Turbidity hysteresis in an estuary and tidal river following an extreme discharge event

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Key points

- Turbidity-discharge relationships are found in long-term observations (≥12 years) at multiple locations along the tidal Hudson River
- In the tidal freshwater, turbidity for a given discharge increased for 2 years following major discharge events and sediment input in 2011
- In the saline estuary turbidity hysteresis was less apparent, consistent with greater background sediment concentrations and availability

Abstract

Non-linear turbidity-discharge relationships are explored in the context of sediment sourcing and event-driven hysteresis using long-term (≥12 year) turbidity observations from the tidal freshwater and saline estuary of the Hudson River. At four locations spanning 175 km, turbidity generally increased with discharge but did not follow a constant log-log dependence, in part due to event-driven adjustments in sediment availability. Following major sediment inputs from extreme precipitation and discharge events in 2011, turbidity in the tidal river increased by 20-50% for a given discharge. The coherent shifts in the turbidity-discharge relationship along the tidal river over the subsequent 2 years suggest that the 2011 events increased sediment availability for resuspension. In the saline estuary, changes in the sediment-discharge relationship were less apparent after the high discharge events, indicating that greater background turbidity due to internal sources make event-driven inputs less important in the saline estuary at interannual time scales.

Plain language summary

Turbidity is a widely accepted proxy for suspended sediment concentration and an important factor for contaminant transport and water quality. Here we show that turbidity depends on river discharge in long-term observations at multiple locations in an estuary. Such relationships are often used in rivers, but have not been commonly used in estuaries and tidal rivers, where tides and salinity also contribute to variability. Turbidity in the freshwater tidal region was more sensitive to discharge than in the saline estuary. Massive inputs of sediment due to extreme precipitation and flooding in 2011 resulted in increased sediment availability in the tidal river over multiple years. Turbidity throughout the tidal river was elevated for 2 years following the events, but changes were not apparent in the saline estuary. The observations provide guidance on recovery time scales for estuaries and tidal rivers to event-driven sediment inputs, which affects the delivery of material from the watershed to the coastal ocean as well as other impacts relating to water clarity.

1. Introduction

Due to the challenges in continuously monitoring suspended sediment concentration (SSC), SSC and sediment discharge in rivers are often empirically related to volumetric freshwater discharge (Helsel and Hirsch 2002). Volumetric discharge varies by orders of magnitude at event and seasonal time scales, and it is the dominant factor controlling variability in sediment discharge. Sediment discharge increases nonlinearly with volumetric discharge, commonly increasing to approximately the cube of river discharge at high flow (Nash 1994; Syvitski et al. 2000). Consequently, large, relatively infrequent events disproportionately contribute to cumulative sediment discharges.

Sediment-discharge rating curves are often treated as static, and yet variability in precipitation patterns, vegetation, land use, and tectonic activity can all affect sediment delivery and sediment-discharge relationships (Walling 1977; Morehead et al. 2003; Warrick and Rubin 2007; Yellen et al. 2016). Disturbance from extreme floods can increase sediment concentrations for months to years as rivers adjust to bed incision and landslide scarps revegetate (Warrick et al. 2013; Dethier et al. 2016; Ahn et al. 2017; Gray 2018). The duration and timing of low-discharge conditions can also affect in-stream storage and SSC during subsequent higher discharge periods (Walling et al. 1998; Gray et al. 2014). The sampling frequency can also contribute to uncertainty or introduce bias into measurement of sediment discharge (Coynel et al. 2004).

Rivers supply sediment to coastal regions, where tides, waves, and density-driven circulation also play central roles in sediment transport. In estuaries, salinity gradients drive landward near-bottom circulation that leads to sediment trapping and regions of higher sediment concentration, or estuarine turbidity maxima (ETMs) (Postma 1961; Burchard et al. 2018). River discharge alters sediment input from the watershed but also affects the salinity distribution, and thus the location and magnitude of sediment trapping at seasonal and event time scales. Tidal currents also contribute to variability in SSC, directly through sediment resuspension and indirectly by affecting the salinity distribution. In the tidal freshwater part of an estuary, tidal resuspension and sediment supply from the river are the key factors in SSC variability (Dalrymple and Choi 2007; Ralston and Geyer 2017). Tidal freshwater regions provide crucial links in the movement of material to the coastal ocean, and yet they have received less study than fluvial or estuarine environments (Hoitink and Jay 2016).

This study uses long-term (≥12-year) observations to characterize turbidity-discharge relationships in a tidal river and estuary, including the response following sediment inputs from major discharge events. Because it is easier to measure, turbidity is often used as a proxy for SSC (Yellen et al., 2014; Ahn et al., 2017), and turbidity has been shown to correlate well with SSC in the tidal river (Ralston and Geyer 2017) and within the watershed (McHale and Siemion 2014). In late summer 2011, tropical cyclones Irene and Lee delivered intense precipitation over much of the U.S. Northeast, increasing discharge and sediment delivery. In the Delaware estuary, sediment input of 1.4 Mt in two weeks was similar to the long-term annual average, and SSC in the ETM remained elevated for several months (Sommerfield et al. 2017). In the Connecticut River estuary, input from Irene of 1.2 Mt was twice the annual average, and the sediment-discharge relationship in the tidal river was elevated for the following 2 years compared to before the storm (Yellen et al. 2014). In the Hudson River estuary, sediment input from Irene and Lee was about 2.7 Mt, more than twice the annual average (Wall et al. 2008; Ralston et al. 2013). The events increased turbidity in the months following the events, but the response to this sediment input has not been examined at longer time scales. In this study we use long-term monitoring data to assess the turbidity-discharge relationships at multiple locations along the tidal Hudson River and quantify the time scales over which the discharge events altered turbidity in the system.

2. Methods

2.1 Site description

The Hudson River estuary extends about 265 km from the Atlantic Ocean to tidal limit at Troy (NY). Along-estuary distances in the Hudson are typically reported with respect to The Battery in New York Harbor as 0 river km (rkm), but The Battery is located about 25 km landward of the natural mouth between Sandy Hook and Rockaway Peninsula. The tidal range averages about 1.5 m at the mouth, decreasing to 1 m mid-estuary and increasing to 1.5 m at the head of tides (Ralston et al. 2019). The salinity intrusion varies from about 40 rkm during high river discharge to 120 rkm during low discharge (Bowen and Geyer 2003; Ralston et al. 2008).

The primary ETM in the Hudson is located near 20 rkm, formed by bottom salinity fronts associated with a constriction (Geyer et al. 2001; Traykovski et al. 2004). During moderate and low discharge, a secondary ETM forms near 55 rkm (Nitsche et al. 2010; Ralston et al. 2012). In the primary ETM, near-bottom sediment concentrations can exceed 1 g L^{-1}, and concentrations are greater than 100 mg/L in much of the saline estuary. In the tidal river, sediment concentrations are generally less than 100 mg L^{-1} and vary with river discharge and tidal forcing (Wall et al. 2008; Ralston and Geyer 2017). Sediment inputs come from the two largest tributaries, the Mohawk and Upper Hudson Rivers, which converge just above the tidal limit. Numerous smaller tributaries also discharge into the tidal Hudson, cumulatively increasing the sediment load by 30-70% (Wall et al. 2008).

2.2 Observations

Turbidity data were collected from monitoring stations located along the estuary. Data were accessed through the Hudson River Environmental Conditions Observing System (www.hrecos.org), which organizes monitoring data from multiple partner organizations, and the Centralized Data Management Office (cdmo.baruch.sc.edu). Monitoring stations were at Schodack Island (212 rkm, available 2008-2019, partner organization Cary Institute of Ecosystem Studies), Tivoli North Bay (156 rkm, 2000-2019, Hudson River National Estuarine Research Reserve, HRNERR), Norrie Point (132 rkm, 2008-2019, HRNERR), and Piermont (37 rkm, 2008-2019, Lamont-Doherty Earth Observatory) (Fig. 1). Under most forcing conditions, Piermont is in the saline estuary and the other three stations are in the tidal freshwater (Hoitink and Jay 2016).

All stations recorded near-surface turbidity. Time series were processed for quality control based on visual inspection to remove spurious outliers or anomalous trends indicative of instrument fouling. The quality control removed 0.3% to 2.8% of the measurements, depending on the station. The Tivoli North Bay sensor is located in a small channel connecting to a side embayment, so we only used measurements during flood tides. Daily median turbidity values were used to minimize the influence of individual bad measurements on longer term variability. At Tivoli, water samples were collected, filtered, dried, and weighed to measure suspended solids concentration for comparison with turbidity. The regression slope for total suspended solids (mg L^{-1}) was 1.2 times the turbidity (NTU, $r^2 = 0.52$, n = 219). Turbidity sensors at the other stations were not calibrated to SSC, but previous studies in the saline estuary and tidal river have also found calibrations with slopes of around 1 (Ralston et al. 2013; Ralston and Geyer 2017).

Volumetric discharge (Q_r) and sediment discharge (Q_s) measurements were collected from USGS gauging stations on the Mohawk and Upper Hudson. The Mohawk (at Cohoes, #01357500) has volumetric discharge 1917-2019 and sediment discharge 1954-1959, 1976-1979, and 2002-2019. The Upper Hudson (Waterford, 01335770) has volumetric discharge 1887-1956 and 1976-2019, and sediment discharge 1976-2014. Mean daily mean SSC were calculated with $SSC = Q_s/Q_r$.

Turbidity was related to Q_r by locally weighted scattered smoothing, or LOWESS (Cleveland 1979; Helsel and Hirsch 2002). The LOWESS approach has been used for sediment discharge rating curves in rivers, including in trend analyses following discharge events (Warrick et al. 2013; Gray 2018). LOWESS regressions were calculated for log-transformed discharge and turbidity with a smoothing factor of 0.25. A bias correction factor was included to calculate turbidity from discharge using the regression (Ferguson 1986; Cohn 1995), with the form $C = 10^\wedge(C_{out} + \sigma^2/2)$, where C_{out} is the output from the LOWESS regression to $\log_{10}(Q_r)$ and σ^2 is the variance of the residual. The variance of the residual was calculated in fractional subsets of Q_r similar to the LOWESS smoothing factor to account for variability in the regression fit.

3. Results

Over the observation period (2008-2019), Irene and Lee accounted for the highest river discharge and observed turbidity (Fig. 1). The turbidity during and immediately following the 2011 events was greatest in the upper tidal river at Schodack Island, with 1000 NTU during Irene and 500 NTU during Lee. At the other stations in the tidal river, Tivoli North Bay and Norrie Point, turbidity was 200-300 NTU during the events. Increased turbidity was recorded during other high discharge periods, including spring freshets in 2013, 2014, and 2016, but those maxima were less than half than during Irene. In the saline estuary, the Piermont station was not operational during the 2011 events. During other years, the maximum turbidity at Piermont was typically around 100 NTU, with generally higher turbidity during the winter and spring and lower in the summer.

Turbidity from the four stations is plotted against discharge, and all the locations have positive slopes (Fig. 2). At Schodack Island, the turbidity dependence on discharge has a form similar to many rivers (Nash 1994), with a greater slope at higher discharge ($Q_r > 400$ m^3 s^{-1}), and weaker dependence at lower Q_r. Schodack is in a shallow and sandy part of the tidal river (Nitsche et al. 2007; Collins and Miller 2012), so resuspension of fine sediment is limited and turbidity varies strongly with river inputs. The slightly negative slope at low discharge may be an artifact of limited data, or may be due to increased organic particles during summer low discharge (Ralston and Geyer 2017). Farther seaward, at the Tivoli and Norrie Point stations, turbidity increases more gradually with discharge (Fig. 2b,c). Discharge varies annually by about an order of magnitude, and turbidity in the tidal river varies by more than an order of magnitude. The turbidity variability in the tidal freshwater river is greater than that in the saline estuary, where the annual range typically spans a factor of 2-3 (Bokuniewicz and Arnold 1984; Ralston et al. 2012; Ralston and Geyer 2017). Correspondingly, the turbidity-discharge regression at Piermont has a narrower range than those at the upstream tidal river stations, and discharge dependence is weaker (Fig. 2d). The LOWESS fits between discharge and turbidity at the tidal river stations had higher correlations ($r^2 = 0.42$ at Schodack, 0.24 at Tivoli, and 0.19 at Norrie) than at Piermont in the saline estuary ($r^2 = 0.12$).

Scatter in the turbidity-discharge relationships is due to the many processes that affect turbidity in addition to discharge. Tidal amplitude affects sediment resuspension, and residuals in the LOWESS fits were positively correlated with tidal amplitude at all four locations, but the correlations were weak ($r^2 < 0.005$ at the tidal river stations and $r^2 = 0.02$ at the estuarine Piermont station). Sediment resuspension and trapping can also vary with the salinity distribution, wind, and bed sediment properties. Lags in sediment transport can be weeks to months (Ralston and Geyer 2009; Ralston and Geyer 2017), distorting the correspondence between the daily discharge and turbidity along the estuary. Antecedent discharge conditions affect sediment availability in the estuary, with fine sediment accumulating during higher discharge and subsequently increasing tidal resuspension, potentially changing the relationship with daily discharge (Wall et al. 2008).

To evaluate whether inputs from Irene and Lee affected sediment availability in the estuary and thus turbidity over longer time scales, the turbidity vs. discharge relationship is considered on a yearly basis. Turbidity time series are segmented by water year (October 1-September 30) to reflect the seasonality of higher discharge in the late fall, winter, and spring and lower discharge summer. As an example, observations for individual years are shown for Tivoli North Bay and compared to the regression for the entire record (Fig. 3). Clustering of median daily observations above or below the LOWESS fit of the full 12-year record represents a shift in the turbidity-discharge relationship. Increased sediment availability following Irene and Lee corresponds to higher than average turbidity (for a given discharge) in 2012 and 2013, as well as a few anomalously high turbidity observations during water year 2011 (Fig. 3d,e). In contrast, turbidity tends to be less than the long-term regression for most discharge conditions in 2015 (Fig. 3g).

Over the turbidity observation period, the combined annual average discharge from Upper Hudson and Mohawk Rivers varied by almost a factor of 2, from 350 $m^3 s^{-1}$ to 650 $m^3 s^{-1}$, and the maximum combined daily discharge varied by about a factor of 3, from 1460 $m^3 s^{-1}$ to 4460 $m^3 s^{-1}$ (Fig. 4a). Annual sediment inputs from the rivers were calculated based on observed discharge and regressions to long-term sediment discharge observations (Ralston et al. 2020), since the direct measurements of sediment discharge did not span the full period (Fig. 4b). The most notable variability in sediment inputs over this period was the large increase from the Mohawk with the storm events in 2011.

Annual averages of turbidity in the tidal freshwater and saline estuary varied by about a factor of 2 over the same period (Fig. 4c). The interannual variability in average turbidity is in part due to variation in river discharge, with higher turbidity during years with greater average discharge. However, the goal here is to assess whether hysteresis in the turbidity-discharge relationship may also contribute. To quantify this, we calculate the annual average of the ratio of the measured turbidity to that predicted by the turbidity-discharge regressions shown in Fig. 2. This turbidity ratio represents the factor by which the turbidity differed from the long-term regression, accounting for interannual variations in discharge (Fig. 4d). Discretization at semi- and quarter-annual intervals was also examined, with similar (but noisier) results.

Similar interannual variation in turbidity relative to the long-term regression was observed among the three tidal freshwater stations (i.e. Schodack, Tivoli, and Norrie Point), despite separation of about 80 km and differences in local bed sediment. In 2012 and 2013, turbidity at all 3 locations was greater than expected based on the long-term regression, by factors of about 1.4 at Schodack, 1.3 at Tivoli, and 1.5 at Norrie. In 2010 and prior years, the turbidity factors were close to or less than 1 at all three stations. The turbidity factor increased at Tivoli and Norrie Point in 2011, but this could be due to large sediment inputs from tributaries near these stations during Irene and Lee at the end of 2011 water year (Ralston et al. 2013). After 2013, the turbidity ratios returned to values similar to 1, representing a return to long-term average conditions, with values less than 1 before and after 2011-2014 potentially explained by the long-term regression including the elevated turbidity from Irene and Lee. Average turbidity in the tidal river thus depended both on Q_r that year and on hysteresis in the turbidity-discharge relationship. For example, the mean Q_r in 2012 (390 $m^3 s^{-1}$) was less than average (460 $m^3 s^{-1}$), and yet the average turbidity that year was the second highest overall (Fig. 4c). In 2013 the turbidity increased in part because the discharge increased, but also because of the above-average turbidity-discharge relationship (Fig. 4d).

Another approach to characterizing the temporal variability in the turbidity-discharge relationship is to calculate the slope of the cumulative residual between the observed and predicted turbidity (Gray 2018). Periods when observed turbidity was greater than expected have a positive slope for the cumulative residual, and periods with turbidity less than expected have a negative slope. Results using the cumulative residual slopes were consistent with the turbidity ratios, with positive slopes during years with turbidity ratio greater than 1 and negative residuals for turbidity ratios less than 1 (Suppl. Fig. 1). Similarly, the cumulative residual slopes at the tidal river stations were maximum in 2012 and 2013, after Irene and Lee, and decreased to zero or negative values in 2014 or 2015.

The temporal variability in the turbidity-discharge relationship was coherent among the freshwater tidal stations, but observations in the saline estuary did not exhibit the same interannual response (Fig. 4c). For example, the turbidity ratio at Tivoli was strongly correlated with that at Norrie Point (r^2 = 0.93, p<0.001, n=11) and had a weaker correlation with Schodack Island (r^2 = 0.63, p=0.028, n=12), but the correlation with Piermont in the saline estuary was not significant (r^2 = 0.33, p=0.35, n=10). The Piermont station exhibited only a modest increase in the turbidity ratio in 2012 after Irene and Lee (with a data gap in 2013), and in general has less variability in the turbidity-discharge relationship.

The turbidity ratios in the estuary were not significantly correlated with the year-to-year variability in the sediment mass inputs from the Mohawk and Upper Hudson (Fig. 4b). To evaluate the influence of the variability in watershed inputs, we also calculated the residual of the LOWESS regressions of $\log_{10}(SSC)$ vs. $\log_{10}(Q_r)$ for the tributaries on an annual basis. Precipitation from Irene and Lee was focused in the Mohawk watershed and the Catskill Mountains east of the Hudson, leading to mass wasting, increased erosion, and potential hysteresis in the sediment-discharge relationship for these regions (Ahn and Steinschneider 2019). In water years 2012-2014 following the events, the average *SSC* in the Mohawk increased by a factor of about 1.2 above the regression values, but the Mohawk turbidity ratio was not significantly correlated with the turbidity ratios in the estuary. As expected from precipitation patterns during Irene-Lee, the turbidity-discharge ratio for the Upper Hudson did not change post-event.

4. Summary and discussion

Long-term monitoring data allow for characterization of turbidity-discharge relationships in the estuary that might be obscured by variability at tidal to seasonal time scales. In the tidal freshwater, turbidity depended strongly on discharge (Fig. 2). Average residuals between observed turbidity and that predicted from the discharge regressions were coherent among stations in the tidal river, with increased turbidity in the 2 years following tropical storms Irene and Lee (Fig. 4). Similarly, in New England watersheds adjustment time scales for channel morphology following Irene, and for subsequent, smaller discharge events, were found to be 1-2 years (Renshaw et al. 2019). Watershed sediment supply also depends on revegetation of landslides and bank failures, which adjusts at multi-year time scales (Gray et al. 2014; Yellen et al. 2014; Dethier et al. 2016). In the tidal Hudson, variations in the turbidity residuals in the estuary were not directly tied to the interannual sediment inputs from the two largest tributaries, which suggests that increased sediment availability for resuspension in the tidal river led to hysteresis in the sediment-discharge relationship. The similar response among stations separated by 80 km suggests that the increased sediment availability was not limited to a small region or due to localized influence of a particular tributary.

Increased turbidity suggests an increase in SSC, particularly for a fixed particle size distribution. Alternatively, temporal decreases in the dominant particle size could increase turbidity and change the relationship to SSC (Downing 2006). Seasonal variation in the slope between turbidity and SSC of about a factor of 2 has been noted in the tidal Hudson, likely due to changes in particle size with discharge

(Ralston and Geyer 2017). Thus the shift toward higher turbidity ratios may reflect a combination of greater availability and finer grain size following discharge events (Yellen et al. 2016). The contribution of organic material to turbidity also varies seasonally, as on average SPM samples in summer and fall had higher organic fractions than in the first half of the year. However, our averaging of turbidity ratios at annual time scales reduces effects of seasonal variation in the relationship between turbidity and SPM on discharge dependence. Due to the relatively turbid conditions and low light availability, phytoplankton are also not expected to contribute significantly to the turbidity signal (Cole et al. 1992).

The turbidity responses differed between the tidal river and saline estuary, where changes in the turbidity-discharge relationship were less apparent following the discharge events. In the tidal river, SSC tends to be lower and the bed less muddy than in the saline estuary (Nitsche et al. 2007). The sediment available for resuspension at event to seasonal time scales has been termed the mobile sediment pool (Wellershaus 1981; Schoellhamer 2011; Geyer and Ralston 2018). While the size of the mobile pool is difficult to quantify, the persistent increase in turbidity in the tidal river following Irene and Lee suggests that the sediment input from the storms represented a major increase in the size of the mobile pool. Based on sediment flux time series, about 2/3 of the sediment input by the events remained in the tidal river several months after the events (Ralston et al. 2013), and the 2-year period of increased turbidity may be indicative of the time scale for the tidal river to adjust back to pre-storm conditions.

In the saline estuary, turbidity on average is greater, the bed is muddier, and the mobile pool is larger than in the tidal river. Previous studies have highlighted the seasonal to annual variation in SSC and deposition (Geyer et al. 2001; Woodruff et al. 2001). Observations in the lower ETM found that the freshets in 1998 and 1999 each deposited about 0.3 Mt of new sediment, despite large differences in the watershed sediment inputs in those years (Woodruff et al. 2001). This decoupling between deposition in the ETM and the watershed inputs is consistent with the limited variability in the turbidity-discharge residual at Piermont. If the mobile pool in the saline estuary is many times the annual average input, then the fractional increase from Irene and Lee may be minor. Similarly, in San Francisco Bay a decrease in sediment supply associated with dam construction did not affect sediment concentrations until decades later, first in the tidal freshwater Delta and subsequently in the saline estuary (Schoellhamer 2011; Hestir et al. 2013; Schoellhamer et al. 2013). In the Penobscot estuary, the mobile sediment pool was estimated to be 6-8 times the annual average input based on recovery time scales following a contaminant release (Geyer and Ralston 2018).

Differences between the tidal river and saline estuary in the hysteresis of the turbidity-discharge relationships reflect the relative coupling between sediment supply and river discharge. In the saline estuary, the mobile pool is large compared to the annual supply, such that a major discharge event does not drastically increase sediment availability. In contrast, fine grained bed sediment in the tidal river is more limited, so event inputs represent a fractionally bigger change, and turbidity is increased for a couple of years as the added sediment gradually moves seaward and deposits in lower energy shoals and wetlands (Ralston and Geyer 2017; Yellen et al. 2020). For comparison, the hysteresis in turbidity-discharge relationship in the tidal river is similar in duration to observations on steep streams following Irene (Renshaw et al., 2019), but shorter in duration than observed in rivers along the U.S. West Coast, where sediment concentrations remained elevated for 5 years or longer after events (Warrick et al. 2013; Gray 2018). Long-term measurements at stream gauging stations allow for assessment of the variability in turbidity/sediment-discharge relationships in the watershed, but such long-term measurements are far less common in estuaries. These results point to the utility of such measurements for assessing the multiple time scales of sediment variability in other estuaries.

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Figures

Figure 1

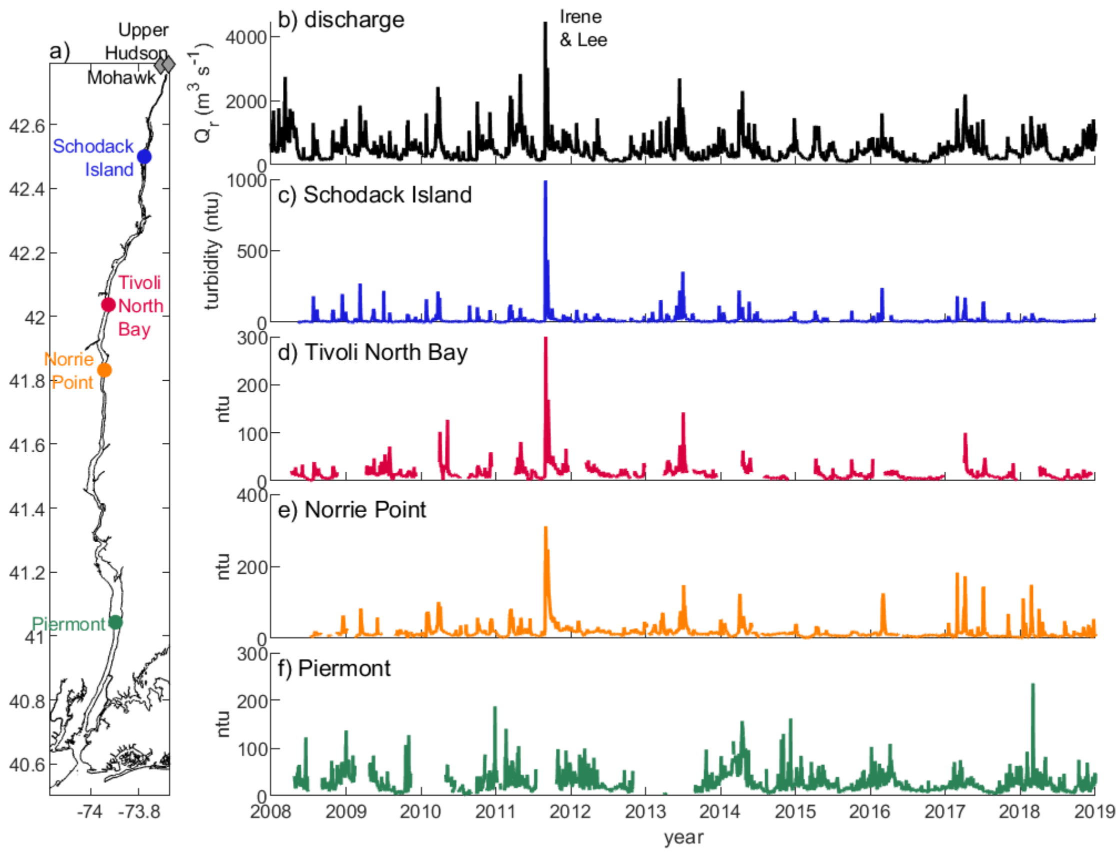


Figure 1. Turbidity at monitoring stations along the estuary. a) Station locations, b) daily average discharge from the Upper Hudson and Mohawk, noting Tropical Storms Irene and Lee in 2011, c-f) daily median turbidity from Schodack Island, Tivoli North Bay, Norrie Point, and Piermont.

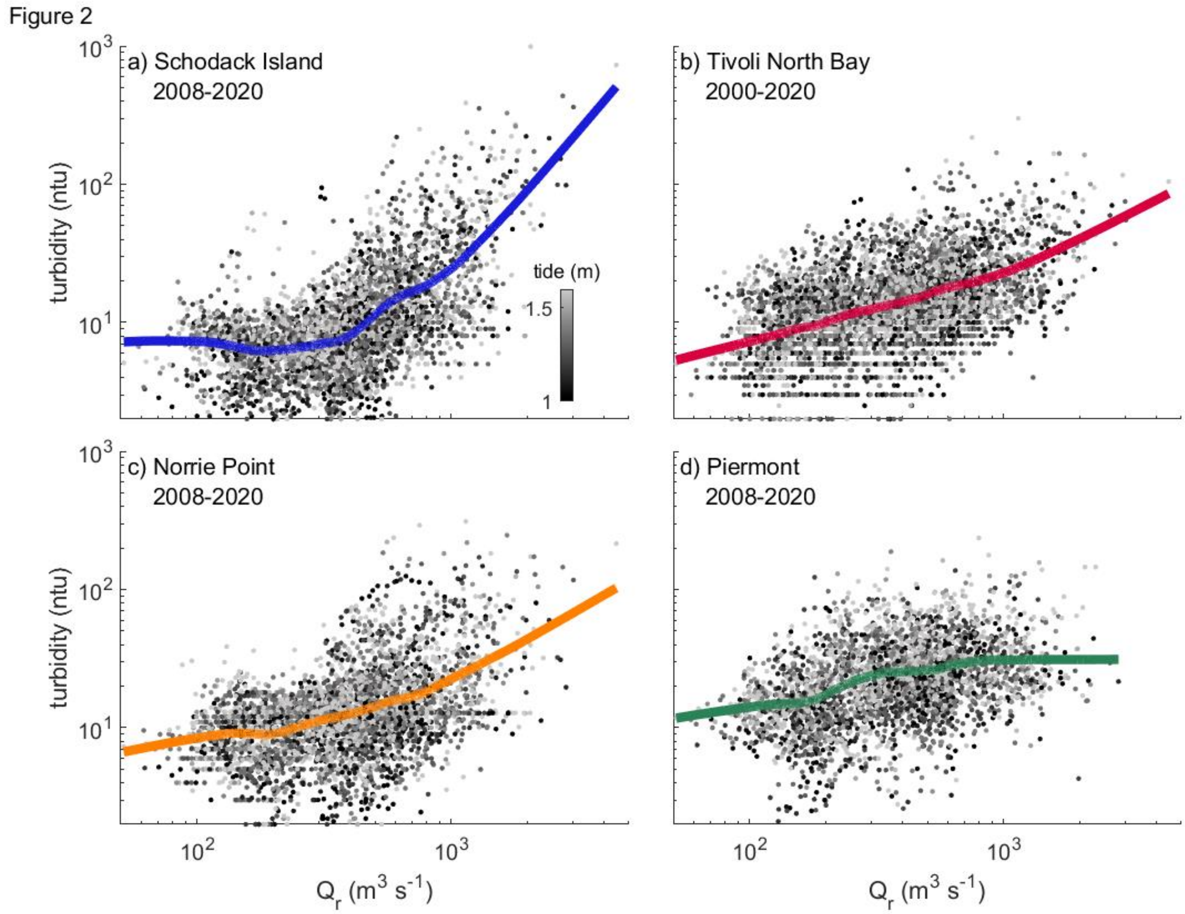


Figure 2. Turbidity vs. river discharge a) at Schodack Island, b) Tivoli North Bay, c) Norrie Point, and d) Piermont. Daily turbidity data are in black and LOWESS regressions are colored. Marker shading represents tidal amplitude based on the tidal water level range at The Battery (NOAA # 8518750), located near the mouth of the Hudson.

Figure 3

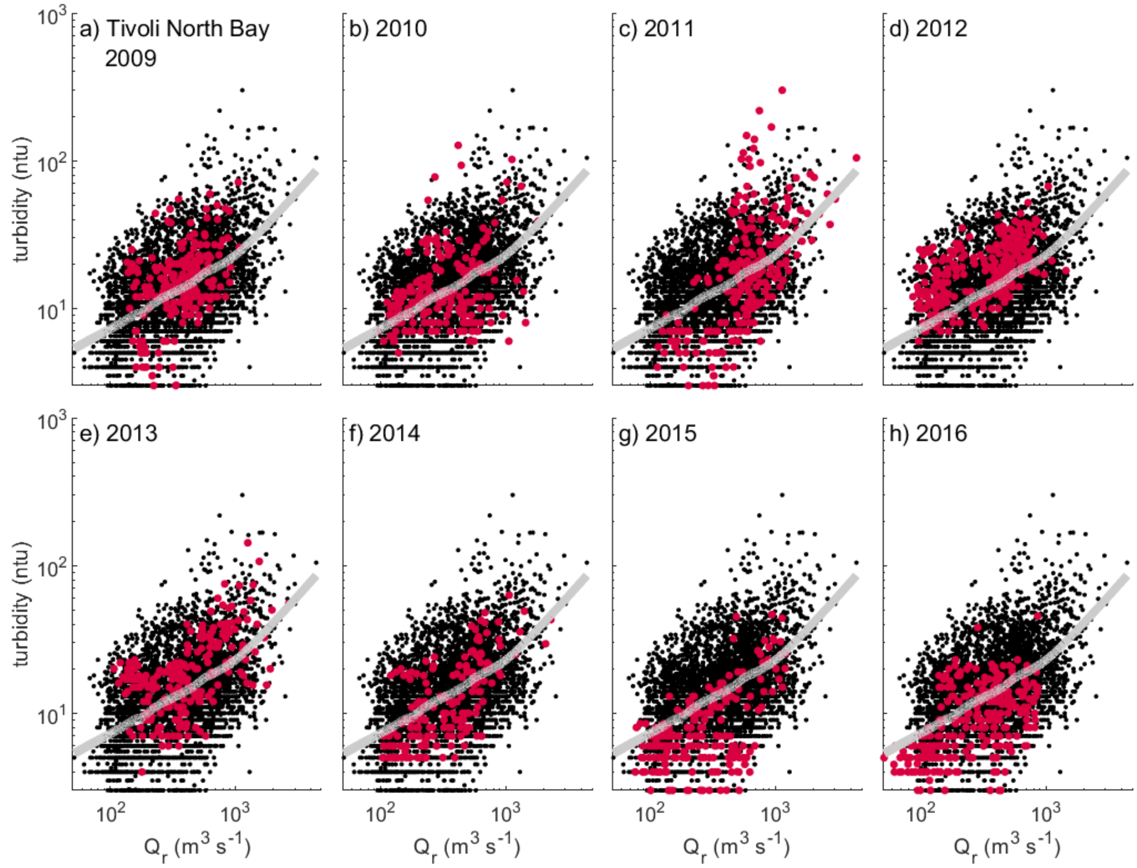


Figure 3. Turbidity vs. river discharge at Tivoli North Bay by water year from 2009 to 2016. The full record is in black, and data for each year are colored. The LOWESS fit to the full record is gray.

Figure 4

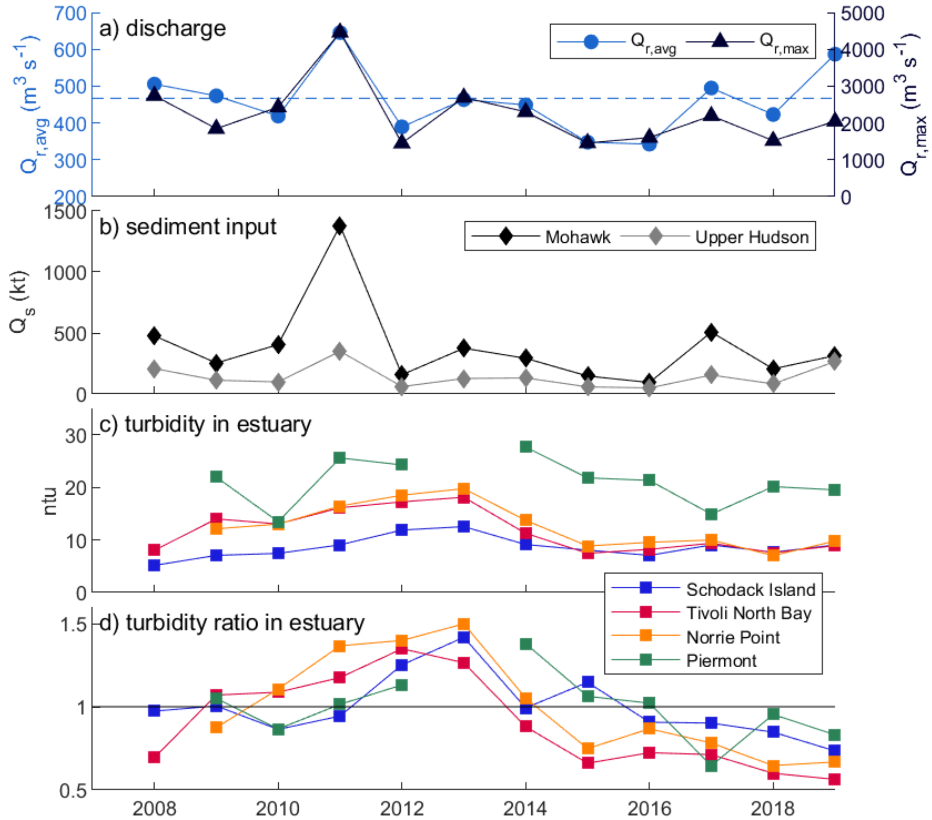


Figure 4. Discharge and turbidity by water year. a) Mean and maximum discharge of the Upper Hudson and Mohawk rivers, b) annual sediment input from the Mohawk and Upper Hudson, c) annual average turbidity in the tidal river and estuary, d) annual average of the ratio of measured turbidity to that predicted by the long-term Q_r regressions (Fig. 2).

S1

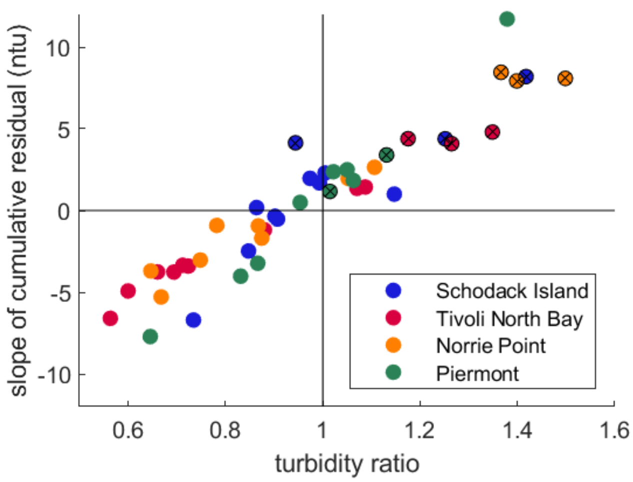
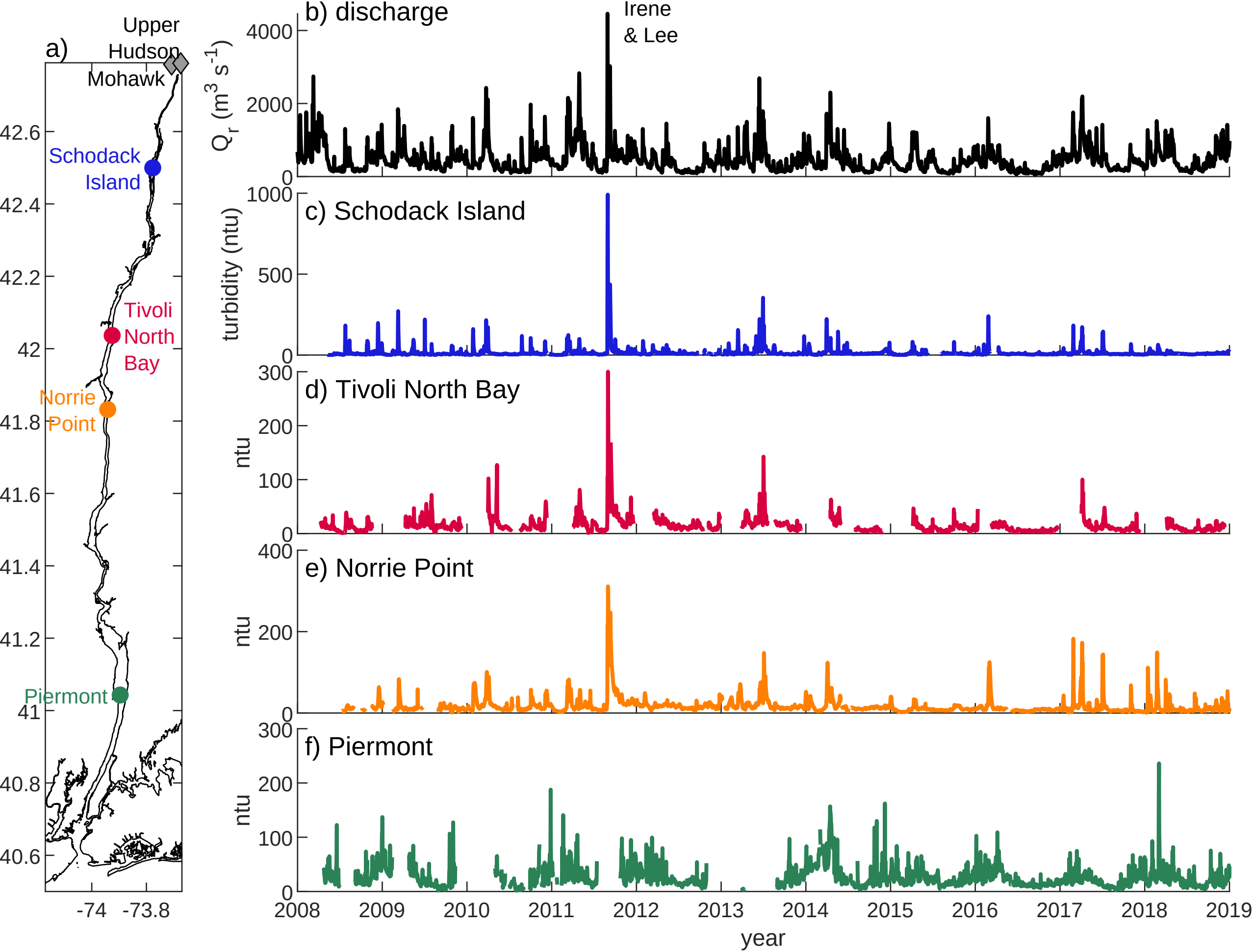


Figure S1. Annual averages of the slope of the cumulative residual vs. turbidity ratio. Turbidity ratio same as in Fig. 4d. Positive slopes and turbidity ratios greater than 1 correspond with years when the turbidity vs. discharge relationship was greater than the long-term regression. The years following Tropical Storms Irene and Lee (2011-2013) are marked with an ‘x’.

Figure 1.



a)
Upper Hudson
Mohawk
Schodack Island
Tivoli North Bay
Norrie Point
Piermont
42.6
42.4
42.2
42
41.8
41.6
41.4
41.2
41
40.8
40.6
-74
-73.8
b) discharge
Irene & Lee
Q_r (m^3 s^{-1})
4000
2000
0
c) Schodack Island
turbidity (ntu)
1000
500
0
d) Tivoli North Bay
ntu
300
200
100
0
e) Norrie Point
ntu
400
200
0
f) Piermont
ntu
300
200
100
0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
year

Figure 2.

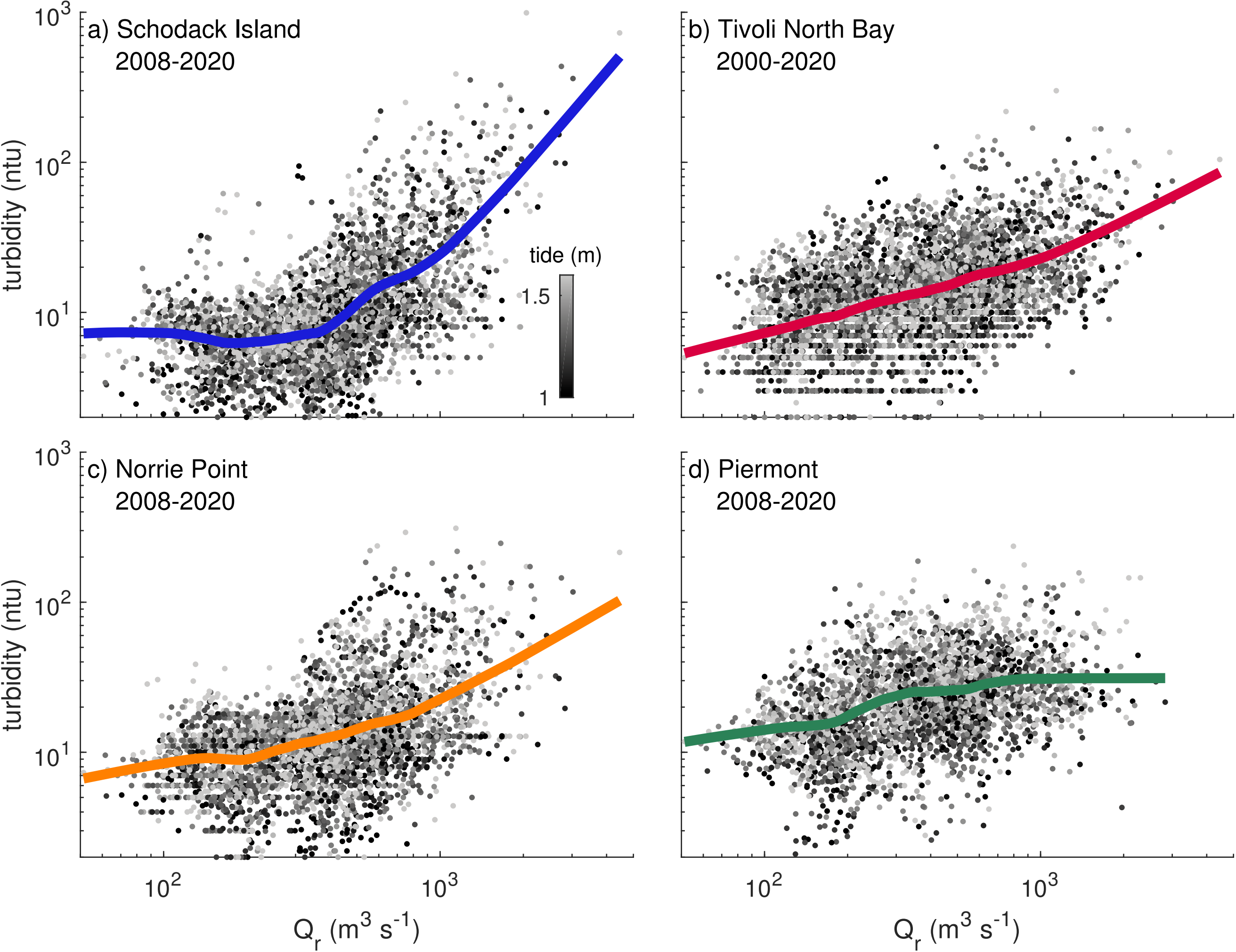
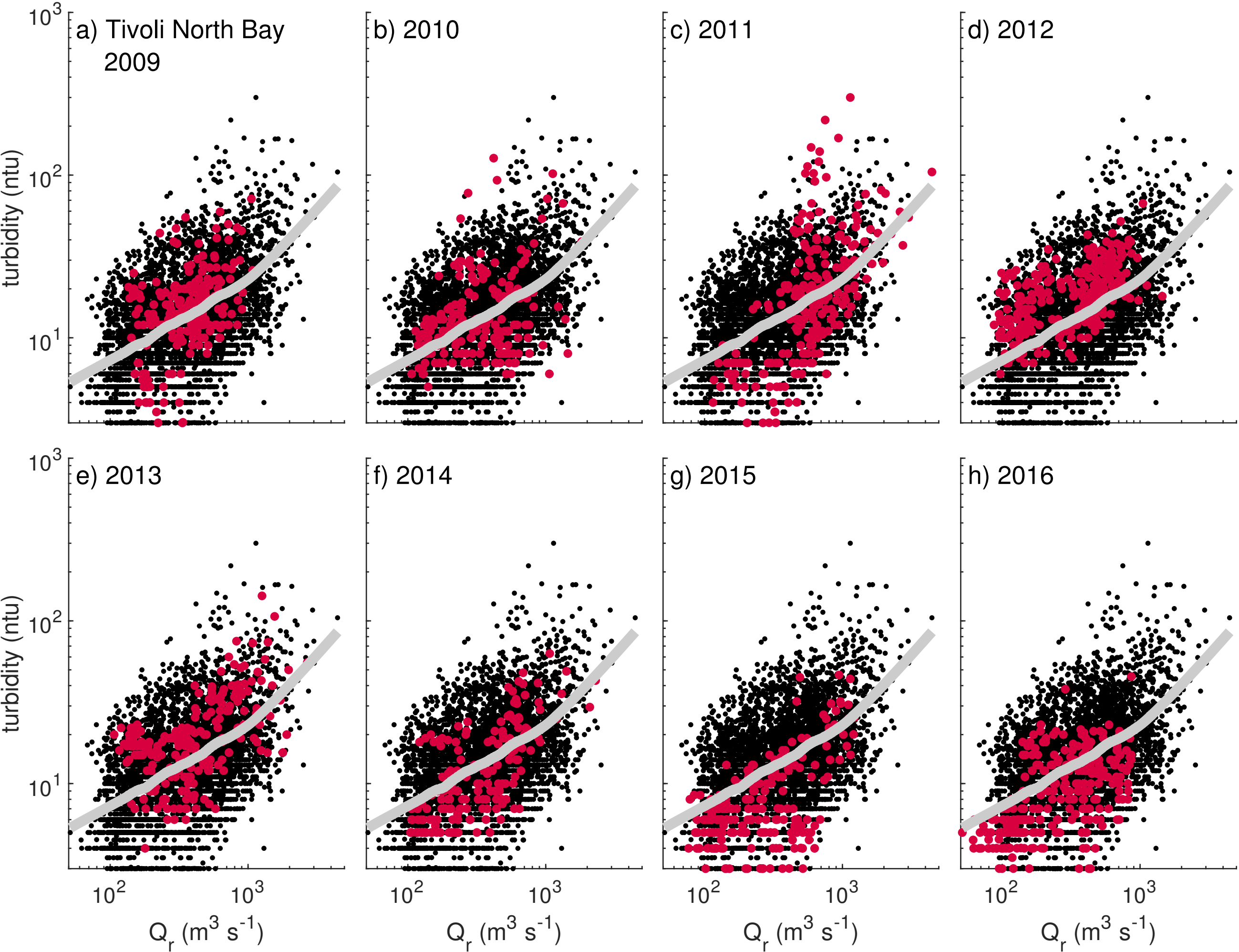
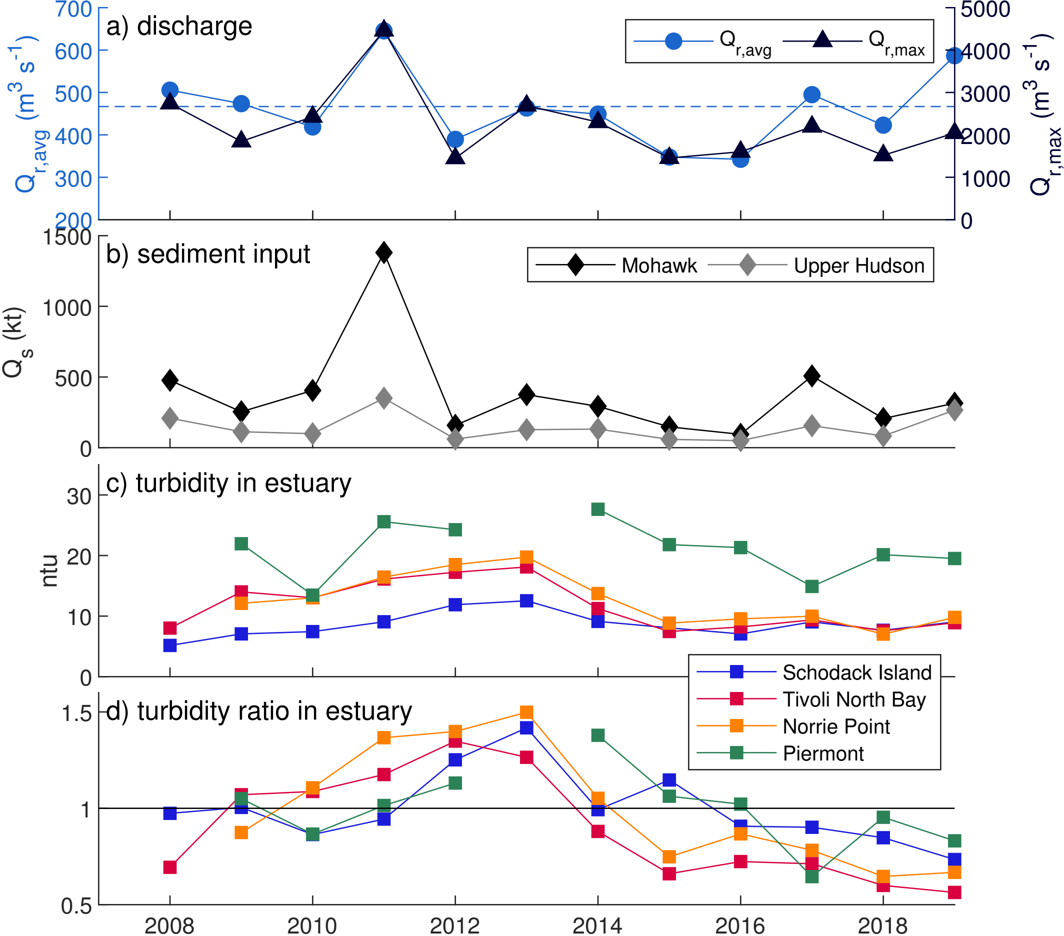

a) Schodack Island
2008-2020
b) Tivoli North Bay
2000-2020
c) Norrie Point
2008-2020
d) Piermont
2008-2020
tide (m)
1.5
1
turbidity (ntu)
10^1
10^2
10^3
Q_r (m^3 s^{-1})

Figure 3.



a) Tivoli North Bay
2009
b) 2010
c) 2011
d) 2012
e) 2013
f) 2014
g) 2015
h) 2016
turbidity (ntu)
turbidity (ntu)
10^3
10^2
10^1
10^2
10^3
Q_r (m^3 s^{-1})

Figure 4.



a) discharge
$Q_{r,avg}$
$Q_{r,max}$
$Q_{r,avg}$ (m^3 s^{-1})
$Q_{r,max}$ (m^3 s^{-1})
700
600
500
400
300
200
5000
4000
3000
2000
1000
0
b) sediment input
Mohawk
Upper Hudson
Q_s (kt)
1500
1000
500
0
c) turbidity in estuary
ntu
30
20
10
0
Schodack Island
Tivoli North Bay
Norrie Point
Piermont
d) turbidity ratio in estuary
1.5
1
0.5
2008
2010
2012
2014
2016
2018