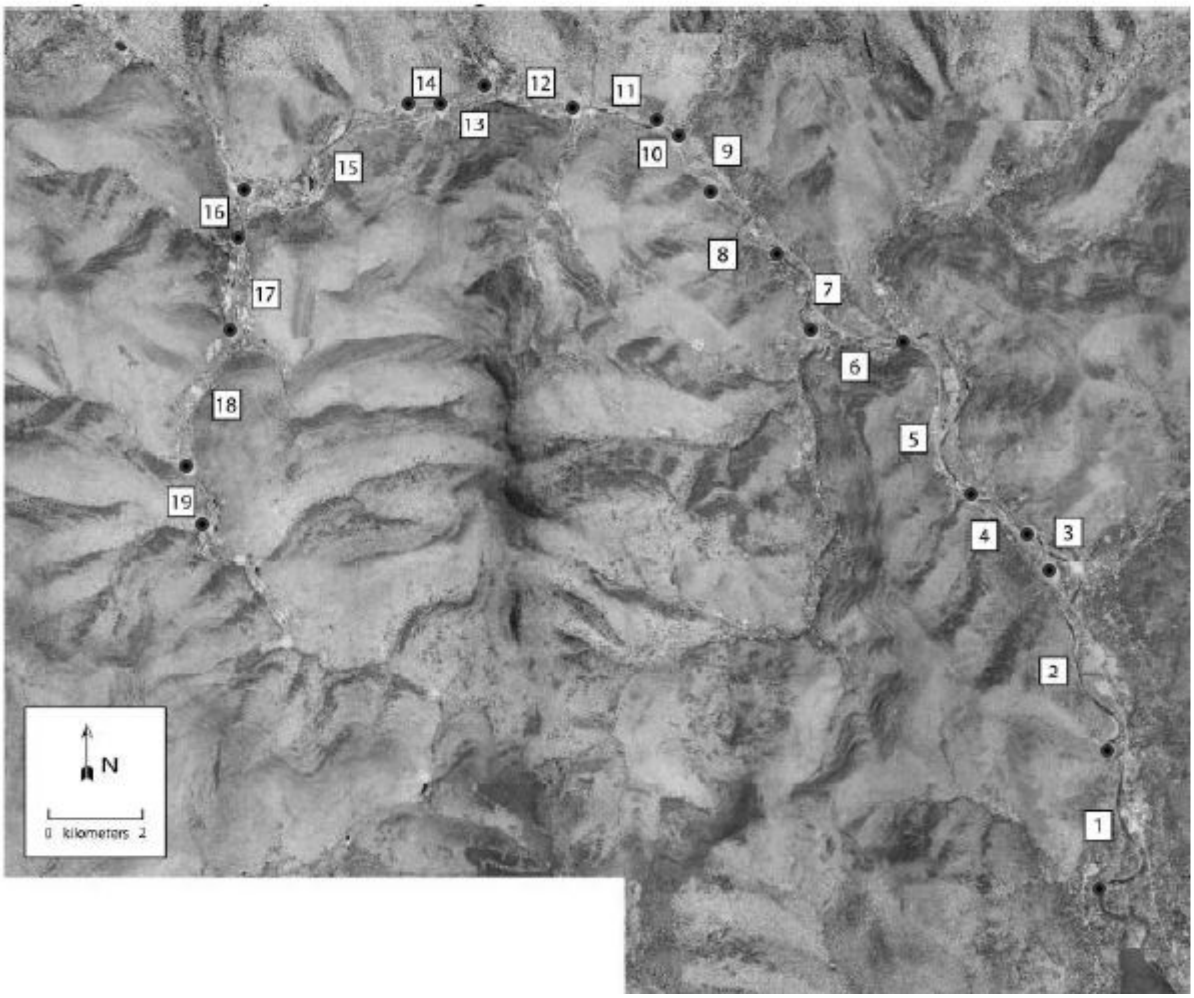


Figure 5. Reach breaks along Esopus Creek as defined in Erwin et al. (2005). Breaks based on changes in valley width, channel slope and channel pattern, and location of tributary confluences.

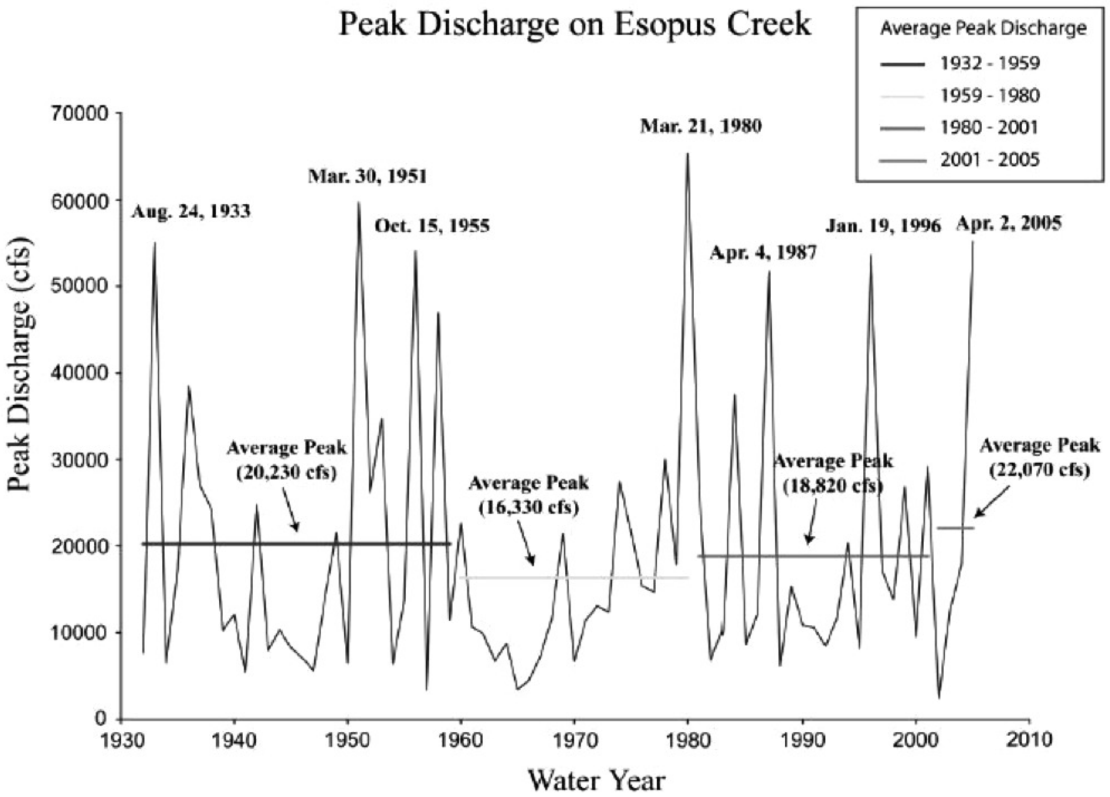


Figure 6. Historic peak discharge on Esopus Creek at the Coldbrook gage. Average peak discharge calculated for periods between aerial photographs. Especially low discharges characterize the 1959-1980 period (despite the flood of record in 1980). From Miller (2009).

stream reaches because of the use of the form (geomorphology) and function (hydraulics and sediment transport) of minimally impacted stream reaches.

The DEP Stream Management Program and partners have undertaken a number of demonstration projects in the Catskills with three occurring in the Upper Esopus watershed (Stops 2, 5, and 6). Two of these projects used the "Natural Channel Design" methodology taught by hydrologist Dave Rosgen (Rosgen, 1996). This methodology uses analog, or reference, morphology to determine channel and floodplain grades, width-to-depth ratios, planform and meso-feature spacing and sizing appropriate to the valley settings, based on Rosgen's stream-classification system (Rosgen, 1996). One of the challenges in this approach is identifying bankfull stage and discharge—the benchmark discharge from which design parameters are drawn in the Rosgen method—particularly in the absence of gage records and detailed studies. Dunne and Leopold (1978) argued that the relationship between bankfull geometry and drainage basin area is reasonably consistent within individual hydrophysiographic provinces. Miller and Davis (2003) developed regional curves for the Catskill Mountains in order to provide a more appropriate basis for applying Rosgen's classification system. The restoration projects themselves have used a variety of techniques, including the placement of instream structures to provide grade control, reduce shear stress at the channel margins and allow vegetation to mature sufficiently to perform these functions; reestablishment of meander patterns consistent with the "stable" reference reaches; and re-planting of riparian buffers using native riparian tree, shrub, and herb species (e.g., Greene County Soil and Water Conservation District, 2008).

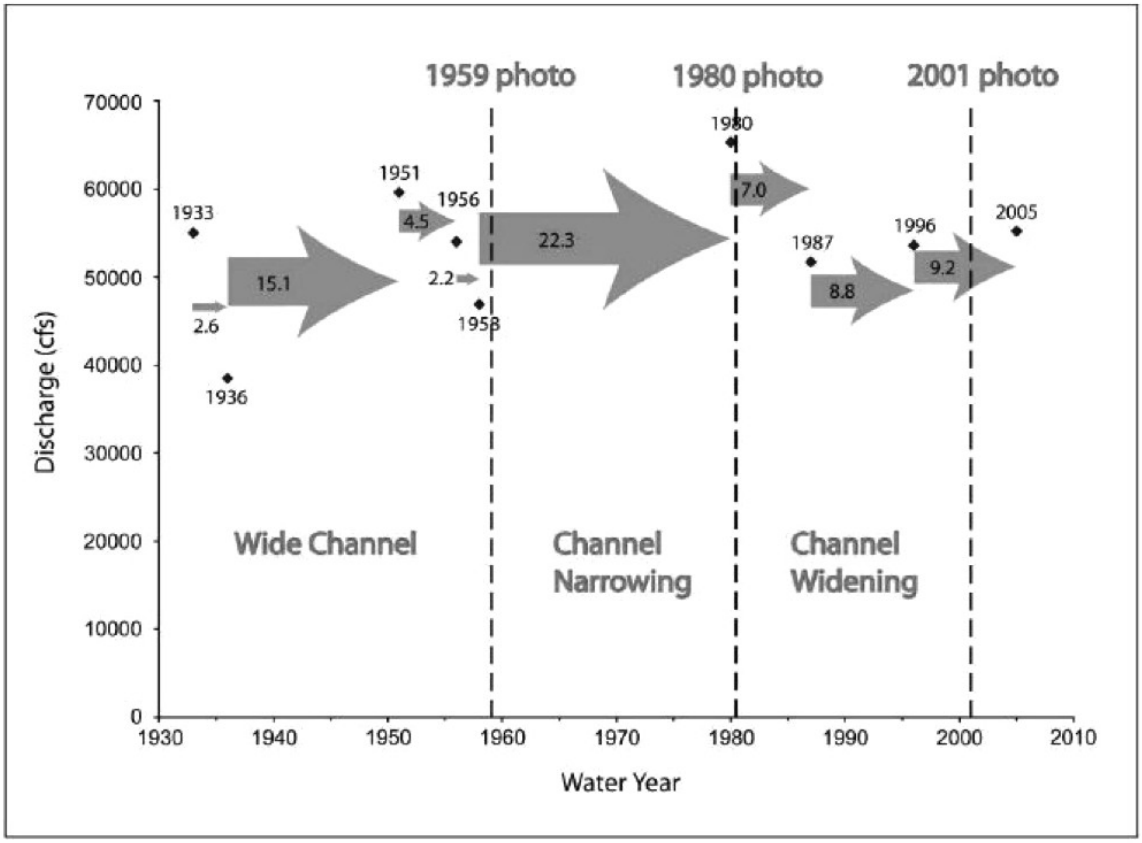


Figure 7. Intervals between large discharge events at Coldbrook gage and interpreted stream response. Note that bank erosion appears to occur mostly during intervals of frequent large flows. From Miller (2009).

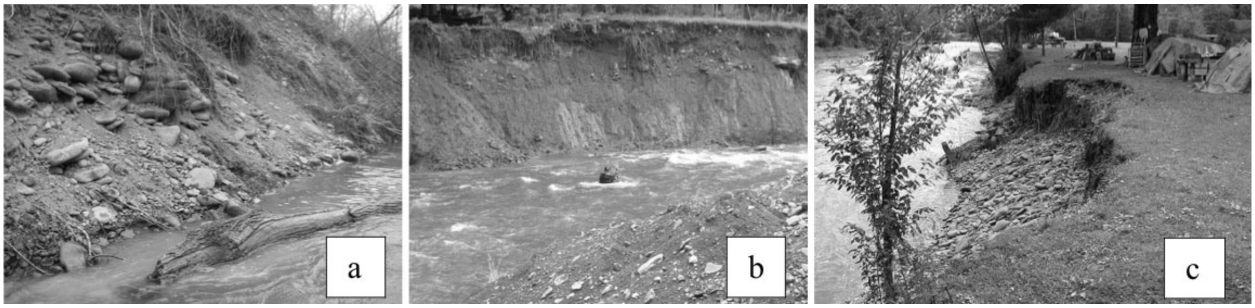


Figure 8. Bank erosion in different materials. a. Exposure of glaciolacustrine clay and silt has been armored by raveling of overlying coarse fluvial gravels. Such a process can decrease sediment loading compared to an un-armored exposure of glaciolacustrine sediments. b. Exposure of till (lighter color) overlain by post-glacial fluvial sediments. Note the steep exposure. c. Failure of a bank in unconsolidated fluvial deposits. All photos from NYCDEP et al., 2007.

SCOPE OF THE FIELD TRIP

The accompanying road log and site description provide a number of details about the Upper Esopus watershed, historic channel changes and the restoration demonstration projects. In addition, we will visit sites that have not been remediated, but are critical remediation targets, in order to better consider the application of natural channel design to the complex channel, bed, and bank geometries and geology that are found in the Esopus system.

ROAD LOG

Cumulative Mileage	**Miles from Previous Site**	**Description**
0.0	0.0	Leave Wooster Hall Parking Lot, SUNY New Paltz campus
0.1	0.1	Left turn onto South Mannheim Blvd (Hwy. 32)
0.4	0.3	Right turn onto Main St (Hwy. 299)
1.3	0.9	Right turn onto NY State Thruway onramp (Interstate 87)
1.9	0.6	Merge onto Thruway north towards Albany
7.5	5.6	Cross Wallkill River, incised into Ordovician shales and siltstones
10.0	2.5	Cross Rondout Creek, also incised into Ordovician shales. Lefever Falls on the left.
16.8	6.8	Cross Esopus Creek
17.0	0.2	Exit 19, NY State Thruway, to Kingston and Hwy. 28
17.5	0.5	Traffic circle at jct. Hwy. 28; exit to Hwy 28 W. Note that there is a Park and Ride just past the 3rd exit off the traffic circle (to Hwy. 587 and 28 E) that serves as an alternative starting and ending point for the trip.
20.2	2.7	Kings Town Stone Quarry on right into Middle Devonian Mt. Marion Formation.
21.8	1.6	Catskill Mountain Coffee on right.
27.3	5.5	Kenozia Lake on right. Drained in 2008 for repairs, the lake has refilled quickly in 2009 due to the heavy spring meltoff and rains.
29.8	2.5	Reservoir Road, Shokan; turn left (south) toward Ashokan Reservoir.
31.2	0.4	Weir that divides West and East basins of Ashokan Reservoir. Drive across to Stop 1.
31.6	0.4	Turn right into parking area (if you're an official vehicle); otherwise, turn left, find location to pull over, and walk back to Reservoir Road junction. Note that Monument Road here is on the Ashokan Dam.

STOP 1. ASHOKAN RESERVOIR AND ESOPUS CREEK WATERSHED. (15 MINUTES) (UTM location 18 T 565712E 4644450N). Ashokan Reservoir was the first of the New York City water-supply reservoirs to be constructed in the Catskills. The dam across Esopus Creek was completed in 1913 and the reservoir was impounded by 1914 (Schneiderman, 2000; New York City Department of Environmental Protection, 2009). Water is carried to New York City through the Catskill Aqueduct, completed in 1915. Because of concerns about the influx of suspended sediment from Esopus Creek, the reservoir is managed in two basins. The West Basin receives input from Esopus Creek (and the Shandaken Tunnel from Schoharie Reservoir), and is designed to act as a settling basin. It is separated from the East Basin, from which water is withdrawn into the Catskill Aqueduct, by the weir across which we have just driven (Figure 9). This overview provides a dramatic view into the mountainous upper Esopus Creek watershed. Also, an automated suspended sediment sampling site is located just east of the weir, visible from this overview site.

33.4	1.8	Retrace route back to Hwy. 28 and turn left (west).
37.6	4.2	Descend into Esopus Creek valley bottom. Jct. Hwy. 28A (on left) in Boiceville.
40.1	2.5	Junction Hwy. 212 (into Beaver Kill valley, location of optional field trip stops).
40.3	0.2	Cross Esopus Creek
41.5	1.2	Catskill Mountain Railroad on right
43.6	2.1	Turnoff to Phoenicia on right

43.8	0.2	Bridge across Esopus Creek; Stony Clove enters from left just downstream (right) of bridge. Stony Clove is a significant source of suspended sediment load/turbidity during high flow events and will be the location of Stops 6 and 7.
44.0	0.2	Junction Hwy. 214 (to Phoenicia and Stony Clove)
44.5	0.5	Junction Woodland Valley Road; turn left.
44.8	0.3	Bridge across Esopus Creek. Cross bridge and turn into unpaved parking area on left.

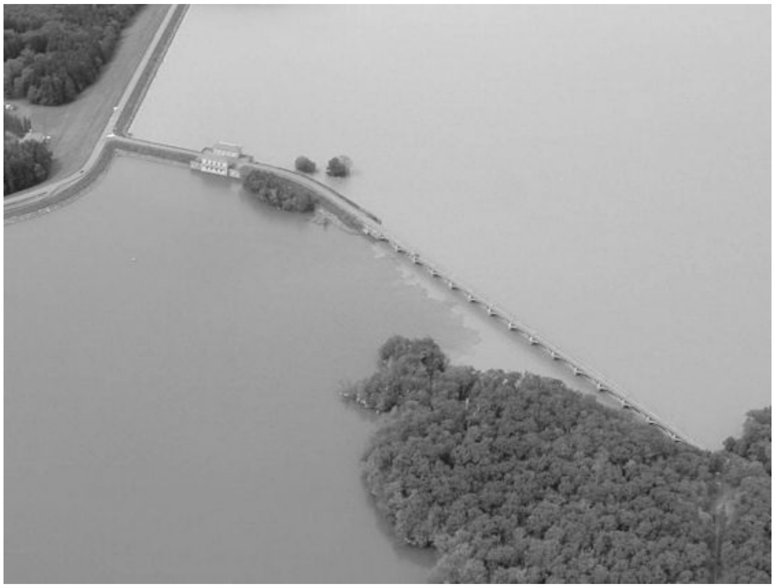


Figure 9. Weir across Ashokan Reservoir; view looking west after the June 2006 flood. Light colored water at top of photo (upstream side of weir) is actually red due to high suspended sediment load; note "leakage" across weir into East Basin of Ashokan Reservoir. Photo from NYCDEP et al., 2007.

STOP 2. ESOPUS CREEK AT WOODLAND VALLEY RESTORATION DEMONSTRATION SITE. (30 MINUTES) (Location UTM 18 T 555458E 4659007N). This stop in Esopus Creek Reach 7 will provide an introduction to the challenges in stream management of the Esopus Creek watershed and an illustration of the application of channel stabilization/stream restoration techniques. There is an informational kiosk at the site documenting the project history. The site is at the confluence of Woodland Creek with Esopus Creek–a setting that is inherently dynamic given the variability in magnitude of water and sediment discharge from the two mountain streams (Figure 10). Anecdotal and aerial photo evidence suggests that the channel and bar formation have undergone dramatic shifts in response to large flood events. The setting's inherent "instability" is compounded by a double-span bridge located just downstream of the confluence that produces a clear constriction in channel dimensions. Following the January 1996 flood, a headcut into underlying glacial lake clay propagated through a secondary channel along the left bank and eventually captured most of the Esopus Creek flow (Figure 10). The altered alignment of the channel, the stratified composition of the 32-foot (9.8-meter) high terrace (from bottom to top: glacial lake clay, glacial till, pre-historic stream deposits; Figure 11) and subsequent floods resulted in a rapidly retreating eroding bank (approximately 3 feet or 0.9 m per year). Risks associated with continuing erosion

Figure 10. Aerial photo of the Woodland Creek/Esopus Creek confluence. The project reach extends from the head of the bifurcated reach down to the Woodland bridge (2001, DOQQ)

Figure 11. Esopus Creek at Woodward Valley restoration site before (left) and after (right) restoration project. Post-project photo taken July 13, 2004, approximately 9 months after construction, but before major flood in April 2005. From Barnet, 2004.

included increasing potential for exhuming several residential septic systems, causing additional property damage, producing a continuing source of turbidity and creating a hazard to recreational users of the stream (Figures 10 and 11).

In 2000, DEP hired FIScH Engineering (principal engineer Dr. Craig Fischenich) to complete an assessment and conceptual design for remediating this reach (Fischenich, 2001). The hydraulic and stability analyses, sediment transport calculations, and geomorphic assessment resulted in recommendations for an approach that incorporated several technical techniques including a channel relocation based upon natural channel design principles, bioengineering and traditional bank revetment, and habitat and recreational enhancement features. DEP selected this project to be the demonstration stream restoration project for Esopus Creek required by the US EPA as part of the FAD schedule of compliance (US EPA, 2007). The project was constructed in 2003 in two stages: the channel work, bank revetment, and flood plain reconstruction were completed by Oct. 1, 2003 and the vegetation (trees and willow fascines) and bioengineering (VRSS) were completed in early Dec., 2003. Figure 12 is an aerial view of the site taken approximately one year after construction (Aug., 2004).

Figure 12. Esopus Creek Restoration Demonstration Project - one year after completion (August, 2004).

45.1	0.3	Retrace route back to Hwy. 28 and turn left (west).
46.7	1.6	Office of Ashokan Watershed Stream Management Program on left (which will be lunch stop)
47.6	0.9	Bridge across Broadstreet Hollow (location of Stops 5a and 5b)
47.9	0.3	Shandaken Tunnel (location of Stop 4b) emerges on right side of highway

48.9	1.0	Fox Hollow Road on left (location of Stop 4a)
49.7	0.8	Esopus Creek bridge
52.6	2.9	Big Indian; junction County Route 47 to Oliverea and Frost Valley, up the uppermost Esopus Creek.
52.8	0.2	Start of bridge across Birch Creek
53.1	0.3	Junction Lasher Road. Turn left.
53.5	0.4	Pull off at barn and walk down to Esopus Creek.

STOP 3. ESOPUS CREEK BANK FAILURE ON REACH 16. (40 MINUTES) (Location UTM 18 T 545312E 4661394N). Note: This is Private Property. Get permission from owner across road before crossing property to creek. Esopus Creek has been actively changing its channel configuration through an anabranching reach from near Hatchery Hollow about 3 km upstream from this site. This has included a number of avulsions and meander-bend migrations (Miller, 2009). At this site, a very tight meander bend has been expanding westward at least since 1959 (Figure 13). This expansion has resulted in undermining and rapid headward growth of propagating failures in an elevated terrace that forms the left descending stream bank. Fluvial gravels overlie interbedded glaciolacustrine clays and silts and glacial till. Stormwater runoff and groundwater flow off the adjacent mountainside has limited infiltration potential due to the impermeable glacial deposits and emerges as springs on the creek bank. Water does infiltrate into rotational slip surfaces in the underlying lacustrine unit resulting in very active collapse of the bank (Figures 14 and 15). This reach is often the upstream source of suspended sediment into Esopus Creek following high water events. This reach is part of DEP's long-term geomorphic monitoring program with 6 monumented cross sections, repeated longitudinal profile surveys, sediment sampling, and GPS-based mapping of channel feature alignment.

53.9	0.4	Return to Hwy. 28 and turn right, back down the Esopus Valley
57.5	3.6	Junction Hwy. 42 on left at Shandaken. The highway climbs up Bushnellsville Creek through Deep Notch and into the Schoharie Creek watershed.
58.1	0.6	Junction Fox Hollow Road. Turn right.

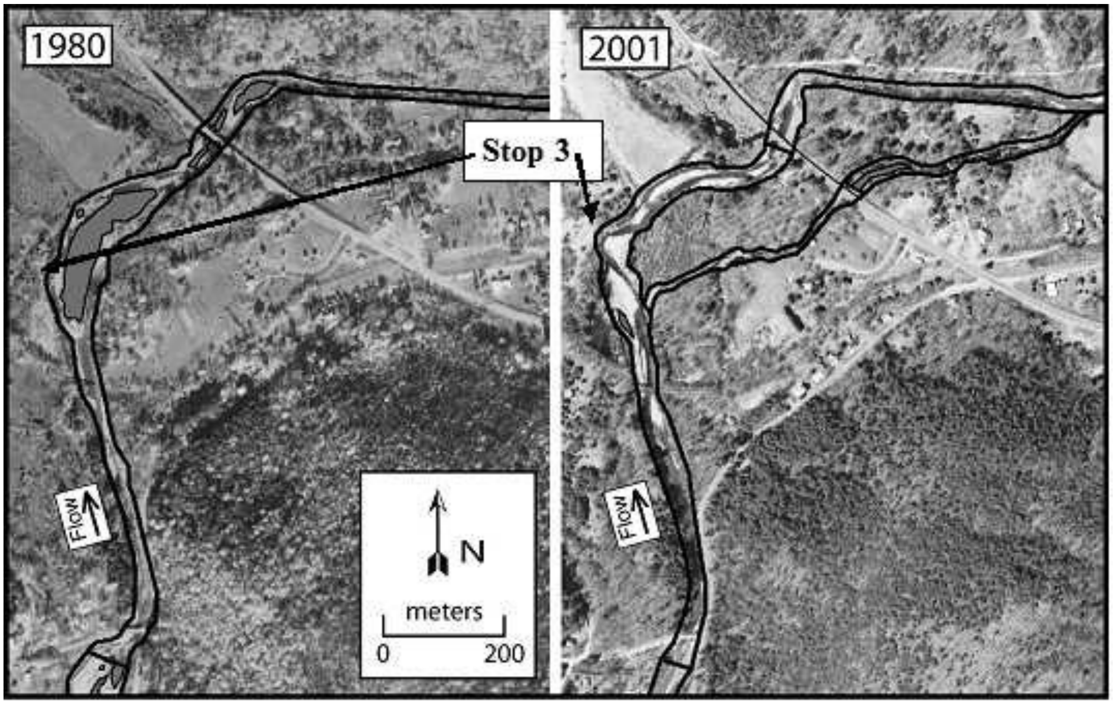


Figure 13. Changes in channel complexity and meander migration, vicinity of Stop 3. From Miller, 2009.

58.3	0.2	Cross Esopus Creek and pull off.

STOP 4A. ESOPUS CREEK GAGE AT ALLABEN (REACH 11/12). (20 MINUTES) (Location UTM 18 T 551243E 4662925N). A USGS gaging station, maintained in cooperation with the DEP, has been operating at this site since 1988; from 1963 to 1988 a gage was located about 0.8 km upstream. Bankfull discharge is ~3000 cfs (85 cumecs) has been exceeded numerous times during the period of record, and the site has recorded peak discharges of at least 15,000 cfs (425 cumecs) 4 times. The estimated 100-year flood at this site is around 26000 cfs (~740 cumecs) (NYCDEP et al., 2007), whereas the largest flood of record—April 2, 2005—was 21,700 cfs (~615 cumecs). This site also has been used as a location to measure the hydraulic geometry of the bankfull channel. Miller and Davis (2003) used this as one of their calibration sites in developing regional bankfull discharge and hydraulic geometry curves for the Catskills region.

Figure 14. Aerial view of meander bend along Esopus Creek undergoing failure at Stop 3. Photo taken April 10, 2005. From NYC DEP et al., 2007.

Realignment of Hwy. 28 in the 1960s was accompanied by cutoff of a natural meander downstream of the bridge (Figure 16; Miller, 2009). Miller (2009) describes the changes in this way: In 1959 the stream bifurcated around a large island (I11-1) upon entering the meander bend. But with road construction and cutoff of this meander, a new island (I11-3) formed just upstream of the old meander bend, as seen on the 1980 aerial photograph (Figure 16). The stream impinged on the road 200 meters farther upstream (20.2 km). By 2001, this island was attached to the left bank and no longer part of the channel. A new island (I11-5) has formed 140 meters farther downstream due to a channel avulsion across the floodplain leaving the old thalweg between the newly formed island I11-5 and the road.

58.4	0.1	Return to Hwy. 28 and turn right
59.4	1.0	Pull off on left side of highway at Shandaken Tunnel portal.

STOP 4B. SHANDAKEN TUNNEL PORTAL. (10 MINUTES) (Location UTM 18 T 552615E 4662710N). The Shandaken Tunnel brings water from Schoharie Reservoir to Esopus Creek to contribute to the New York City water supply system. This 18-mile (29-km) long underground tunnel, built by hand between 1917 and 1924, was the longest handmade aqueduct in the world when it was completed. Both minimum and max-

Figure 15. View upstream toward actively retreating streambank with rotational failure scarps exposed in adjacent terrace (photo courtesy DEP, 2006).

imum discharge from the tunnel as well as turbidity limits are regulated by the New York State Department of Environmental Conservation in order to balance recreational (and ecological) uses of Esopus Creek downstream of the tunnel with water-supply needs of New York City.

60.6	1.2	Pull into Ashokan Watershed Stream Management Program office parking lot. **LUNCH STOP** (40 MINUTES).
61.5	0.9	Turn left (west) on Hwy. 28 to retrace steps to Broadstreet Hollow Road; turn right.
63.8	2.3	Pull off to side of road to observe reference reach used in the Broadstreet Hollow restoration project.

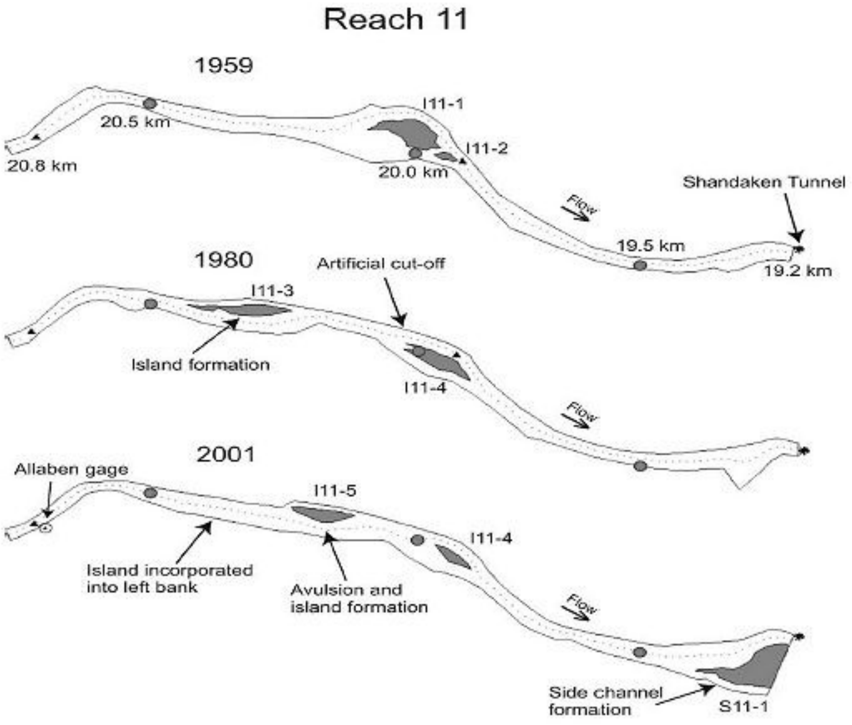
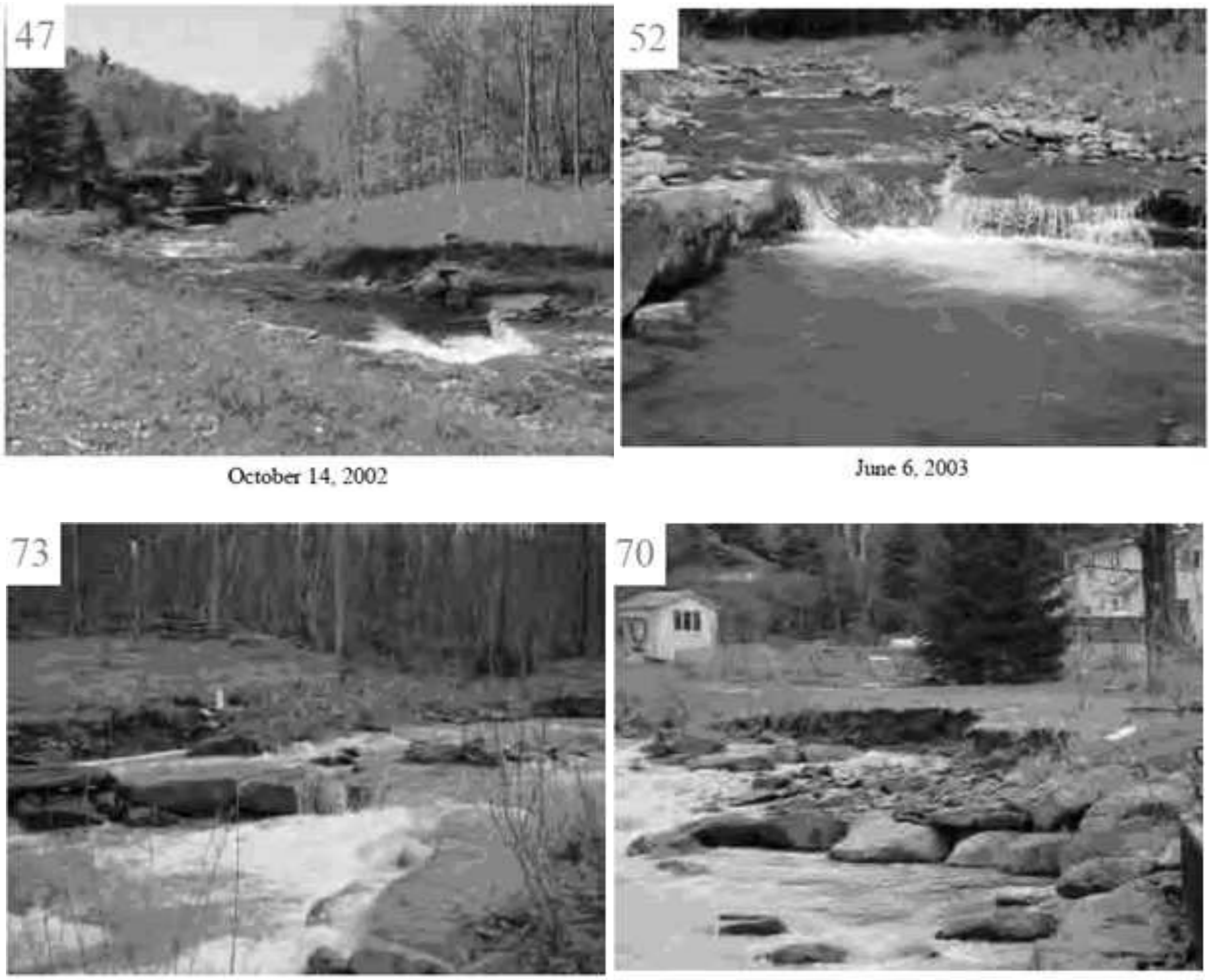


Figure 16. Overlays of georeferenced aerial photographs downstream of Allaben gage showing channel changes in response to artificial meander cutoff during construction of Hwy. 28. From Miller, 2009.

STOP 5. BROADSTREET HOLLOW RESTORATION PROJECT. Severe flooding in 1996 resulted in destabilization of a section of the right bank of the Broadstreet Hollow stream, with bank widening that threatened some houses on the left bank. An emergency response team relocated the channel and used extensive rock riprap to harden the banks and stream bed, but in doing so further destabilized the channel (Greene County Soil and Water Conservation District, 2008). Rapid incision of the channel into underlying glacial lake sediment was exacerbated by a high flow in 1999, resulting in destabilization of the left bank and development of a migrating artesian mud boil within the channel. This produced high turbidity levels, with Broadstreet Hollow becoming a significant source of turbidity for Esopus Creek. By 2000, the Broadstreet Hollow Restoration Project was initiated cooperatively among the Greene County and Ulster County Soil and Water Conservation Districts and the DEP Stream Management Program. The project was designed according to Natural Channel Design guidelines, using a reference reach upstream of the project area to define "natural" step-pool conditions and a construction program that attempted to recreate such conditions in the project reach.

STOP 5A. BROADSTREET HOLLOW RESTORATION SITE: REFERENCE REACH. (30 MINUTES) (Approx. location UTM 18 T 554947E 4665246N). The Broadstreet Hollow creek here displays a typical step-pool pattern with large cobble and boulder bedload. This reach is classified as a Rosgen B3 channel (Rosgen, 1996). Sediment size and distribution as well as channel morphology (hydraulic geometry and slope) provide the targets for design of the restoration reach using Rosgen's natural channel design methodology. This site also has been monitored since project initiation; repeated cross-section measurements have been coupled with monitoring transport of large marked boulders to document changes in this "natural" channel reach.



October 14, 2002

June 6, 2003

April 2, 2005

April 2, 2005

Figure 17. Broadstreet Hollow restoration site. Image 47 was taken prior to construction of the remediation project. Image 52 shows one of the rock vanes constructed across the creek. Images 70 and 73 show bank erosion resulting from high flow in 2005. Photos from GCSWCD, 2008.

64.2 0.4 Turn around and drive back down Broadstreet Hollow Road. Pull off on right at house to observe restoration site.

STOP 5B. BROADSTREET HOLLOW RESTORATION SITE: RESTORATION REACH. (30 MINUTES) (Location UTM 18 T 554624E 4664764N). Complex glaciolacustrine and post-glacial geology along with residential development have contributed to the challenges in restoring and stabilizing this reach of the Broadstreet Hollow stream. As reported by GCSWCD (2008), slumping of glaciolacustrine clays on the right bank has been fostered by artesian pressure in an interlayered sand deposit that has resulted in an artesian boil within the stream channel. Dewatering wells were installed; they have since been decommissioned. However, mud boils have continued to propagate upstream within the channel, still present in June 2009. Channel restoration was designed using the step-pool bedform and hydraulic geometry of the reference reach. Large quarried rocks were used to construct “cross vanes” to function as boulder-dominated steps in a constructed B3 channel (Figure 17). Several high flow events through this reach have caused some of the rock structures to be flanked or to need repair. Also, some of the structures have caused excess scour in the pool below the constructed step resulting in impaired fish passage at low flow. Willows and other riparian trees also were planted along the bank to add to bank stabilization.

Figure 18. Pre-restoration landsliding along right bank of Stony Clove at Lanesville site. Photo from DuBois, 2003.

66.1	1.9	Return to Hwy. 28 and turn left to continue downstream.
68.4	2.3	Junction Hwy. 214. Turn left into Phoenicia.
68.6	0.2	Left on Hwy. 214 into Stony Clove.
69.8	1.2	Left side of road undergoes routine repairs due to collapse of underlying glaciolacustrine clays. Note bedrock exposure across creek.
70.3	0.5	Bridge over Stony Clove; Stony Clove gaging station.
70.8	0.5	Junction Silver Hollow Road on right.
72.2	1.4	Greene County line
72.9	0.7	Pull off into field on right just before Lanesville hamlet sign.

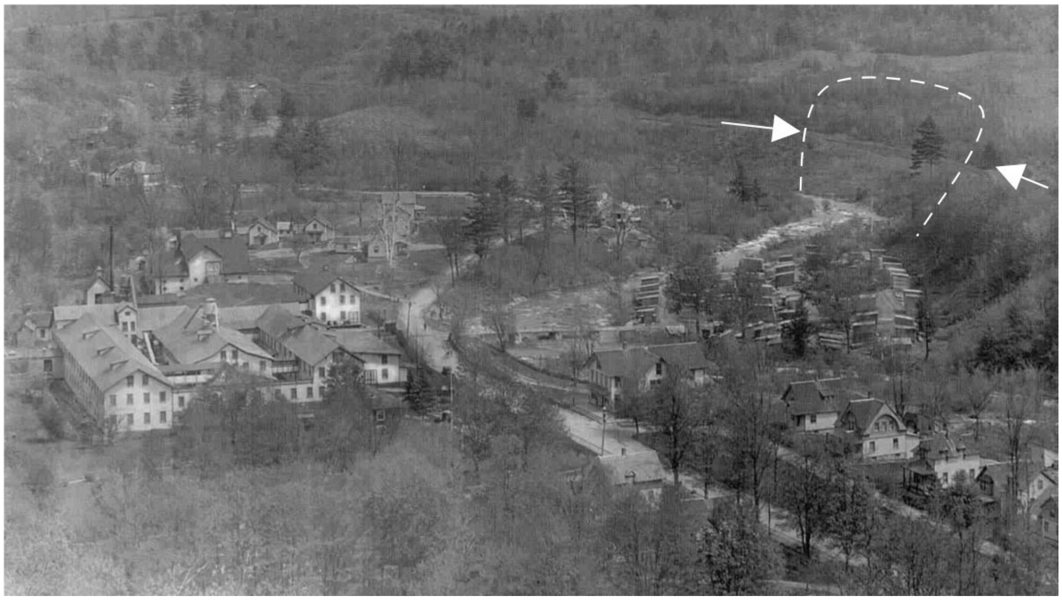


Figure 19. Photograph of Chichester, NY, ca. 1900 looking upstream on Stony Clove (channel on right side of photo). Note railroad grade above stream and alignment of channel away from bank and near the road. Area of modern landslide indicated.

STOP 6. LANESVILLE DEMONSTRATION RESTORATION PROJECT SITE ON STONY CLOVE CREEK. (30 MINUTES) (Location UTM 18 T 566227E 4663260N). A long history of channel modification and response has led to severe bank erosion and undermining of the right bank of Stony Clove just downstream of the hamlet of Lanesville. This reach was chosen for remediation because the development of a landslide on the left bank (Figure 18) was a significant source of fine sediment and turbidity into Stony Clove, Esopus Creek, and Ashokan Reservoir. This reach also had become increasingly confined by channel modifications, exacerbating the tendency to undermine the unstable left bank. Bank stabilization was promoted through construction of a bankfull bench at the toe of the slope, designed to re-establish a floodplain and minimize the interaction of most flows with the unstable bank (DuBois, 2003). Natural channel design principles were followed, including the construction of rock vanes and cross vanes within the channel and planting of a riparian buffer along the right bank and on the constructed bench (DuBois, 2003). The project was begun in 2003 but not completed until 2005 because of high water levels in the creek. Since construction this project has received several flow events around or greater than the bankfull discharge and has functioned quite well in stabilizing the reach and reducing turbidity downstream.

73.2	0.3	Turn around and drive back down Stony Clove. Meteorological station on right.
75.3	2.1	Pull off on left side of road to walk down to creek.

STOP 7. LANDSLIDE ALONG STONY CLOVE CREEK. (45 MINUTES) (Pulloff location UTM 18 T 567436E 4661227N). Get permission from landowner before walking down to creek. The Ashokan Watershed Stream Management Program Action Plan (http://www.catskillstreams.org/majorstreams_ec.html) identifies this reach of the stream between the Silver Hollow Bridge and the Route 214 crossing 1 km downstream as the highest priority restoration target for improving water quality in the Esopus Creek watershed. This area has a long history of modification, including development and construction of a railroad line (Figure 19) and various efforts to control the creek channel alignment. Today there are three distinct streambank/hillslope failures into glacial lake sediment and glacial till that are quite active. During spring snow melt and after rainfall runoff events this reach of stream is the most significant "point source" of turbidity for days and sometimes weeks after high water events (Figures 20 and 21). This stop is located at the largest and most problematic of the failures. It is a large active landslide initiated sometime prior to 1995. Upslope propagation of the slope failure resulted in collapse of a railroad right-of-way as well as increased groundwater and sediment discharge. The scale of this landslide presents especially great challenges for channel restoration and suspended sediment management. We will discuss restoration and management strategies being considered here. Given what we have seen elsewhere in the basin, how might the stream be managed through this reach to preserve/restore water quality?

Figure 20. Landslide along Stony Clove upstream of Chichester Post Office. Photo from NYCDEP et al., 2007.

77.3	2.0	Return to Phoenicia and turn left onto old Hwy. 28.
79.3	2.0	Mt. Tremper trailhead on left.
81.2	1.9	Entrance to Zen Monastery on left.
81.3	0.1	Junction State Hwy. 212. Turn right on Hwy. 212 to continue trip or turn left for optional side trip.

OPTIONAL SIDE TRIP UP BEAVER KILL. This optional trip gives access to a spectacular exposure of interbedded till and glaciolacustrine sediments as well as another extensive landslide that presents a stream management challenge. Mileage readings are for this side trip.

1.0	1.0	Bridge over Beaver Kill
3.1	2.1	Bridge over Beaver Kill
3.3	0.2	Exposure of "Willow moraine". Pull over on left side of road.

STOP BK 1. EXPOSED WILLOW MORAINE. (40 MINUTES) (Location UTM 18 T 0563899E 4657667N) This cutbank exposes a complex sequence of interbedded till and lacustrine sediments currently being studied by Andrew Kozlowski and colleagues from the New York State Museum as part of surficial geologic mapping of the quadrangles in this area. A lower, consolidated till is overlain by some 18 till units interbedded with lacustrine sediments. This exposure illustrates the complexity of glacial deposits in the Upper Esopus watershed and highlights the difficulties in mapping stratigraphy—and identifying possible sources of suspended sediment turbidity into Esopus Creek and its tributaries.

Figure 21. Downstream-looking view of suspended sediment from landslides entering Stony Clove Creek and increasing downstream turbidity. Photo by Dan Davis, DEP, March 19, 2009.

5.6	2.3	Turn around and drive back down Beaver Kill (Hwy. 212). Pull off on right side of road at second bridge.

STOP BK 2. LANDSLIDE IN GLACIAL DEPOSITS. (15 MINUTES) (Location UTM 18 T 561108E 4656095N) A landslide along the right bank of Beaver Kill has propagated as much as 70 m upslope and at least 70 m along the channel downstream of the Hwy. 212 bridge (Figure 22). This site is a dramatic representation of several similar stream bank erosion/hillslope mass failures in the confined portions of the Beaver Kill watershed that seem to be significant sources of bedload sediment supply resulting in numerous gravel/cobble bars that induce further lateral erosion of the channel. An assessment of this stream corridor is planned for late summer 2009.

6.6	1.0	Continue down Hwy. 212 to junction with Old Hwy. 28.

Figure 22. Landslide along Beaver Kill. Stop BK2 at bridge. Photo from NYCDEP et al., 2007.

Figure 23. Changes in meander geometry at Beechford. From Miller, 2009.

END OF OPTIONAL SIDE TRIP

81.3	0.0	Restart main road log.
81.9	0.6	Continue down Hwy. 212 to junction with Hwy. 28. Turn left toward Kingston.
83.1	1.2	Turn right onto Lower Winnie Road and pull off. Walk over to edge of river bank.

STOP 8. MEANDER BEND MIGRATION ON ESOPUS CREEK AT BEECHFORD. (15 MINUTES) (Location UTM 18 T 560476E 4652445N) The meander of Esopus Creek just upstream of this location has been migrating eastward and downstream, as recognized from comparison of aerial photographs from 1959, 1980, and 2001 (Miller, 2009; Figure 23). The channel here appears to have been left (east) of the island on the 1903 topographic map. By 1959, the channel had avulsed to the right (west) side of the floodplain, though the original channel was still occupied (at least in part) as a secondary channel, creating a mid-channel island. We do not know exactly when this occurred, nor whether this was a natural avulsion or was induced to protect the Hwy. 28 alignment. However, the main channel has been migrating eastward since 1959, eroding the island and creating a point bar on the right (west) bank. This continuing meander migration likely will result in reoccupation of the original channel and could threaten the Hwy. 28 alignment in the future.

83.3	0.2	Continue on Lower Winnie Road back to Hwy. 28 and turn right to continue back toward Kingston.
101.1	17.8	Return to Kingston traffic circle on Hwy. 28 and merge onto NY State Thruway (I-87).
117.3	16.2	Return to New Paltz on NY State Thruway (I-87). Take Exit 18.
119.2	1.9	Take Hwy. 299 west to Hwy. 32 in New Paltz. Turn left, then right at East Entrance to SUNY New Paltz and back to parking lot.

END OF FIELD TRIP

REFERENCES

Baldigo, B.P., Warren, D.R., Gallagher-Ernst, A.S., Miller, S.J., Davis, D., Keller, W., Baudanza, T.P., DeKoskie, D., and Buchanan, J.R., 2008, Restoring geomorphic stability and biodiversity in streams of the Catskill Mountains, New York, USA: Proceedings of the Fourth World Fisheries Congress, Reconciling Fisheries with Conservation, (Symposium 49): Bethesda, Maryland., American Fisheries Society, p. 1777-1790.

Barnet, D.G., 2004, City Efforts to Protect Riparian Buffer Areas: Report by New York City Department of Environmental Protection, Bureau of Water Supply, 44 p. http://www.hydroqual.com/projects/riparian/nyc_efforts.pdf, accessed July 9, 2009.

Cadwell, D.H., 1986, Late Wisconsinan stratigraphy of the Catskill Mountains, *in* Donald H. Cadwell, ed., The Wisconsinan Stage of the First Geological District, Eastern New York: New York State Museum Bulletin 455, p. 73-88.

Cornell Cooperative Extension Ulster County, New York City Department of Environmental Protection, and U.S. Army Engineer Research Development Center, 2007, Upper Esopus Creek Management Plan, Volume I, Summary of Findings and Recommendations: Cornell Cooperative Extension, 68 p. http//www.catskillstreams.org/pdfs/esopus_smp_es.pdf

Czekanski, A., 2005, Annual snowmelt and the New York City water supply: Term project for GIS in Water Resources course, University of Texas. http://www.crwr.utexas.edu/gis/gishydro06/Introduction/TermProjects/GIS%20Term%20Paper.htm, accessed July 9, 2009.

Dineen, R.J., 1986, Deglaciation of the Hudson valley between Hyde Park and Albany, NY, *in* Donald H. Cadwell, ed., The Wisconsinan Stage of the First Geological District, Eastern New York: New York State Museum Bulletin 455, p. 89-108.

DuBois, J., 2003, Lanesville Demonstration Restoration Project: Section 5 of Stony Clove Creek Stream Management Plan: Greene County Soil and Water Conservation District, 23 p. http://www.catskillstreams.org/pdfs/Section%205%20Lanesville%20Demonstration%20Restoration%20Project.pdf, accessed July 9, 2009.

Dunne, T., and Leopold, L.B., 1978, Water in Environmental Planning: San Francisco, W.H. Freeman, 818 p.

Erwin, S., Davis, D., and Tuscanes, J., 2005, Phase 1 Geomorphic Assessment of Upper Esopus Creek: New York City Department of Environmental Protection Stream Management Program Technical Report.

Evers, A., 1972, The Catskills: From Wilderness to Woodstock: Garden City, NY, Doubleday, 821 p.

Fischenich, C., 2001, Design for Stabilization and Reconstruction of Esopus Creek near the Woodland Valley Bridge, Shandaken, New York: Report prepared for the New York City Department of Environmental Protection Stream Management Program.

Fisher, D.W., Isachsen, Y.W., and Rickard, L.V., 1970, Geologic Map of New York State: Hudson-Mohawk Sheet: New York State Museum, Map and Chart Series no. 15, scale 1:250,000.

Frumhoff, P.C., McCarthy, J.J., Melillo, J.M., Moser, S.C., and Wuebbles, D.J., 2007, Confronting Climate Change in the Northeast; Science, Impacts, and Solutions: Cambridge, MA, UCS Publications, 146 p.

Greene County Soil and Water Conservation District, 2008, Broadstreet Hollow Stream Restoration Project; Implementation & Monitoring Report (Updated March 2008): Report prepared for the New York City Department of Environmental Protection, 15 p. plus appendices. http://www.catskillstreams.org/pdfs/BSHimplementationreport.pdf, accessed July 9, 2009.

Kudish, M., 2000, The Catskill Forest: A History: Fleischmanns, NY, Purple Mountain Press, 218 p.

Miller, N.R., 2009, Historic channel change on Esopus Creek upstream of the Ashokan Reservoir, Catskill Mountains, New York: M.S. Thesis, Binghamton University.

Miller, N.R., and Knuepfer, P.L.K., 2009, Historic channel change on Esopus Creek, upstream of the Ashokan Reservoir, Catskills, New York: Geological Society Abstracts with Programs, Northeastern Section, v. 44, no. 3, p. 38.

Miller, S.J. and Davis, D., 2003, Optimizing Catskill Mountain regional bankfull discharge and hydraulic geometry relationships: Paper presented at AWRA 2003 International Congress, Middleburg, Virginia, Paper TPS-03-2, 10 p. http://www.nyc.gov/html/dep/html/watershed_protection/pdf/smp.pdf, accessed July 10, 2009.

New York City Department of Environmental Protection, 2009, Ashokan: http://www.nyc.gov/html/dep/html/watershed_protection/ashokan.shtml, accessed July 9, 2009.

New York City Department of Environmental Protection, US Army Engineer Research Development Center, and Cornell Cooperative Extension Ulster County, 2007, Upper Esopus Creek Management Plan, Volume III, Watershed and Stream Characterization (Draft): New York City DEP Report, 225 p.

Rich, J.L., 1935, Glacial Geology of the Catskills: New York State Museum Bulletin 299, 180 p.

Rosgen, D. 1996, Applied Fluvial Morphology: Pagosa Springs, CO, Wildland Hydrology, 390 p.

Schaffner, M., Evans, M., and Arnott, J., 2008, The June 19, 2007 Delaware County Flash Flood: a Meterological and Hydrological Analysis: National Weather Service Eastern Region Technical Attachment 2008-5, 36 p. http://www.erh.noaa.gov/er/hq/ssd/erps/ta/ta2008-05.pdf, accessed July 21, 2009.

Schneiderman, J.S., 2000, From the Catskills to Canal Street: New York City's water supply, in Schneiderman, J.S., ed., The Earth Around Us: Maintaining a Livable Planet: Boulder, Westview Press, p. 166-180.

Thaler, J.S., 1996, Catskill Weather: Fleischmanns, NY, Purple Mountain Press, 167 p.

US EPA, 2007, New York City Filtration Avoidance Determination: Environmental Protection Agency, 92 p. http://www.epa.gov/region02/water/nycshed/2007finalfad.pdf, accessed July 20, 2009.