Short-term Sediment Dynamics of Urban Estuaries under Altered Tidal Conditions

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I. Introduction

Estuaries along the Connecticut coast are important ecosystems that provide wildlife habitat and water quality improvement and flood mitigation services (1–3). Many of these estuaries are drowned stream valleys that were formed when the glaciers receded after the last ice age (3). Given the high rate of development along the coast, estuaries are often situated in urban areas (3,4), a condition which is certainly the case along the Connecticut coast of Long Island Sound (Figure 1). Urbanization around estuaries has resulted in the degradation of estuaries as they receive discharge from sewage treatment plants, contaminants in urban runoff, and elevated sediment supply associated with land use changes (3–7). The challenges facing estuaries are amplified by the effects of global climate change as sea levels rise, which is likely to significantly alter estuarine processes (2,8,9). Understanding how development and sea level rise induced changes will impact these processes is essential to maintaining the health of these valuable ecosystems and the services they provide.

Figure 1: Examples of small drowned river valley estuaries (in blue) along the Connecticut coast of Long Island Sound. Note the high levels of urbanization around these estuaries. The study area is circled in red. Data from Connecticut Department of Energy and Environmental Protection (CT DEEP).

Sediment dynamics represents one of the key processes controlling the functioning and health of estuaries. Sediment supply, deposition, and transport influence the health of benthic communities and marsh survival, which are key ecological components of estuarine systems (1,7,10). In addition, sediment is also heavily associated with the chemical and physical processes that drive contamination and water quality issues is estuaries (3,7,11). A study that improves the scientific community's understanding of sediment dynamics will prove useful to managers aiming to restore or maintain estuaries along coastal regions.

Unfortunately, estuaries represent one of the most complex systems to in which to study sediment dynamics as they are influenced by both tidal fluxes and contributions from the watershed, which can vary on time scales from hours to days to weeks and even months or years (3,12). Additionally, the study of Connecticut's urbanized drowned stream valley estuaries is relatively limited (3). A previous study by Benoit and coworkers (2016) developed a robust budget for one such estuary on the Branford River, however, the contribution of tidal flushing was inferred by difference (3). This represents a gap in knowledge of sediment dynamics since tidal mixing is a primary factor controlling circulation in northeastern estuaries (13). Therefore, this study aims to fill this gap by directly measuring and quantifying the influence of the tidal flushing term and watershed contribution in the sediment budget for a small drowned stream valley estuary at time scales ranging from individual daily tidal events, to monthly, along with individual storm events.

II. Project Context

The study discussed in this report exists as a piece of a larger project proposal (West and Mill Experiment) to inform the topic of tidal flushing's contribution to sediment transport in estuaries. In order to give context to the work discussed in this report, I will provide a brief description of the West and Mill Experiment, which will continue under the supervision of my advisor, Professor Gaboury Benoit, with funding from Connecticut (CT) Sea Grant. The essence of this larger study is to compare a control site (The Mill River) with tide gates, to a treatment site (the West River) with self-regulating tide gates (SRTGs), which remain open most of the time. Both systems are located in New Haven, CT. A previous study by Benoit and coworkers (under review) determined that the two watersheds have nearly identical areas, land uses, and other characteristics (Figure 2).

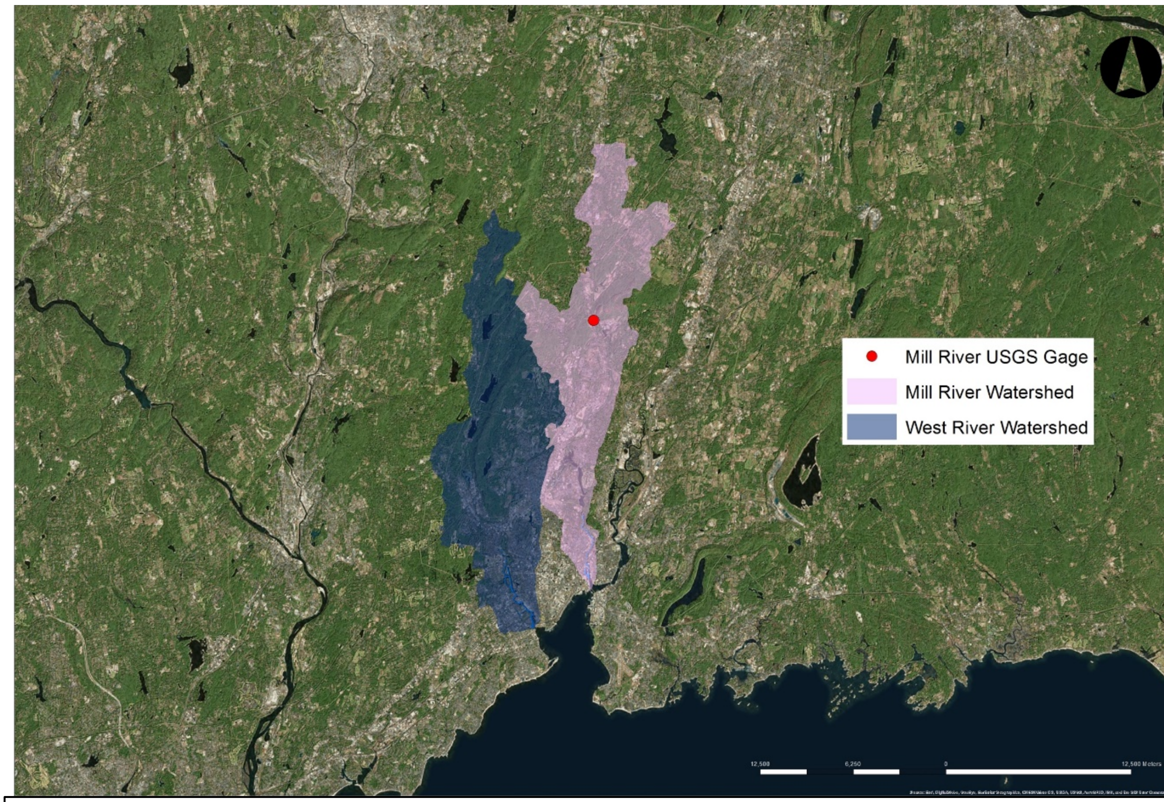

Figure 2: The West River watershed (blue) and Mill River watershed (pink) share nearly identical areas - 28 sq. miles and 25 sq. miles, respectively. They also share similar land use characteristics and are adjacent to one another which means they will likely receive similar rainfall amounts, making them comparable on an event basis. Data from CT DEEP.

The two estuaries share comparable tidal patterns and hydrology, and contain dynamic tide gates that allow controlled alteration of water level and tidal range in each of the systems (Figure 3). The West and Mill Experiment will exploit this feature by conducting a large-scale experiment through tide gate manipulation by opening and closing the SRTGs (see Section III for description of SRTGs). By performing the methods highlighted in Section IV of this report for both estuary systems under altered tidal conditions, the West and Mill Experiment aims to isolate the tidal flux term of the sediment budget. The current study looks only at the West River and its SRTGs.

Even though this report focuses only on work completed in the West River estuary, the results have important scientific and management implications outside of their contribution to the West and Mill Experiment. This includes an understanding of tidal flux relative to watershed contribution for sediment inputs to a small drowned stream valley estuary. Also, since the West River system has been the subject of an ecological restoration effort (installation of SRTGs), this study provides a valuable evaluation of such an effort. Understanding how low-impact tide gate designs perform and influence sediment transport will be useful for managers seeking to (1) protect communities from flooding as sea levels rise (14) and (2) retrofit existing tide gates to restore ecological functioning, which is the case for many municipalities along Connecticut's coast (15–17).

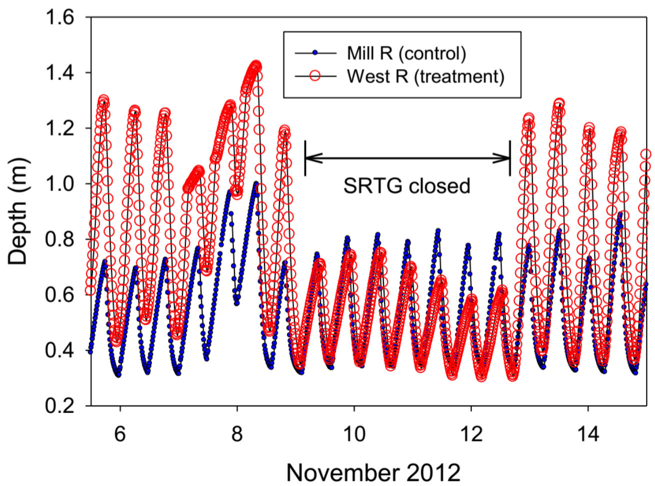

Figure 3: Unpublished data by Benoit and coworkers demonstrating utility of tide gate manipulation

The hypotheses associated with this study are:

H1: West River estuary behaves as a leaky sediment trap (i.e. a fraction of the sediment deposited is released)
H2: West River estuary is a less efficient leaky sediment trap during storm events than during baseflow
H3: Tidal flushing term is more important than watershed contribution term in the sediment budget of the West River estuary during baseflow
H4: Tidal flushing term is more important than watershed contribution term in the sediment budget of the West River estuary during storm events

III. Study Site – West River Estuary

The West River estuary forms the boundary between the towns of West Haven and New Haven, CT, located in South Central Connecticut. The watershed of the West River is 73 km^2 and consists of mostly mixed urban and residential land use. This area receives slightly higher annual precipitation than the Connecticut state average of 114 cm. Runoff from the watershed eventually reaches the West River, enters the estuary, and discharges into New Haven Harbor, where it mixes with the larger Long Island Sound. The West River estuary is influenced by semidiurnal tides, receiving two high tides and two low tides per day.

In addition to being similar to the Mill River estuary (see Section II), the West River shares characteristics with close to 20 other estuaries in Connecticut. The fact that the West River estuary is integrated into the urban fabric of New Haven and West Haven makes it representative of estuaries around other Connecticut municipalities including: Pawcatuck/Westerly, Groton/New London, Branford, Milford, Stratford, Bridgeport, Norwalk, Stamford, and Greenwich.

A somewhat unique but important aspect of the West River system is that it has tide gates installed near its mouth. The original tide gate system consisted of 12 large wooden flap valves that open, allowing flow out of the estuary during the ebb tide but close, blocking flow into the estuary during the flood tide (Figure 4). This system significantly changed the environmental conditions of the estuary upstream of the tide gates as it was converted from salt to fresh tidal, and reducing the tidal range by about a factor of two. In addition to salinity, the tide gates altered water flows, sediment transport, and chemical processes within the estuary, which added to the detrimental ecological impacts of urbanization on the system (15). In Fall 2012, the City of New Haven and Save the Sound sought to mitigate some of these impacts by replacing three of the flap tide gates with SRTGs (Figure

4). The three SRTGs on the West River, remain open during flood tides except during extreme storm surge events, a regime which has re-established salt water tidal flushing of the system and restored salinity levels in the estuary.

Figure 4: SRTG system on the West River – Left photo shows perspective on downstream (harbor side) of SRTG (i.e. those with orange floats) and traditional wooden flap tide gates. Right photo shows perspective on upstream (river side) of SRTG. Blue gate valves on right side of photo show means of manually closing SRTG (photo credit: Laura Green)

Professor Gaboury Benoit, in conjunction with other School of Forestry and Environmental Studies (FES) faculty have performed prior water quality and hydrologic studies on the West River estuary both before and after SRTG installation, which provides the valuable opportunity to evaluate a restoration project years after completion (18). The current report will contribute to this effort by characterizing the impact on short term sediment transport in the estuary. The SRTG system also provides a useful hydrogeological locus, a pinch point at which to monitor estuarine processes in general. The three SRTG are essentially 4 ft. (1.22 m) diameter steel pipes, which allow relatively easy and uniform measurements to be taken across this section of the estuary. By performing continuous monitoring at this point in the estuary, this study is able to accurately quantify the flux of water and sediment both in and out of the estuary during the diurnal flushing events.

IV. Methods

To quantify the flux of sediment into and out of different compartments of the West River estuary at a variety of short time scales, it is necessary to utilize accurate and continuous river discharge measurements and total suspended sediment concentrations (TSS). To complete the sediment budget for the West River estuary, these measurements were taken at the inlet and the outlet of the estuary (Figure 5). The inlet is defined as the point where the river discharges into the estuary (i.e. there are no tributaries entering further downstream and the system is not tidal). Monitoring at the inlet represents the watershed contribution to the sediment budget. The outlet is defined as the location of the SRTG system. Flux across the tide gates downstream towards the harbor represents flux out of the estuary and flux across the tide gates upstream represents flux into the estuary. Detailed methods for measuring discharge and sediment fluxes at each of these end points are described below.

Figure 5: Monitoring locations at the inlet (green) and outlet (red) of the West River estuary

River Discharge – Inlet

River flow into the estuary was measured continuously at 5 minute intervals from May 2017 until December 2017. A 1 m long stream gage was attached to a metal U-post and installed into the streambed in the channel. A Solinst Levelogger was attached to the base of the U-post with zip ties and programmed to record water level every 5 minutes. In order to relate depth measurements to discharge, a rating curve was developed by taking manual flow measurements across the channel via the mid-point method (19) and an acoustic Doppler flow meter (Marsh-McBirney, Inc., FLO-MATE 2000) to measure velocity. After taking measurements during both the spring's high flows and the summer's low flows, a robust rating curve was established (Figure 6), which allowed for the calculation of discharge based on the continuous depth measurements.

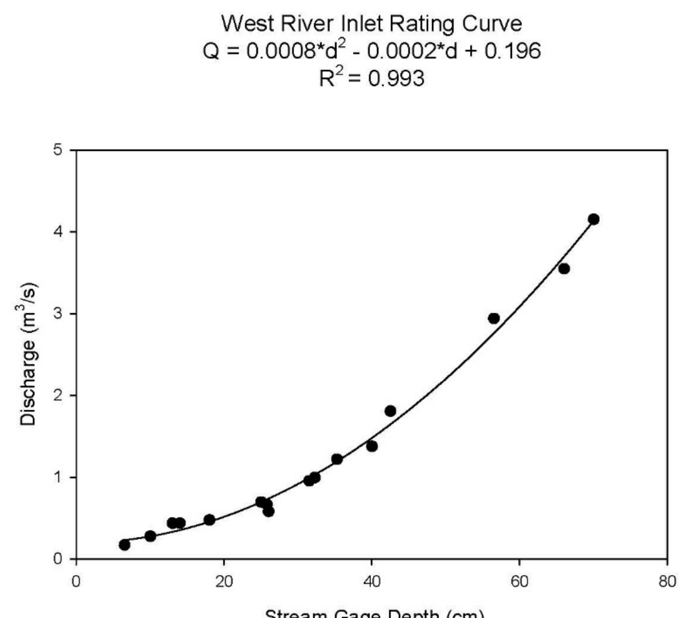

Figure 6: Rating curve relating depth to discharge for the stream gage at the inlet to the West River estuary

While flow at the inlet is not tidal, the water level is influenced by the tides. During high tide, the water level backs up but velocity decreases and therefore net flow remains the same. All rating curve measurements were taken during low tide periods since this would represent the baseflow water level. Subsequently, all water level measurements influenced by high tide were adjusted using a best fit algorithm in MATLAB (20) (Figure 7). We interpolated net flows less the tidal elevation changes. This allowed calculation of net discharge from all water level measurements and continuous discharge monitoring at 5 minute intervals at the inlet.

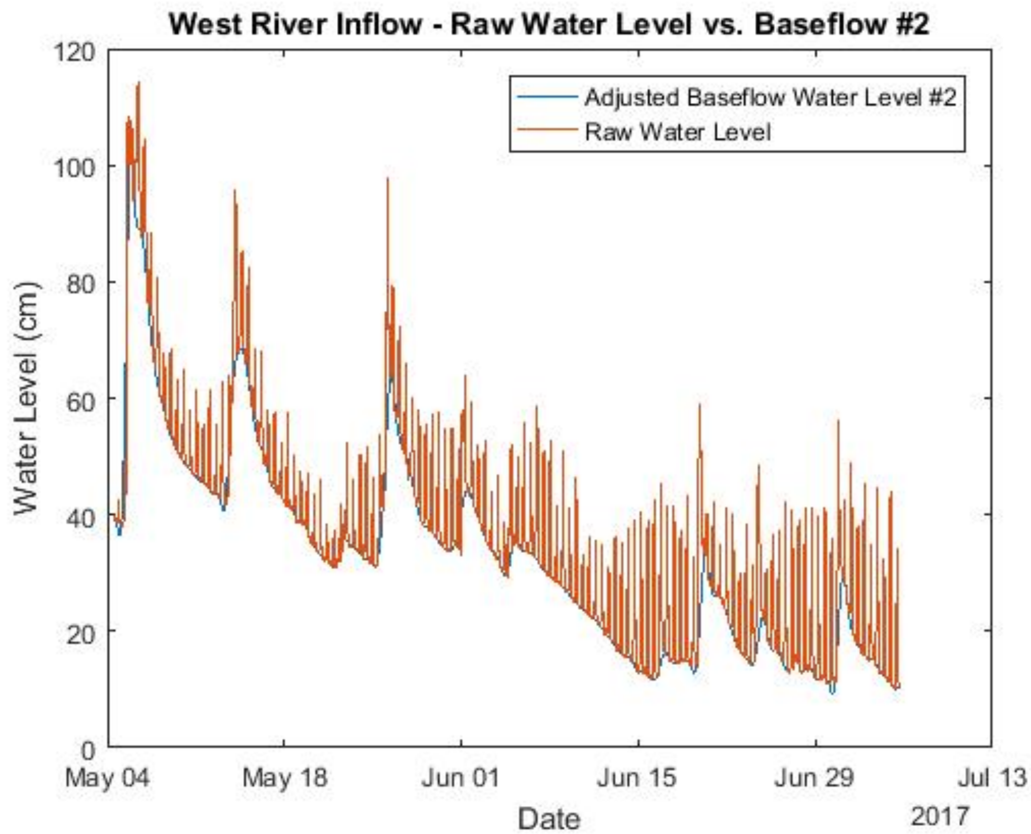

Figure 7: Results of MATLAB program to correct for tidal influence of water depth at inlet

River Discharge – Outlet

Flow across the tide gates (i.e. into and out of the estuary) was measured using a Starflow Doppler Flowmeter (Unidata, Model 6526H). Independent laboratory studies have shown these instruments to be accurate, and the best available measurement technology (21) from June 2017 through December 2017. A Starflow instrument was installed in one of the steel pipes associated with the SRTG via the manufacturer supplied bracket. The instrument was installed slightly up the side of the pipe due to the bottom being inaccessible because of the presence of water. This location also helps to avoid dislodgement by current-borne debris, and is recommended by the manufacturer. This adjustment, which causes a slight offset in depth, was accounted for in all subsequent data analysis.

The Starflow measured depth and velocity values at 3 minute intervals and logged the average of all measurements taken over each 15 minute period. Velocity measurements could be positive (flow into the estuary) or negative (flow out of the estuary). Total discharge in the SRTG pipe was calculated by multiplying the average velocity measurement by the cross sectional area of the pipe associated with the average depth measurement. This value was multiplied by three (3) to calculate the total discharge across all SRTGs.

During the flood tide the flow across the flap tide gates into the estuary was assumed to be zero. However, during the ebb tide flow out of the estuary through the flap tide gates must be accounted for. This was calculated by using the ratio of total cross sectional area between the flap tide gates and the SRTG and multiplying the SRTG flow by this ratio. In order to confirm the accuracy of this method a tidal prism analysis is currently underway.

Water Quality Measurements – Inlet and Outlet

At both the inlet and the outlet, continuous turbidity and conductivity measurements were taken at 15 minute intervals from August 2017 through December 2017. Measurements were completed with YSI 6920 sondes that were submerged in the water column. At the inlet, the sonde was fastened with zip ties to the same metal U-post as was used to mount the stream gage. At the outlet, the sonde was fastened to the concrete wall of one of the tide gates with metal mending plates and hose clamps. Data was retrieved from the sondes at monthly intervals and the sondes were recalibrated at the beginning and end of each deployment.

In preliminary analyses presented here, turbidity was correlated to TSS through the approximate relationship of 1 NTU = 1 mg/L TSS, which is based on existing studies (G. Benoit, unpublished data for the West River). This relationship is being confirmed as grab samples are collected and analyzed for TSS, which is then correlated to the associated turbidity measurement from the sonde.

TSS was measured by taking water column samples of volumes about 300 mL at both the inlet and the outlet. Water column samples were taken manually or with an ISCO 3000 autosampler. Samples were processed within 24 hours of collection. A known volume (V) of each sample was filtered through a pre-weighed (M_1) 45 µm filter. The filter was then dried and re-weighed (M_2). TSS was calculated as $(M_2 - M_1)/V$ in mg/L.

Sediment Flux and Budget

Sediment flux at the inlet and the outlet was calculated by multiplying the measured flow rate (m^3/s) by the TSS concentration inferred from the turbidity data (mg/L). Unit conversions (e.g., 1000 L/m^3) were employed to calculate continuous sediment flux in kg/min at the inlet and the outlet. The information was used to develop sediment budgets at the various short-term time scales discussed in Section I.

Beryllium-7 Analysis

In addition to the continuous monitoring efforts described above, this study also includes using Beryllium-7 (^7Be) as a sediment pulse tracer throughout the estuary. ^7Be is a short-lived radioisotope (half-life of 53.3 days) that is added as a pulse from the atmosphere during storms and sorbs quickly to particles, which makes it ideal for studying short-term sediment processes in estuaries (3,12,22–25). The study on the Branford River estuary by Benoit and coworkers (3) used this method, but the tidal flushing term was inferred by difference (Figure 8). This study aims to shed light on this tidal exchange value by quantifying the contribution of ^7Be from the atmosphere and the watershed while also measuring the loss associated with tidal flushing.

In order to quantify the ^7Be contribution from each compartment, measurements were taken on precipitation (atmospheric contribution) and the water column at the inlet (watershed contribution) and water column at the outlet (tidal flux in and out of estuary) at multiple times during storm events.

Precipitation was collected on the roof of the Yale University Environmental Science Center (ESC roof) located at 21 Sachem St., New Haven, CT (lat 41.315994, long -72.921820). Collection was in a HDPE 76 cm x 76 cm x 10 cm (L x W x D) tray elevated 1 m above the roof surface (25). 10% HNO_3 was added to the tray prior to deployment to prevent adsorption. The collected precipitation was processed at approximately monthly intervals.

Baseflow water column samples were taken at various times throughout the tidal cycle at both the inlet and the outlet during baseflow conditions. Storm event water column samples were taken at 72 minute intervals throughout a tidal cycle before, during, and after a storm event. Water column samples at the inlet were collected with 18 L HDPE jerry cans by wading to the center of the channel and submerging the mouth of the container about midway down the water column (approximately 0.5 m in depth, maximum). Water column samples at the outlet were collected through use of an ISCO 3000 autosampler that collected 24 1.0 L samples at 3 minute intervals. These samples were combined into one composite sample for analysis. Prior to processing for ^{7}Be analysis, water column subsamples were processed for TSS (see above).

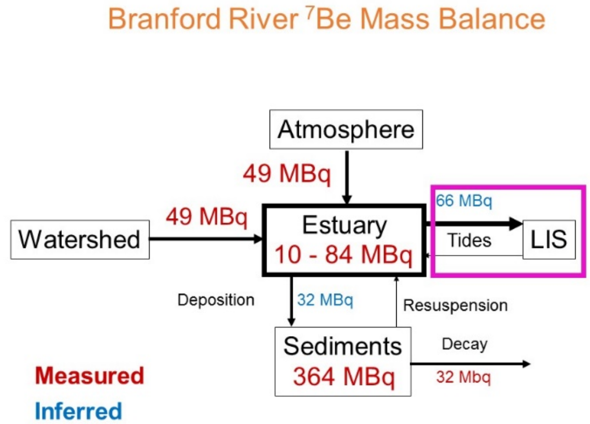

Figure 8: ^{7}Be mass balance from the study in the Branford River estuary by Benoit and coworkers. This report will contribute to directly measuring and quantifying the inferred tidal flushing term in this budget (term within magenta box).

Water samples (precipitation and water column) were analyzed for ^{7}Be by first acidifying all samples to a pH of 2.0 to ensure no ^{7}Be sorbed to the walls of the container. Stable Be was added as a yield monitor and measured by ICP-OES (3). Samples were then co-precipitated with $Fe(OH)_3$ by adding 40 mg – 60 mg of Fe in the form of $FeCl_3$ dissolved in 1 % HNO_3 and raising the pH to 8.5 with NaOH (3,26). The $Fe(OH)_3$ was the concentrated in an Imhoff cone and allowed to settle for at least 24 hours. After concentration and decanting the supernate, the samples were re-acidified to a pH of 2.0 to dissolve the Fe floc and associated Be isotopes and transferred to a 100 mL can for analysis by gamma spectroscopy on a Canberra gamma counter with planar geometry (3,26). A small subsample was first taken for analysis of stable Be for analysis of total recovery. Correction for self-absorption was completed through the use of ^{23}Na standard since it has a similar energy level to ^{7}Be (3).

V. Results

Discharge Measurements

Through the monitoring period of April 2017 through December 2017, we collected continuous flow measurements at the inlet, which provided valuable data regarding the watershed contribution to hydrologic budget of the estuary. The rating curve established to correlate the stream gage depth measurements to discharge was accurate with an R^2 value of 0.993 (Figure 6). This and continuous depth measurements provided detailed and accurate inlet flow data during baseflow (Figure 9) and storm events (Figure 10). Summer baseflow discharges at the inlet averaged around 0.20 m^3/s – 0.25 m^3/s. During the October 25, 2017 storm event, the peak discharge was recorded at 13 m^3/s.

With minor intermittent gaps, we collected continuous discharge measurements at the outlets, which provided accurate and valuable data regarding the contribution of tidal fluxes to flow into and out of the estuary. The calculated discharges from the Starflow depth and velocity data appear accurate based on field observations and manual measurements. Detailed data for the tidal prism analysis is currently being collected (depth variations at 6 locations) which will provide further independent verification of the accuracy of these discharge measurements integrated over full tidal cycles. This analysis will allow calibration of our continuous flow measurements. Throughout the monitoring period we collected continuous flow measurements into and out of the estuary during both baseflow (i.e. regular tidal cycle) conditions (Figure 9) and during storm events (Figure 10). The outlet flow data indicates an ebb dominated estuary system with peak flood tide flow rates of ~15 m^3/s and peak ebb tide flow rates of between 25 m^3/s and 30 m^3/s during baseflow conditions. During the storm event, the ebb tide peak discharge was over 40 m^3/s.

Water Quality and Sediment Flux

During the monitoring period of August 2017 through December 2017, continuous turbidity measurements were taken at the inlet and the outlet, which allowed for the calculation of sediment flux into and out of the estuary when combined with the discharge results discussed above. As discussed in Section IV, turbidity was translated to TSS concentration with a provisional conversion factor we are currently refining. At baseflow conditions, TSS at the inlet were very low or nearly zero (Figure 9). During the October 25, 2017 storm event, TSS concentrations reached peaks that exceeded 100 mg/L (Figure 10). This translated to a total sediment input to the estuary of 27,000 kg.

At the outlet, continuous turbidity and associated TSS monitoring provided valuable data to determine the contribution of tidal flushing to the West River estuary's sediment budget. TSS concentrations during baseflow at the outlet range from nearly zero to maximum values of near 300 mg/L (occurring during flood tides); however most peak values were closer to 40 mg/L. During the storm event, peak TSS measurements were also around 40 mg/L at the outlet. This enormous range highlights the need for monitoring at the timescales we use (minutes). Incorporating the TSS measurements with the outlet discharge measurements shows that for a two-day tidal cycle period under baseflow conditions, the West River estuary retains nearly 3,000 kg of sediment over this period. This result is largely dominated by the characteristic high TSS concentrations observed during the flood tide (see Section VI for discussion). During the October 25, 2017 storm event, the West River estuary had an almost zero net flux of sediment across the tide gates. This suggests that the import of 27,000 kg of sediment from the watershed during the storm event was ultimately deposited in the estuary and remained there for at least four tidal cycles.

TSS Measurements

TSS measurements have been taken throughout the study period at both the inlet and the outlet under baseflow and storm event conditions. At the inlet, baseflow TSS concentrations were generally between 1 and 3 mg/L. During the storm event on October 25, 2017, measured concentrations reached values as high as 32 mg/L. At the outlet, baseflow measured TSS concentrations ranged from 1 mg/L to values over 100 mg/L with most averaging between 30 and 40 mg/L. During the storm event measured TSS concentrations at the outlet ranged from 13 mg/L to 37 mg/L. These measurements will continue to inform the relationship between turbidity and TSS as discussed in Section IV.

^{7}Be Analysis

Samples for the ^{7}Be analysis were collected throughout the monitoring period. Precipitation samples were collected for the months of March, June, July, August, September, October, and November to characterize the atmospheric ^{7}Be contribution over monthly timescales. A precipitation sample was also collected for the individual storm event on October 25, 2017 to analyze atmospheric contribution on the time scale of a storm event. Final results for ^{7}Be activity in precipitation samples are still being calculated (as of 18 December 2017).

Water column samples for ^{7}Be analysis were collected at the inlet and the outlet under baseflow and storm event conditions. Analysis of baseflow water column samples indicate insignificant ^{7}Be activity at both the inlet and the outlet. This is not a negative result, but rather confirms our model of ^{7}Be pulses during storm events interspersed with low amounts under baseflow conditions. Given the long period required for processing and analysis (on the order of days for each sample) the water column samples from the October 25, 2017 storm event are still being processed at the time of this report. However, initial results indicate significantly higher activities for the samples during the storm event.

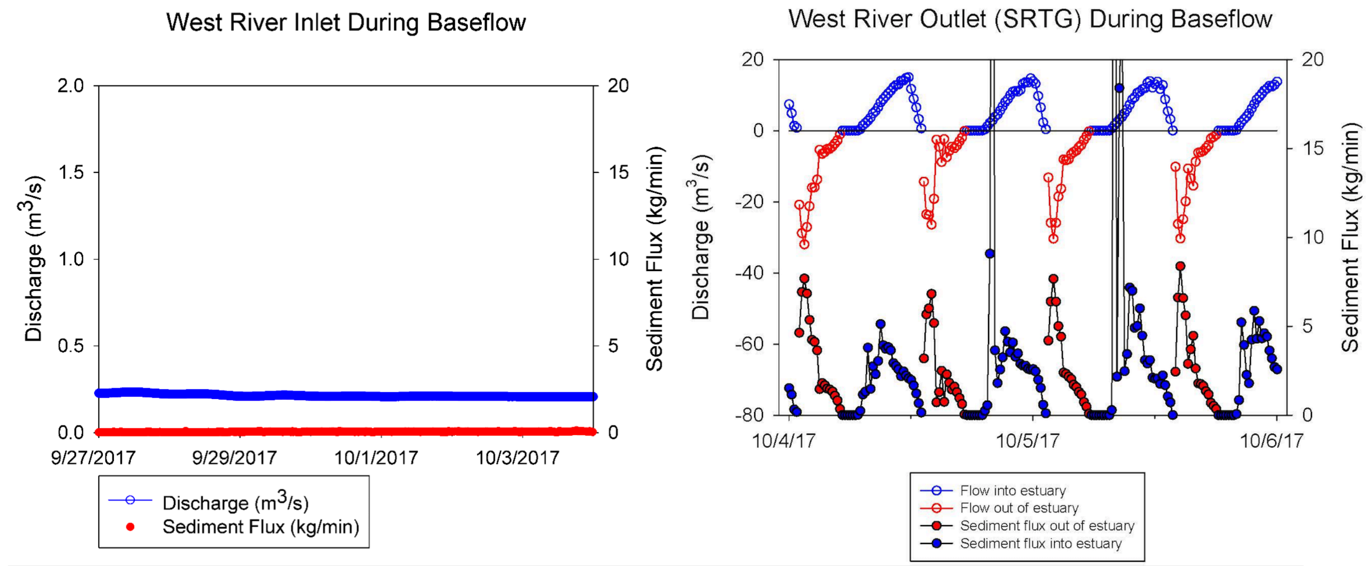

Figure 9: Discharge and sediment flux results during baseflow conditions at the West River estuary inlet and outlet. Note that peak sediment fluxes into of the estuary (i.e. those controlling total mass balance) are not shown on this plot for scaling purposes.

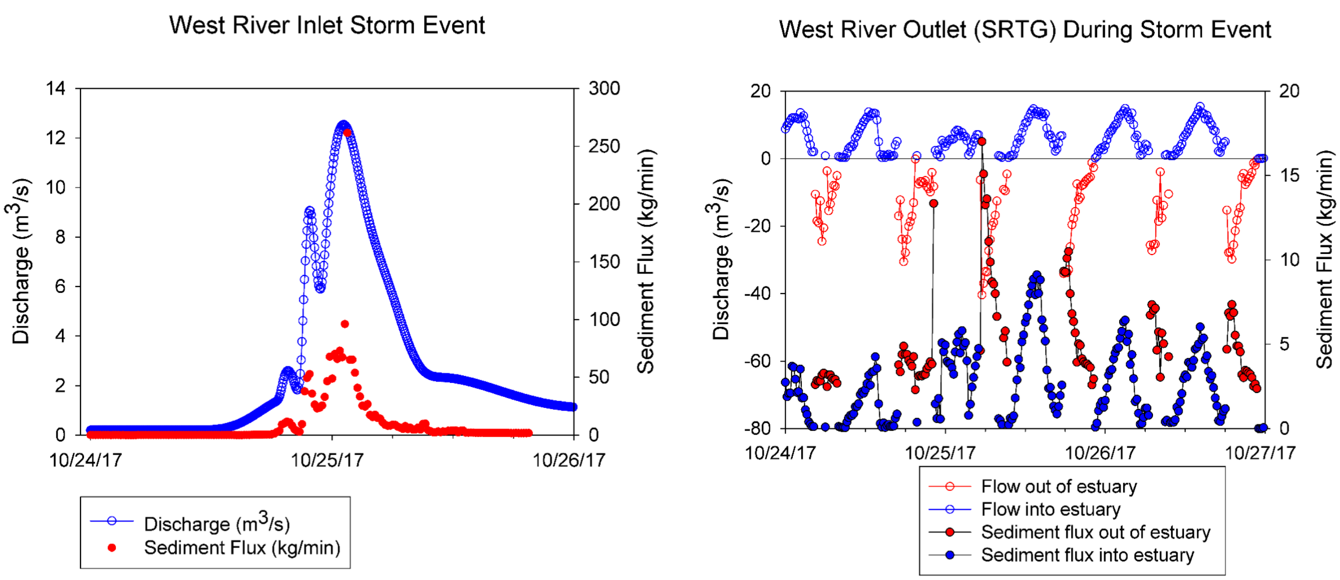

Figure 10: Discharge and sediment flux results during October 25, 2017 storm event at the West River estuary inlet and outlet.

VI. Discussion

Challenges

Throughout the monitoring period we encountered a number of setbacks that limited the project's ability to meet some of its proposed targets, though in most cases we met or exceeded expectations. The most obvious challenge was working in the extreme environment of the West River estuary. Installing the Starflow in the SRTG, required Dr. Benoit perfecting timing with tides to ensure that water levels were low enough in the pipe, which still required installation below the water level. In the words of Geoffrey Chaucer: "Time and tide wait for no man." Even after the Starflow was installed, the conditions at the SRTG caused issues. The brackish water and high flows corroded the bracket fasteners of one instrument and severed the cable of another, which caused unforeseen delays in data collection. This resulted in the project's focus on the West River for the summer of 2017, neglecting the Mill River for now.

Other issues that required constant attention related to common problems associated with working in an estuarine environment. Being at the mouth of a major river, the instruments at the SRTG were sometimes impacted by debris. In some cases, large debris (entire trees) ended up blocking the instrument or wedging open the flap tide gates – affecting data reliability in both cases (Figure 11). In many cases, the high flows during tidal flushing dislodged this debris within one tidal cycle; however, in extreme cases we worked with the City of New Haven Engineering Department to remove large pieces. In addition to debris, biofouling was a major concern during monitoring, especially during the summer. In order to reduce the effect of biofouling on the YSI probes, we installed copper mesh around the protection guard. The Starflow was at lower risk of fouling since it was located in an area of regular high flows that make recruitment difficult for most organisms.


Figure 11: Examples of large debris in SRTG (left) and traditional wooden flap tide gates (right) during study period. While these issues complicated monitoring at the site, they were often resolved through regular tidal flushing or coordinated removal with the City of New Haven Engineering Department.

Finally, a major challenge during the monitoring period was the weather. Since the project was largely dependent on storm events – for the delivery of sediment from the watershed and for delivery of ^{7}Be from the atmosphere. The study period was a relatively dry period, which limited the number of storm events that could be monitored. Over the fall 2017, several storm events were captured, yet due to the time for processing and analysis of samples, some of the data from these storms is missing in this report. The data will be added to updated versions as they become available.

Utility of SRTG for Monitoring

One of the most promising results from this study is the confirmation that the SRTG on the West River can be utilized as a point of monitoring of hydrologic and sediment transport processes in the estuary. The pipes of the SRTG serve as a confined point at which the entire estuary's flow can be directly measured and accurately scaled to account for tidal flow into and out of the estuary. Given the complexity associated with tides and salinity levels in estuaries, directly measuring flow is often a complicated task that is left to models or expensive equipment (27). However, this data is essential to understanding the important hydrodynamic and geomorphic properties of estuaries (27). Therefore, this study demonstrates a valid alternative to analyzing hydrodynamics in a small estuary system. The current study uses a SRTG as the point of monitoring, but the same opportunity would exist in other small riverine estuaries where there is a road crossing or culvert – most similar systems along the U.S. eastern seaboard.

In addition to the contained, known geometry of the SRTG monitoring point, this study utilizes a location where estuarine tidal processes can be manipulated. Even though the current report does not include data from periods of time when the SRTG have been experimentally closed, the results from the period when the gates were open suggest that the proposed study of the larger West and Mill River Experiment is feasible.

Discharge Contribution from Watershed vs. Tidal Flushing

The results from flow monitoring at the outlet suggest that the West River estuary is an ebb dominated system as peaks flows out of the estuary during the ebb tide are greater than peak flows into the estuary during the flood tide. This pattern is generally expected in tide-gated systems, since the flap gates prevent flow into the estuary but allow flow out. However, it is interesting to note that this pattern is still so pronounced in the West River estuary, where the SRTG have been installed to restore a more natural tidal flow regime. It is likely due to the fact that only ¼ (3 out of 12) of the tide gates were retrofitted with this design. This means that flow is still slightly restricted (at least in timing) on the flood tide, as the rising tide is forced through the three (3) 4 ft. diameter pipes. On the ebb tide, discharge rushes out through all 12 tide gates.

In addition to the accurate water flux measurements taken at the SRTG of the West River, the inlet monitoring location was also practical for taking continuous discharge measurements over various flows. After adjusting the measurements to remove the tidal component, the measurements proved to be consistent and accurate. The high R^2 value of the stream gage rating

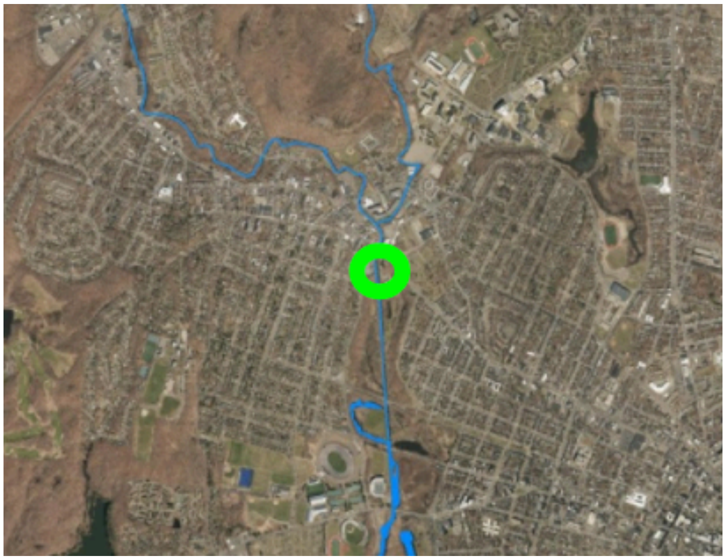

Figure 12: Detail of West River inlet monitoring location, showing channelization of segment where discharge and water quality data was collected

curve, demonstrates that the continuous water level measurements accurately represent discharge over a range of flows. This is likely due to the idealized cross-section of the monitoring location, which is a channelized segment of the West River with a fairly uniform trapezoidal cross section (Figure 12). This is typical of many urban streams (6,28), which again makes the application of the monitoring methods in this report applicable to other small urban estuaries.

By recording continuous discharge measurements at the inlet and the outlet, this study effectively captured the hydrologic contribution of watershed runoff and tidal flushing to the water budget of a small urban estuary. During baseflow conditions covering the minimum in annual flows (summer-early fall), the runoff from the watershed was quite small, totaling, on average, about 3% of the volume imported and subsequently exported during a tidal flushing event. The results from the storm runoff event show a similar relationship between the two contributing end members. At the inlet, the storm hydrograph is typical for an urbanized watershed, with a flashy peak and rapid receding limb (Figure 10). The high peak discharge of over 12 m^3/s and associated volume input to the estuary from the watershed during the storm event is almost double that of a normal tidal flushing event, which is observed in the dampening of the flood tide and by the nearly double flux out of the estuary during the ebb tide (Figure 10). This demonstrates the critical importance of quantifying the tidal flushing term when evaluating the hydrodynamics associated with estuarine processes, especially during typical baseflow conditions (3,13).

Sediment Fluxes in West River Estuary

The initial results from the continuous turbidity and discharge monitoring suggest that the West River estuary behaves as a sediment trap with sediment being deposited during baseflow flood tides and storm events. During baseflow conditions, contribution of sediment from the watershed is relatively insignificant. The contribution from tidal fluxes appears to result in net deposition of sediment in the estuary as high sediment fluxes are observed on the flood tide and not removed during the flood tide. A potential reason for this pattern may be that sediment accumulated on the downstream side of the tide gates over the decades before tidal flow was restored. Now, as high velocity flows are brought through the three SRTGs during the flood tide, this sediment is re-suspended and deposited upstream of the tide gates. The cause for this pattern will be investigated further in future studies of the system.

Data from the inlet during the October 25, 2017 storm event show the typical pattern of sediment runoff from an urban watershed as peak TSS occurs on the rising limb of the hydrograph (Figure 10). Since the results show a zero net flux across the tide gates during the storm event, they demonstrate that the sediment delivered to the estuary from the watershed are deposited and remain in the estuary in the short-term. Combined with the finding that sediment is generally deposited in the estuary during flood tides, this study suggests that the West River estuary is a net sediment sink over short time periods of storm events, daily tidal fluxes, and perhaps weeks.

Management Implications

The results from this study can inform management decisions with regards to small urban estuaries that face immediate challenges associated with ecological degradation and long-term risks related to sea level rise. As shown in the flow data from the SRTG, retrofitting a section of a traditional flap gate system with SRTG can effectively restore tidal flushing to a degraded estuarine system. As salt water flushing and tidal inundation is restored, the ecological community of the estuary is likely to be restored (29). Additionally, this information is valuable to managers who are seeking to implement protective measures against anticipated rises in sea level. If tide gates are the most cost effective and practical alternative, it is conceivable that a full SRTG system would provide the protection benefits by closing during dangerous storm surges but preserving the natural ecosystem by remaining open during daily tidal fluxes.

Our study on the SRTG of the West River also demonstrate that restoration of only a fraction of the tide gates in a system may not completely restore pre-tide gated conditions. The discharge results show that the tide gates still act as a tidal flow restriction with respect timing. The fact that the system is still heavily dominated by the ebb tide at the tide gates is important to consider as this pattern is common for fully tide gated systems. Since we still observe this strong pattern after the installation of the three SRTGs, it suggests that the replacement of more flap tide gates might be necessary to create a more symmetrical tidal pattern. However, it is important to note that other factors such as vulnerable upstream properties (in this case the Connecticut Tennis Center) may limit the full restoration of tidal patterns.

Finally, this report clearly shows the importance of continuous monitoring when studying short term sediment dynamics in estuarine systems. Since many of the significant transport events occur on the order of minutes, it is not acceptable to take discrete samples once or twice during a tidal cycle and expect to accurately characterize an estuary's sediment budget. By providing continuous monitoring data related to discharge and TSS under baseflow and storm event conditions, this study reveals some of the patterns associated with short-term sediment dynamics in estuaries, which will be useful in studies moving forward.

Next Steps

As we finish processing the data on the study from the West River, we look forward to incorporating lessons learned into larger West and Mill Experiment. The data collected in this study will serve as the baseline data for how a restored estuary (i.e. one with restored tidal flux) behaves under both baseflow and storm event conditions. By continuing the monitoring in this study when the SRTGs are closed and comparing the system to the Mill River, we will develop a set of comparable data for a fully restricted estuary (i.e. no tidal flushing). This will ultimately allow us to more accurately quantify the influence of tidal flushing on a small urban estuary and refine the sediment budget developed in this study.

VII. References

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