TURBIDITY IN RELATION TO HIGH FLOW EVENTS IN THE HUDSON RIVER ESTUARY

ANNABELLE C. MCCARTHY
California State University, Monterey Bay, Seaside, CA 93955 USA

MENTOR SCIENTIST: DR. STUART FINDLAY
Cary Institute of Ecosystem Studies, Millbrook, NY 12545 USA

Abstract. In 2011, Tropical Storms Irene and Lee made their impact on the Hudson River: sediment input was five times the annual average. Following these storms, one of the Hudson's most common underwater plants, Vallisneria americana (water celery), experienced a 90% decline in distribution. Research shows that the storms caused changes linked to increased turbidity. This study aims to expand our understanding of the relationship between high flow events and turbidity in the Hudson. Discharge and turbidity data – spanning 12 years - collected by U.S. Geological Survey and Hudson River Environmental Conditions Observing System were used to test for correlation between high flow and turbidity. By examining a wider range of high flow events – not limited to Tropical Storms and Hurricanes – a strong, exponential relationship between high flow and turbidity was revealed. The results suggest high flow events have the potential to increase turbidity in the Hudson River, with higher flow leading to increasingly greater turbidity. The increased turbidity from flow events we examined would cause an ecologically significant decline in light penetration with negative implications for plant growth. Efforts to reduce sediments loading would be strategic as severe storms are likely to become more frequent in the future as a result of climate change.

INTRODUCTION

Ever since the east coast of the United States was first settled by colonists, humans have made changes to the landscape that had unforeseen effects on the Hudson River. From dams to invasive mussels, humanity has left its imprint on the Hudson forever. Within the past 50 years though, efforts to clean up the Hudson have grown. Although people have become more conscious of their actions towards the river, a new opponent has entered the playing field. The New York State ClimAID assessment reported that climate change will likely cause an increase in intense precipitation events and flooding (Rosenzweig et al. 2011). Studying how storms change river ecosystems can help us mitigate the effects of climate change. Accordingly, scientists have examined the effects of tropical storms in the Hudson River watershed. Studies surrounding the 2011 Tropical Storms Irene and Lee have expanded our understanding of the dangers presented by these high-volume storms. Following TS Irene and Lee, roughly five times the long-term annual average of sediment made its way into the Hudson River, and about a third of the sediment remained in the estuary for over a month (Ralston et al. 2013). The increase in sediment input as a result of high-volume storms is concerning, because sediment deposition has been found to play a role in the decreased distribution of the Hudson's most dominant submerged aquatic vegetation: *Vallisneria americana* (water-celery) (Hamberg et al. 2017). Experimental results showed that sprouting success of *Vallisneria americana* decreased by 30-100% when overwintering tubers were buried by 2 and 5 centimeters of sediment; no sprouting success was recorded when sediment was 10 or more centimeters deep (Hamberg et al. 2017). The findings from the Hamberg et al. study indicate that increased sediment input from storms can smother plants. Submerged aquatic vegetation plays an important role in the Hudson River ecosystem, it serves as a water quality indicator, provides habitat and contributes to primary productivity (Levinton 2006). Massive loss of this vegetation would have negative impacts all the way up the food chain.

Turbidity is a measurement of water clarity, where high turbidity equates to murky water. The Hudson River is particularly turbid which limits sunlight's ability to penetrate far below the water's surface. The distribution of submerged aquatic vegetation is limited by light availability, causing its maximum depths to reside around three meters (Levinton 2006). Submersed plants are not the only lifeform affected by changes in turbidity. Single-celled algae and cyanobacteria, more commonly known as phytoplankton, depend on sunlight to make energy just like plants. Phytoplankton are limited by light availability, deep mixing, and grazing (Levinton 2006). Rainy days can quite literally become the "perfect storm" to limit phytoplankton abundance in the Hudson. High winds, heavy rains, and tidal currents are possible causes for an influx of sediment into the Hudson, and the resuspension of previously settled sediments from the bottom of the river. Seeing as the Hudson River lacks optimal conditions for vegetation growth on the best of days, storms are a serious threat to the river's health because they exacerbate the difficulties already faced by primary producers.

The connection between tropical storms, sediment deposition, and turbidity provide an area of study that is worth exploring, because it is likely that increases in severity and frequency of precipitation will lead to changes in river ecosystems. It is already understood that TS Irene and Lee significantly increased the amount of sediment that was washed into the Hudson River, and we expect future storms will likely have the same effect. Tropical storms, however, are not as abundant as the average rainstorm. It is possible that frequent, smaller storms could have compounding, damaging effects, comparable to a single tropical storm or hurricane. Sediments being flushed into the river, and stirred up, by high flow events have the ability to bury and destroy submerged aquatic vegetation and limit light availability. The resulting decline of available habitat and food in the river can cause effects that magnify all the way up the food web. Additionally, as large amounts of sediment are being flushed into the river, they have the potential to bring along whatever contaminants are coating their surfaces. For example, floodplain soils that are contaminated with polychlorinated biphenyls (PCBs) can become a source of contamination to the Hudson each time they are flooded (New York State Department of Environmental Conservation 2015). Increased contamination of the Hudson River could occur as an indirect result of climate change.

It is unclear if all high flow events in the Hudson River pose as large of a threat as hurricanes and tropical storms. The present research expands the scope of knowledge by exploring a broad range of data from USGS and HRECOS stations along the Hudson. My research goal was to investigate the relationship between turbidity and high flow events. Our questions were: Is there a clear relationship between high flow and turbidity at the head of the Hudson River estuary? How might such a pattern be altered at sites further down-river?

METHODS

Data Collection

Daily average discharge data were obtained from the USGS site at Green Island, New York (42.783 N, -73.677 W) (U.S. Geological Survey 2020). Turbidity data were downloaded from two Hudson River Environmental Conditions Observing System (HRECOS) stations: Port of Albany (42.61954 N, 73.75890 W, 16.3 km below head of tide at Green Island), and Schodack (42.4996 N, 73.7768 W, 30.1 km below Green Island). Data for turbidity at Schodack Island go back as far as 9 May 2008. Turbidity data from the Port of Albany were limited from 4 January 2011 to the present. In order to study a broader data set, discharge data were downloaded from May 9th, 2008 to the present to match the beginning of the record for Schodack, although this is longer than the data record for Albany.

High Flow Events

High flow events were defined using a series of steps. First, the 90th percentile of the discharge data was calculated, with the result being 30600 cubic feet per second. The entire data set was filtered to return only observations from days where the average discharge was equal to, or more than, 30600 cubic feet per second. This brought the number of observations down from 4430 to 444. A single event is defined as any day (or consecutive days) where discharge was more than 30600 cfs. During some events, discharge peaked past this metric, dropped below, and then peaked again. In order to establish a rule for deciding if the second peak should be counted as a new event the following guideline was developed: If the minimum value between peaks is equal to, or less than, half the height of the initial peak, then the peak following that minimum should be counted as a new event. If the minimum is above this threshold, then the flux in discharge is small enough to include the second peak in the same event as the previous peak. After manually lumping observations into events, ten events were randomly selected from each month, except for the months that had fewer than 10 events in which case all the events were selected. Provisional data were omitted. The discharge data for the resulting observations were then combined with the turbidity data by corresponding date. The 278 observations represented 82 separate events, where events ranged from a single day to as many as 20 consecutive days. Events were averaged so that each event was represented by a single observation: the average discharge and turbidity that occurred over the duration of the event. Due to some missing turbidity data, only 65 events could be studied for Albany, and 64 events at Schodack.

Modeling

A linear regression model was used to examine the relationship between discharge and turbidity during high flow events. The residuals were not normally distributed, so the turbidity data for both sites were transformed using log base 10. A quadratic transformation was tested for both turbidity data sets, but it was only used for the Albany model, because it was a poor representation of Schodack data. The quadratic transformations of the models were compared to the original models using Akaike's Information Criterion (AIC).

Light Extinction Comparison

In order to visualize the magnitude of change that occurred following a high flow event, I created three categories using the Green Island discharge data set (Supplemental Fig. 1):

- discharge *less than* (or equal to) 20,700 cfs (75th percentile)
- discharge *greater than* (or equal to) 30,600 cfs (90th percentile)
- discharge *greater than* (or equal to) 75,000 cfs (this is our rough equivalent to the 100-year flood stage for Green Island and is approximately equal to the 99.6th percentile).

I converted the turbidity values, to seston (mg/L), to a light extinction coefficient (k), using unpublished data from a long-term study from the Hudson River Ecosystem Study of the Cary Institute of Ecosystem Studies. I then calculated the median light extinction coefficient (k) for each category, and used the following general equation to generate a table of irradiance at varying depths:

$$I(depth) = 2000 * e^{(k*depth)}$$

Where 2000 μmol m^{-2} s^{-1} is the approximate amount of sunlight at the surface of the Hudson on a sunny, summer's day, and k is unique for each of the three categories.

Analyses were performed using R (R Core Team 2019), and visuals were produced using ggplot2 (Wickham 2016).

RESULTS

Across the 65 events evaluated using turbidity data from Albany, there was a strong relationship between discharge and turbidity (fig. 1a). The relationship was significant ($p < 0.001$) with discharge accounting for about 52% of the variation in turbidity. When discharge is squared in order to create a quadratic transformation, the significance was slightly higher, and about 55% of variability was accounted for by the model (F-statistic: 40.07 on 2 and 62 DF) (fig. 1b). The quadratic transformation received an AIC score of 13.45634, with 4 degrees of freedom, whereas the model that was not transformed received an AIC score of 16.87343 with 3 degrees of freedom. Thus, the quadratic transformation model should be used to predict turbidity at Albany, the best-fit equation to predict turbidity is:

$$-0.7683 + 8.074\text{x}10^{-5}(\text{disch (cfs)}\ ) -4.966\text{x}10^{-10}(\text{disch (cfs)})^2 = \text{turbidity (NTU)}$$

When discharge at Green Island was compared to turbidity at Schodack, the relationship between the variables was not as strong (fig. 2). Discharge explained only 39% of the variation in turbidity. The quadratic transformation for turbidity data from Schodack did not have desirable results. AIC indicated a quadratic model was a slightly better fit for the Albany relationship but not for Schodack, so site comparisons were made using linear models of log-transformed data.

When categorized by season, discharge of events was evenly distributed throughout the events (fig. 3). The median discharge of events stayed within the range 38400 and 39383 cubic feet per second for all four seasons.

We modelled light penetration into the water column under various flow conditions by converting reported turbidity to a light extinction coefficient (fig. 4). To provide ecologically-relevant context we use the inflection point of a photosynthesis-irradiance curve for *Vallisneria* of 178 μmol m^{-2} s^{-1} (Harley and Findlay 1994).

DISCUSSION

Past research provided a clearer understanding of the effects to be expected from Tropical Storms and Hurricanes. Following Tropical Storms Irene and Lee, the Hudson River experienced increased sediment loading into the river, increased turbidity, and decreased distribution of its most abundant submerged vegetation: *Vallisneria americana*. Literature did not indicate whether less severe storms have the potential to damage the Hudson. The aim of the present research was to fill this gap by studying a wider range of high flow events and test for correlation with available turbidity data. The model results were significant enough to reject the null hypothesis of no relationship. The conclusion that high flow events positively correlate with increased turbidity is consistent with the results from the model. Additionally, when comparing the two sites – Albany and Schodack – the upstream site showed a stronger correlation to discharge than the downstream site. The decrease in correlation suggests that maybe turbidity downstream is affected by other factors than discharge at the head of the estuary. Notably, there are no significant tributaries entering between Albany and Schodack.

Prior to analysis, a relationship was expected to exist between discharge and turbidity. Predicting the shape of the curve, however, was less intuitive. The resulting positive curve disproves the idea that sediment is depleted as more water enters at head of tide. The positive, exponential trend could be interpreted as higher flows being increasingly capable of moving more sediment. From a physical standpoint, this idea makes sense, because a higher rate of flow inherently possesses more energy, and therefore should be capable of doing more work.

The relationships defined by this study allowed us to estimate effects of a range of storms on ecologically important variables such as light extinction. The resulting plot (fig. 4) captures the dramatic difference in light availability created by high flow in the Hudson. There was a 0.2-meter difference in depth of light availability that supports half-maximal photosynthesis between the 100-year flood and the 90th percentile representing events we modeled. Between the 100 and 75th percentile, there was a 1.1-meter difference. Assuming a smooth bathymetry and recognizing that the maximal depth is only about 1.5 m below low water, a 0.2- and 1-meter decrease in light penetration would translate into a 14% or 67% loss of spatial habitat. Turbidity eventually decreases after high flow events though, so the changes in light availability don't necessarily imply permanent change in submerged aquatic vegetation distribution. The potential for destructive change increases, however, with increasing frequency of high flow events. “Downpours, with intense precipitation occurring over a period of minutes or hours, are likely to increase in frequency and intensity as the state's climate warms” (Rosenzweig et al. 2011). My research, when paired with climate change projections for New York, suggest that the Hudson may see a rise in baseline turbidity, which could decrease the distribution of submerged aquatic vegetation by limiting its growth to increasingly shallower portions of the river.

Overall, exploring these data has revealed a relationship between discharge, and turbidity. No matter how increases in discharge occur, whether they are driven by snow melt, a tropical storm, or a simple April shower, we know that weather has an effect on turbidity in the Hudson. The exponential relationship between discharge and turbidity is concerning, because as the global climate changes the primary producers in the Hudson are likely to suffer. Additionally, the inorganic sediments that are washed into the river essentially dilute the organic particles (like phytoplankton), which lowers the concentration of edible particles. The decline in edible particle concentration, in addition to loss of SAV, would become a problem for organisms that depend on phytoplankton and SAV as a source of food and habitat. Further research examining the trends in turbidity following high flow events could answer how long turbidity remains elevated after a storm. Another avenue of research worth exploring is the level of contamination associated with the influx of sediment into the Hudson following large storms.

ACKNOWLEDGEMENTS

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APPENDIX

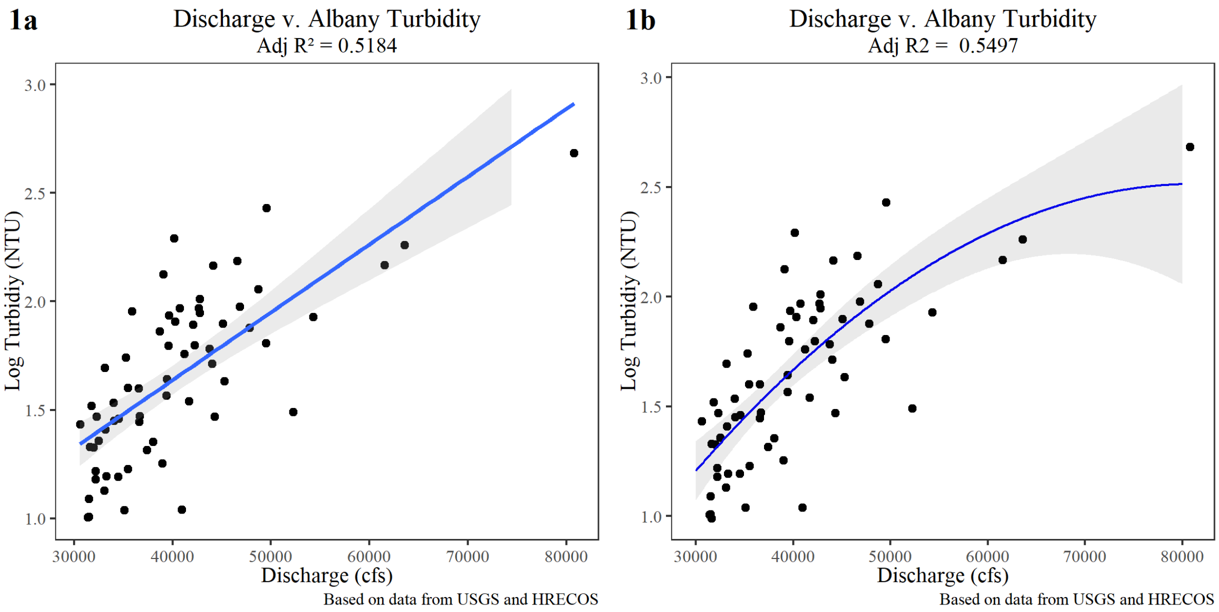
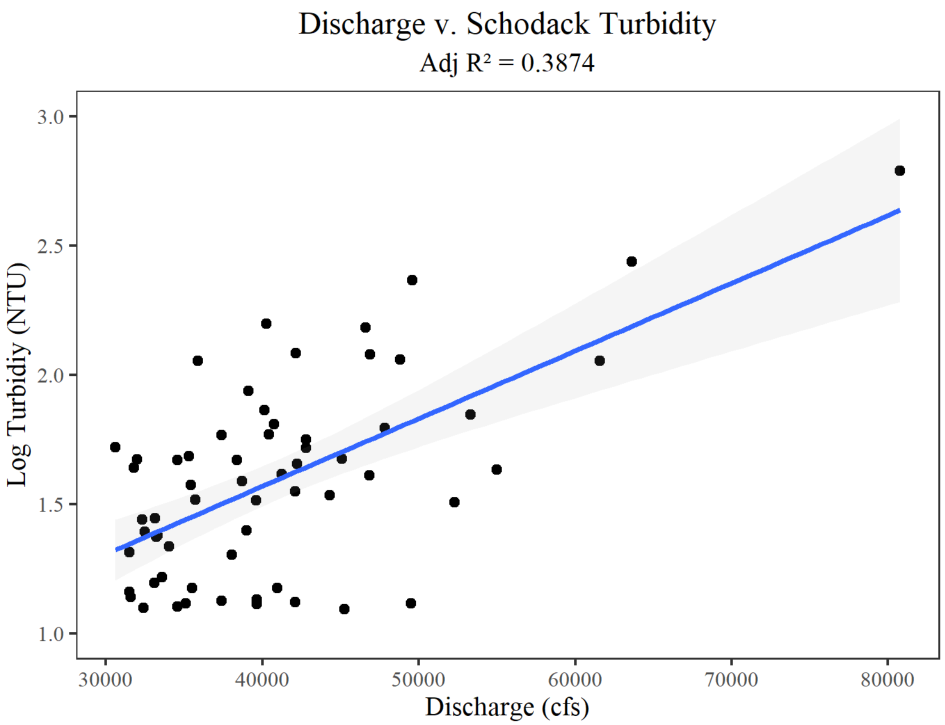


FIGURE 1. Green Island discharge data plotted against the log of Port of Albany turbidity data. Plot 1a displays the linear model. Plot 1b displays the quadratic transformation of the linear model.



Based on data from USGS and HRECOS

FIGURE 2. Green Island discharge data plotted against the log of Schodack turbidity data. Linear model in blue.

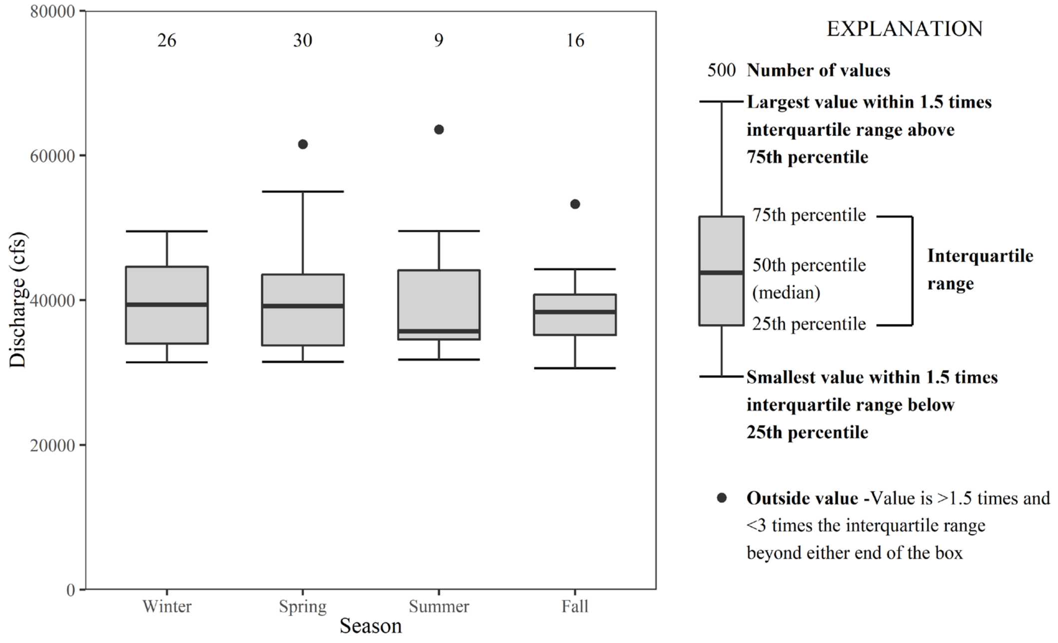


FIGURE 3. Box and whisker plots of events studied (>90th percentile) distributed across seasons. When events were separated by season, the median discharge remained around 40,000 cubic feet per second.

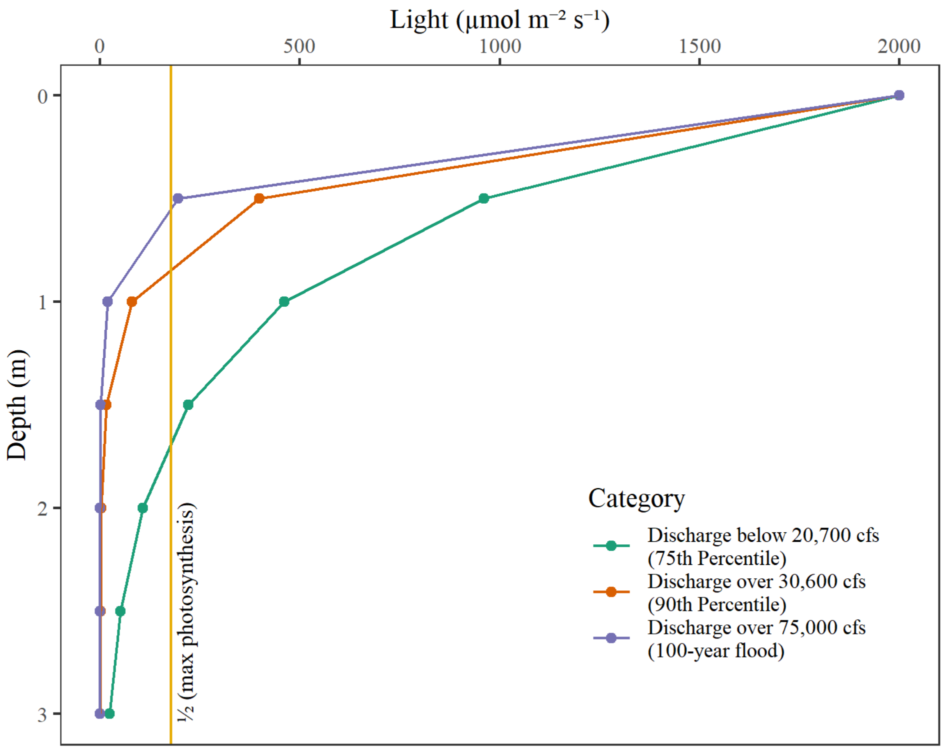
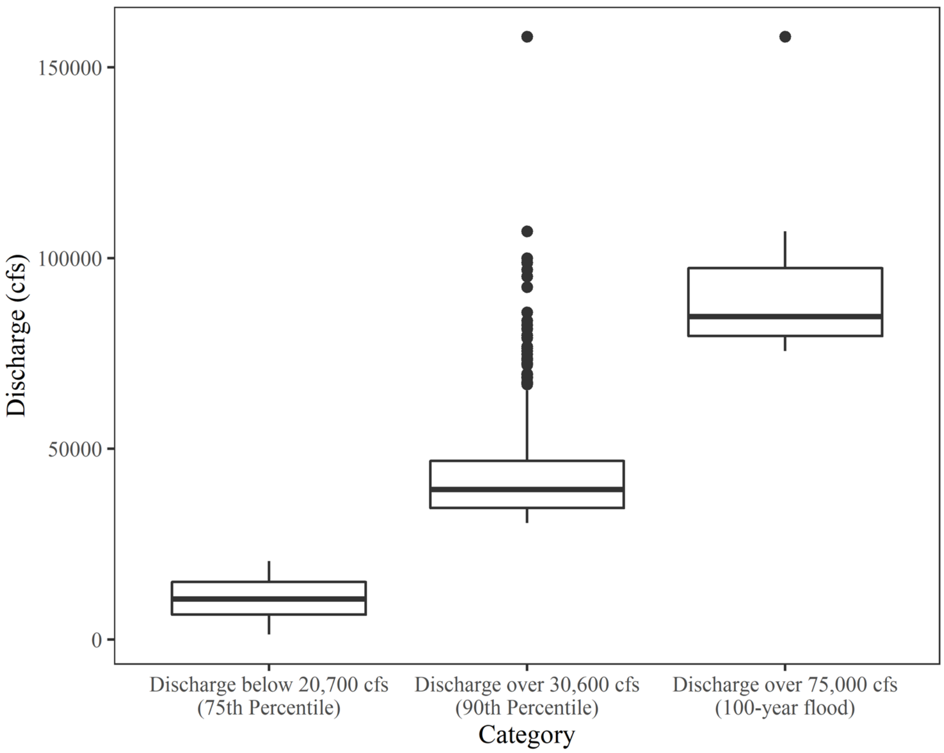


FIGURE 4. Mean turbidities were used to estimate light extinction in the Hudson. The resulting plot highlights the dramatic difference in light availability under varying discharge conditions. A vertical line indicates the light necessary for *Vallisneria americana* to perform photosynthesis at half capacity.



SUPPLEMENTAL FIGURE 1. There are notable differences between the median discharge for each category. Consequently, the categories also had greatly different estimated values for seston and light extinction coefficients.