Effect of Projected Changes in Winter Streamflow on Stream Turbidity, Esopus Creek Watershed in New York, USA

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ABSTRACT

This study focuses on the impact of changes in winter streamflow on in-stream turbidity in the Esopus Creek watershed, one of the New York City (NYC) water supply watersheds. Projected changes in daily precipitation and air temperature from a suite of five global climate models (GCMs) and three emission scenarios for future periods 2046–2065 and 2081–2100 were downscaled for the study region. The simulated climate scenarios were used to project future streamflows using the Generalized Watershed Loading Functions—Variable Source Area (GWLF-VSA) watershed model. Seasonal turbidity rating curves based on measured historical streamflow and stream turbidity were used in combination with the simulated streamflow for generating future stream turbidity scenarios. Results indicate increase in future ambient stream turbidity from November to March and a decrease during April. These results are the effects of increased winter rainfall, reduced snowfall, and a shift to early timing of spring snowmelt runoff causing an increase in streamflow during early winter. It also suggests a reduction in the traditional peak streamflow around April that is expected to occur in this region. As a result, our models simulate a consistent increase in the low to medium percentile range of turbidity values associated with low to medium range of streamflows and no apparent change in high percentile turbidity values associated with high streamflows.

Keywords: climate change, snowmelt runoff, turbidity load, time series model, autocorrelation, rating curves.

INTRODUCTION

High suspended sediment loads and the resulting turbidity can impact the sustained use of rivers for water supply and other designated uses. Changes in stream turbidity can be an indication of changes in material fluxes, aquatic geochemistry, water quality, channel morphology, and aquatic habitats (Walling, 2009). Therefore, understanding the processes and quantifying stream turbidity under present and future conditions will be valuable for watershed-scale management of stream turbidity and for maintaining high water quality. The New York City (NYC) water supply is currently the largest unfiltered water supply in the US, operating under a renewable filtration avoidance determination (FAD) granted by US Environmental Protection Agency. The Catskill Mountain streams provide up to 90% of the municipal water supply for about 9 million residents of NYC through a network of six reservoirs draining approximately 3885 km^2. The Upper Esopus

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Creek that drains into the Ashokan Reservoir along with water diverted from the nearby Schoharie Reservoir (via the Shandaken Tunnel) provide 40% of this unfiltered drinking water supply. The water quality is typically high in the Catskill streams. However, high magnitude runoff events can cause significant increases in stream and reservoir turbidity, which at times limits the use of this unfiltered drinking water supply (Gelda et al., 2009).

An examination of historical data and results of model simulations for the Catskill region have shown an increasing trend in both mean annual precipitation (8–26 cm/50 years) and streamflow over the past fifty years (Burns et al., 2007; Zion et al., 2011). Major climate change impacts identified and predicted for this region include reduced snowfall and an earlier timing of snowmelt driven runoff due to increasing mean annual air temperature at the rate of 0.5–2.0 °C over a 50-year period (Burns et al., 2007). Ongoing research efforts on climate change impact on water resources in NYC watersheds include selecting Global Climate Models (GCM) reasonable for the region, detecting changes in seasonal streamflow, and predicting future changes in water supply and water quality (Anandhi et al., 2011; Matonse et al., 2011; Zion et al., 2011; Mukundan et al., 2012). The potential impact of climate change on stream turbidity in the region is not well understood and reported. This analysis is particularly important since there are differences in sources of turbidity due to land use and geology between NYC water supply watersheds. In this study, we perform a sensitivity analysis of stream turbidity to ongoing and anticipated changes in the seasonality of streamflow, with a focus on the winter period, using data from the Esopus Creek watershed. Stream channel processes are a major contributor of stream turbidity in this watershed (DEP, 2008). Long term (1931–2010) record of measured streamflow data from the US Geological Survey gauge (#1362500) at Coldbrook, where the Esopus Creek enters the Ashokan reservoir, shows that majority of bankfull discharge events with a 1.5 year return interval occur during the period from the beginning of November to the end of April. Therefore, it is important to have a better understanding of potential changes in stream turbidity during this period where major changes in streamflows are observed and predicted due to changes in timing of snowmelt runoff.

METHODS

Turbidity monitoring in the Esopus Creek watershed

The Esopus Creek watershed drains an area of 493 km^2 and is dominated by forests, which occupy more than 90% of the watershed area (Figure 1). The elevation of the watershed ranges from about 194 m near the watershed outlet at Coldbrook to 1275 m at the headwaters. An automated turbidity monitoring system was installed on the main tributary entering the Ashokan Reservoir near the confluence of the creek and the reservoir. Water was pumped into a riverside hut where measurements of turbidity, specific conductivity, and water temperature were made using a water quality sonde. Water samples were also periodically collected and analyzed for turbidity (Tn, NTU) and total suspended solids (TSS) in the laboratory. These data were then used to correct the automated data to account for any drift in the turbidity measurements. A US Geological Survey (USGS) gauging station at Coldbrook provides streamflow data at a daily and 15 minute interval. Since 2003, turbidity measurements were made at intervals between 15 minutes and 1 hour. Sub-daily observations were flow-weighted to provide daily average values, which are comparable in frequency to the most widely available daily USGS streamflow data and are at the time step used by New York City Department of Environmental Protection (NYCDEP) reservoir water quality models.

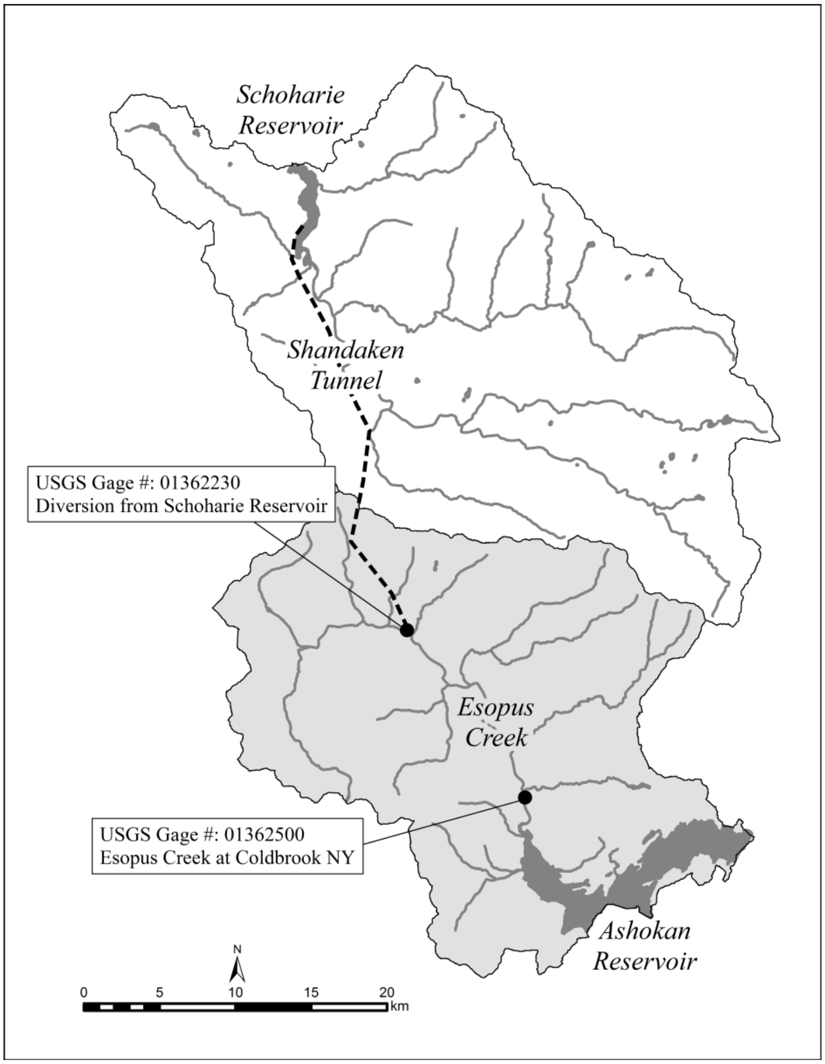

Figure 1. The Esopus Creek watershed, NY, showing the location of Coldbrook sampling location and the diversion tunnel from the adjacent Schoharie reservoir.

Time series model of average daily turbidity

Although continuous turbidity measurements were made for most periods between June 2003 and August 2011, there were periods where turbidity measurements could not be made due to storm related damage and fouling of turbidity sensors. Therefore, turbidity values for missing days were estimated using a time series model. Ordinary least square regression models on time series data often shows highly correlated residuals, and this is particularly true for daily time series data (Richards et al., 2008; Walker et al., 2009). Since the ordinary regression residuals are not independent for time series data, they contain information that can be used to improve the prediction of future values (Reed et al., 2008). More importantly, addressing autocorrelation can avoid incorrect conclusions on significance of parameters, confidence limits for predicted values, and estimates of regression coefficients. The AUTOREG procedure in SAS (SAS Institute, 2003) was used to fit a linear regression with autoregressive errors. Three predictor variables were used for the linear regression: streamflow at the watershed outlet, point source turbidity, and hysteresis effect in streamflow-turbidity relation. For point source effect, a daily time series of measured instantaneous turbidity at the outlet of Schoharie Tunnel was used. Hysteresis effect on stream turbidity was derived using the method proposed by Hirsch (1988). Our previous analysis has shown that for a given value of streamflow, the rising limb of streamflow hydrograph contributed higher turbidity compared to the falling limb (Mukundan et. al., 2010). The hysteresis term will account for such differences. A detailed description on the development of the time series turbidity model and its use as an operational predictive tool is outlined in Wang et al. (2012).

Future climate scenarios

In this study we applied calibrated GWLF model for simulating daily streamflow using daily time series of baseline and simulated future precipitation and air temperature. The potential effect of climate change on in-stream turbidity was evaluated using baseline and future climate scenarios derived from a suite of five Global Climate Models (GCMs) and three green house gas emission scenarios that represent a wide range of future climate conditions during the 2046–2065 and 2081–2100 time slices and a baseline (20C3M) scenario representing historical (1960–2000) conditions. In this study, the A1B, A2, and B1 scenario from the Special Report on Emission Scenarios (SRES) in the IPCC Fourth Assessment Report (IPCC, 2007) were used. Projected values from the selected GCMs for the region surrounding the NYC water supply were extracted and interpolated to a common 2.5° grid using bilinear interpolation for the baseline and future emission scenarios. Climate scenarios were downscaled using a 25-bin change factor methodology. This methodology divides the variable cumulative distribution function into 25 equally spaced percentiles, and a monthly delta change factor (Anandhi et al., 2011) is developed for each bin. Monthly change factors (CFs) were calculated from the difference between baseline and each future GCM/scenario simulation. These monthly CFs were used to adjust the local meteorological data from 1927–2009 and used to generate future climate conditions associated with a given GCM. The use of long-term observed data in generating future climate scenarios has an advantage of representing the observed regional climate patterns but has the disadvantage of relying only on the local historical variability of events (Matonse et al., 2012).

Developing future stream turbidity scenarios

A combination of measured and interpolated daily in-stream turbidity time series and measured streamflow time series were used to derive empirical relationships that relate a wide range of streamflow to stream turbidity (rating curves). To reduce the effect of regulation particularly on low flow turbidity, only streamflow-turbidity pairs from days when the flow diversion from Schoharie Reservoir was less than 10% of the total Esopus Creek daily streamflow were used. Separate turbidity rating curves were developed for winter (November–April) and summer (May–October) periods to account for seasonal variability in turbidity inputs. The rating curves were then applied to baseline and future time series of streamflow simulated by the GWLF-VSA model to develop baseline and future stream turbidity scenarios. These scenarios were analyzed for average daily turbidity, average daily turbidity loads, and annual cumulative turbidity loads. In addition, exceedance probability curves of predicted daily winter in-stream turbidity for baseline and future climate scenarios were compared. Previous studies in this region support the concept of turbidity loading (i.e., units of NTU m^3 s^{-1}), with turbidity being the regulatory pollutant of concern although the product of turbidity and streamflow is not a strict mass loading rate (Peng et al., 2009). Additional support for this approach is provided by the additive nature of turbidity (i.e., the turbidity of a mixture of two volumes can be computed by volume averaging) (Davies-Colley et al., 2003).

RESULTS AND DISCUSSION

Stream turbidity time series

From June 13 to August 31, 2011, a continuous time series of average daily stream turbidity from was used for this analysis. Missing turbidity data was estimated using the time series model described in the *Methods* Section. Residual analysis from the ordinary least square regression model using the three predictor variables showed a lag of 4 days in the autocorrelation function. This information was used in selecting an autoregressive model capable of predicting log-transformed daily turbidity. The selected regression model with AR4 error is as follows:

$$Y(t) = \beta x(t) + v(t)$$

$$v(t) = \sum_{i=1}^{4} \phi_i v(t-i) + \epsilon_t$$

where

x(t) is a vector of predictor variables at time t
β is a vector of regression parameters
ϕ_i represent the autoregressive parameters
v(t) is the model error at time t
ϵ_t is "white noise" which is normally distributed with a mean of 0 and a variance of σ^2.

The selected model was evaluated for its performance in predicting mean daily stream turbidity using coefficient of determination (R2), Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970), and percent bias (PBIAS). The autoregressive daily time series model performed reasonably well with R2 of 0.71 and NSE of 0.46 and PBIAS less than 2%. Model performance was affected by predictions for two data points, without which the R2 and NSE improved to 0.82 and 0.62 respectively. The model predicted average daily turbidity for 04/16/2007 was 1205 NTU when the measured value was only 253 NTU, and for 01/25/2010 the predicted value was 196 NTU when the measured value was 904 NTU. Certain watershed processes, such as stream bank collapse occurring under baseflow conditions resulting in high stream turbidity or travel times for turbidity plumes from sources to the watershed outlet, cannot be explicitly captured by a time series regression model. Moreover, uncertainty due to errors in turbidity measurements can affect the quantitative results presented. A plot of continuous time series of daily turbidity at the Coldbrook outlet is presented in Figure 2.

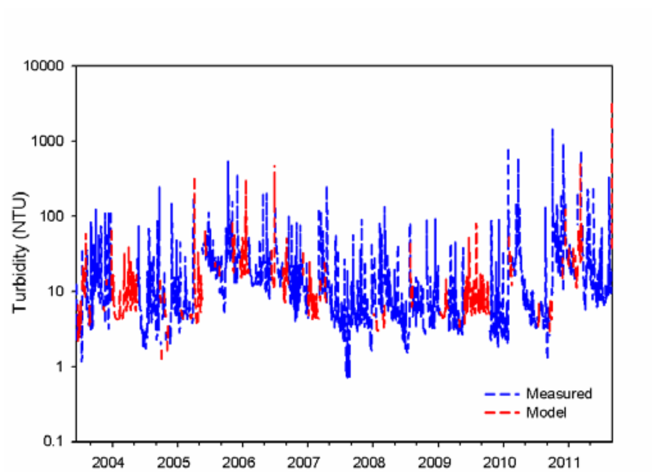

Figure 2. Continuous time series (2003–2011) of average daily turbidity at Coldbrook showing the range in observed and interpolated missing turbidity values

Projected changes in stream turbidity

Modeled long-term average daily in-stream turbidity for the baseline scenario showed a peak in April, and this peak was maintained in future scenarios (Figures 3A and 3B). However, the height of the peak was reduced in the future time slices (2046–2065 and 2081–2100) due to the shift in timing of snowmelt runoff and the resulting increase in streamflow in earlier months. Moreover, a decrease in the amount of precipitation received as snow is predicted in the future as reported in other studies (Frei et al., 2002; Mukundan et al., 2012). The projected increase in ambient stream turbidity during January and February as a result of this shift was up to 45% for the 2046–2065 period and up to 68% for the 2081–2100 period compared to baseline.

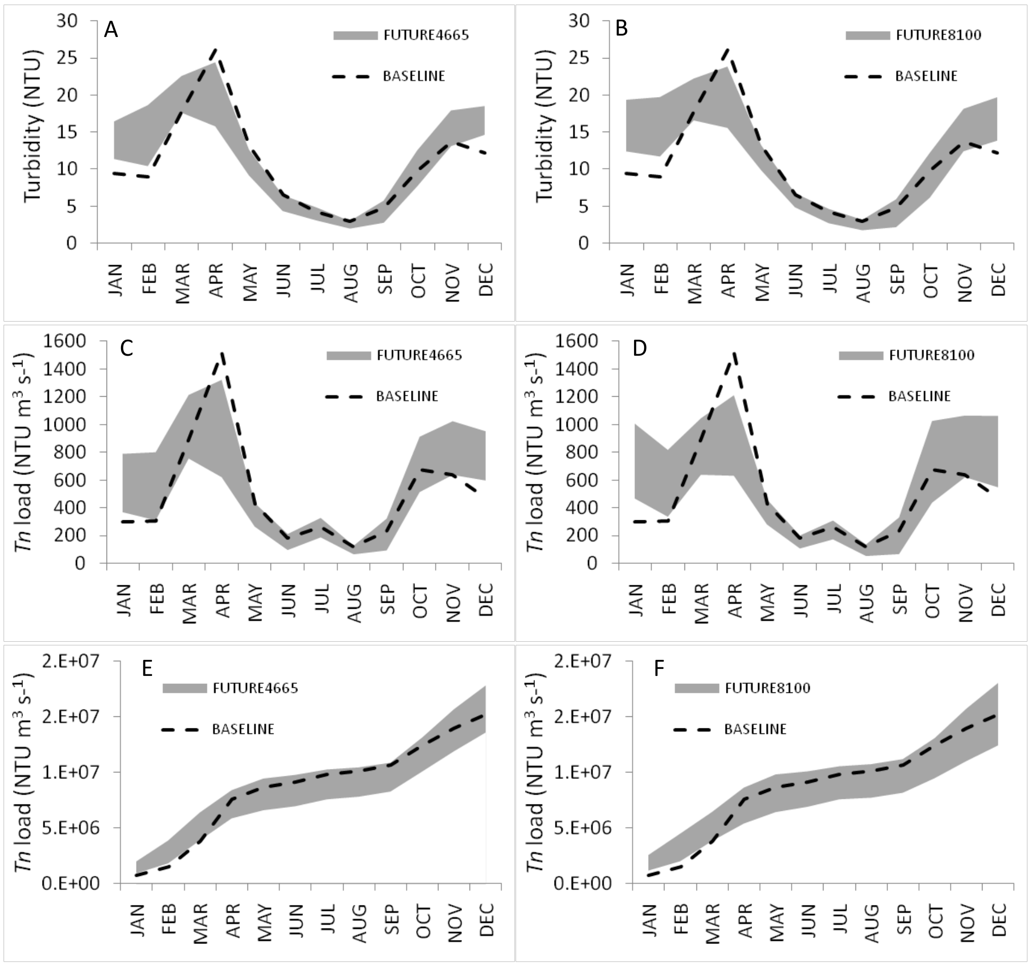

Figure 3. Comparison of baseline vs. future ambient stream turbidity for the 2046–2065 period (A) and 2081–2100 period (B); projected change in average ambient turbidity load by month for the 2046–2065 period (C) and 2081–2100 period (D); projected change in average annual cumulative turbidity loads (E and F).

Projected changes in average daily stream turbidity loads yielded similar results (Figures 3C and 3D). Maximum increase in winter turbidity loads is projected for the month of January and maximum decrease is projected in April. Figures 3E and 3F show the modeled long-term average annual cumulative turbidity load for baseline and future scenarios developed from average monthly values. The percent change in average annual cumulative turbidity load was only +3% and +5% for the 2046–2065 and 2081–2100 time slices and corresponds well with the projected average annual change in streamflow volumes (+4% and +6% respectively) for the same time period. This is interesting as analysis of climate change effects on turbidity loads at the annual time scale would yield no major effects when there is a major seasonal effect in the winter due to a shift in the timing of snowmelt runoff. The modeling results presented here should be viewed as a general sensitivity analysis rather than absolute numerical predictions, considering the uncertainty in future climate projections. Potential changes in frequency of extreme events are not captured by GCMs and the downscaling method used in this study. In addition, the frequency of extreme events can have a larger effect on the loading during any given year.

CONCLUSIONS

Our study reports the effects of projected changes in winter hydrology on winter stream turbidity in the Esopus Creek watershed, one of the NYC water supply watersheds. We use both measured historical data and simulated future scenarios to specifically compare differences in stream turbidity between present and future climate scenarios. Results of model simulations using a suite of five GCMs, three emission scenarios, and two time slices indicate a relative increase in ambient stream turbidity from November–March and a decrease during April for the future period. These results are the effects of increased winter rainfall, reduced snowfall, and a backward shift in the timing of snowmelt runoff that is expected to occur in this region as reported in previous studies. Changes in turbidity loads followed the same pattern as ambient stream turbidity for most months. Changes in average annual cumulative turbidity loads were minimal. This may be due to the fact that the predicted future winter streamflow patterns show a redistribution of the total volume to earlier in the year resulting in higher streamflows from January–March and a reduction in the traditional April peak associated with snowmelt runoff.

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