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The Efficacy of Constructed Stream–Wetland Complexes at Reducing the Flux of Suspended Solids to Chesapeake Bay

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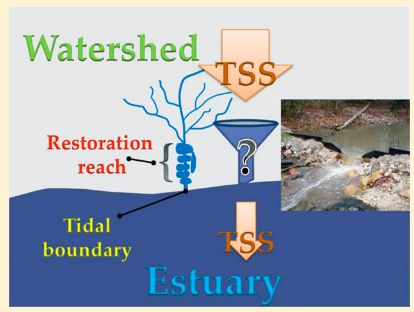
Supporting Information

ABSTRACT: Studies documenting the capacity of restored streams to reduce pollutant loads indicate that they are relatively ineffective when principal watershed stressors remain intact. Novel restorations are being designed to increase the hydraulic connectivity between stream channels and floodplains to enhance pollutant removal, and their popularity has increased the need for measurements of potential load reductions. Herein we summarize input-output budgets of total suspended solids (TSS) in two Coastal Plain lowland valleys modified to create stream–wetland complexes located above the head-of-tide on the western shore of Chesapeake Bay. Loads entering (input) and exiting (output) the reconfigured valleys over three years were 103 ± 26 and 85 ± 21 tons, respectively, and 41 ± 10 and 46 ± 9 tons, respectively. In both cases, changes in loads within the reconfigured valleys were insignificant relative to cumulative errors. High variability of TSS retention among stormflow events suggests that the capacity of these systems to trap and retain solids and their sustainability depend on the magnitude of TSS loads originating upstream, design characteristics, and the frequency and magnitude of large storms. Constructed stream–wetland complexes receiving relatively high TSS loads may experience progressive physical and chemical changes that limit their sustainability.



INTRODUCTION

Streams are considered sentinels and integrators of watershed impacts because of their sensitivity to direct and indirect watershed disturbances.[1−4] Landscape alterations from human activities usually lead to the degradation of stream ecosystems and the loss of ecosystem services.[5−7] Therefore, as more of the Earth's surface is transformed from natural to anthropogenic land-cover states, stream restoration initiatives are increasingly important, especially when based on an ecosystem services framework.[8]

The specific mechanisms that lead to the degradation of streams and the loss of ecosystems services are unclear as they vary according to landscape settings and types of stressors.[9,10] Yet, it is well established that human actions at the landscape scale that disrupt processes controlling water and sediment supply to stream channels tend to deteriorate the physical habitat conditions, ecological processes and ecosystem functions of streams.[11−13] Accordingly, practices that seek to restore water and sediment regimes in streams are commonly prioritized by watershed managers as potential methods to improve water quality, habitat, biodiversity,[14] and the overall functioning of lotic ecosystems. Stream restoration to improve water quality is now common in the United States, Australia, Canada, China, Japan, Korea[15−19] and particularly Europe due to the recent legislation referred to as the "Water Framework Directive".[20] In the U.S., stream restoration is also increasingly used to mitigate impacts of land use and cover changes on the water quality of degraded coastal water bodies such as the Gulf of Mexico, and San Francisco and Chesapeake bays.

Chesapeake Bay (hereafter, the Bay) has the highest land-to-water ratio of any coastal water body in the world.[21] Hence, the Bay is particularly sensitive to the extensive land use and cover changes that have occurred in the region since colonization.[22] The degradation of thousands of miles of headwater streams from watershed transformations has induced large fluxes of fluvial sediment to subestuarine tributaries, propelling a four- to 5-fold increase in sedimentation rates observed in the Bay in recent years.[23−26] Higher sediment loads have been linked to increased turbidity in the Bay over the last quarter century,[27] and decreased water clarity is considered one of the most serious impediments to Bay health and restoration efforts.[28] Therefore, stream restoration focused on reducing sediment export from waterways to the estuary is part of an evolving strategy to meet total maximum daily load (TMDL) requirements to restore the Bay.[29,30] The Chesapeake Bay TMDL for total suspended solids (TSS) is based mostly on mineral sediment, but also includes biologically derived materials that can affect ecological processes in both nontidal and tidal waters.[31]

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Approaches commonly used to reduce sediment export from waterways to the Bay include traditional in-stream interventions intended to modify hydraulic conditions, stabilize stream channels, and prevent bank erosion and sediment export downstream. However, improving water quality and reducing sediment transport using these restoration approaches has proven especially difficult.[8,32] Watershed managers and the stream restoration community in the Chesapeake Bay region have responded to the problem by implementing novel stream corridor restoration designs, including the conversion of eroded channels to stream−wetland complexes that enhance a channel's capacity to trap and retain suspended materials being delivered from upstream sources while reducing erosion.[33]

Nontidal Bay tributaries within the Coastal Plain physiographic province comprise a substantial portion of the watershed drainage network. These fluvial systems are particularly vulnerable to erosion due to limited structural control from bedrock combined with a surficial lithology dominated by highly erodible materials.[34,35] Low-gradient channels within wide valleys at the interface of the tidal zone are sediment "bottlenecks" that have the potential to regulate the transport of sediment to tidal estuaries.[36] The position of the lowland Coastal Plain channels adjacent to the Bay's tidal headwaters may, therefore, help mitigate the turbidity problem in estuarine waters relatively quickly if they reduce the transport efficiency of suspended solids supplied from the catchment.

Lowland Coastal Plain valley channels targeted for the implementation of stream−wetland complexes may augment storage and reduce the export of suspended solids to tidal tributaries of Chesapeake Bay. These novel restoration projects intended to reduce pollutant loads to the Bay are costly and their TSS reduction capabilities relatively unknown, thereby calling for quantitative assessments of their performance and sustainability.[37,38] Completing such assessments is difficult because they require simultaneous stream discharge and TSS data obtained on multiple dates in every season over several years that span a range of hydrological conditions.[39] Thus, load estimates are rarely done to evaluate water quality changes associated with stream restoration practices. For example, that we are aware, there are currently no documented studies estimating changes in TSS loads resulting from a reconfigured valley reach in the Mid-Atlantic Coastal Plain.

In this paper, we monitored lowland valley Coastal Plain streams of Chesapeake Bay to provide a quantitative assessment of changes in TSS loads within reconfigured stream reaches immediately upstream of the tidal boundary. Monitoring data were used to determine if suspended solids are reduced through trapping and retention within the reconfigured valleys. More specifically, our study goals were to (a) quantify the magnitude of TSS retention in these modified stream corridors, (b) evaluate variability in loading patterns and retention rates, and identify factors that explain the variability, and (c) determine how loads entering and exiting the reconfigured valleys compare with loads from other streams in the region that have not been deliberately reconfigured into stream−wetland complexes. We discuss the implications of our findings with respect to the potential for stream corridor restoration to help meet nonpoint source pollution goals, the impacts on nutrient dynamics and primary production, and expected future land-use and climate-induced changes in precipitation patterns expected for the region.

■ MATERIALS AND METHODS

Study Watersheds. Our study was conducted within Maryland's Coastal Plain (Figure S1, Supporting Information) in nontidal lowland valley reaches containing second- and third-order streams draining the western shore of Chesapeake Bay. Stream channels in the region have modest 5−10% longitudinal gradients in their headwater reaches but transition to nearly flat gradients near the tidal boundary. The higher order lowland stream valleys have side-slopes that exceed 30% in some locations and commonly contain sediment deposits derived from many forms of disturbance since European colonization. The particular study valleys also have sediment deposits from damming or ponding of the stream channel in recent decades.

Lowland valleys with degraded stream channels in Maryland are increasingly targeted for reconfiguration to stream−wetland complexes[8,33] to mimic habitat conditions associated with stands of Atlantic white cedar (*Chamaecyparis thyoides*) swamps. However, funding for these projects is usually provided with the intent of reducing pollutant loads to meet Chesapeake Bay TMDL targets.[29,40]

The streams we investigated, herein called Howard's Branch (HBR) and Wilelinor Tributary (WIL), are located within valleys 10 or more times as wide as their active channels (Figure S2, Supporting Information). WIL drains a developed watershed of about 78 ha (Table S1, Supporting Information) with a mix of commercial, industrial, high-density residential, and transportation land covers directly connected to the channel by drainage pipes. HBR drains about 98 ha of mostly low-density residential, transportation, and forest areas (Table S1, Supporting Information), but the impervious areas are also directly connected to the stream channel through stormwater drainage pipes. The valley reaches studied at HBR and WIL were reconfigured in 2002 and 2004, respectively, through mass grading and placement of structural controls to guide water flows. The reconfiguration design objectives were channel stabilization, wetland creation, stream-floodplain reconnection and creation of topographic conditions conducive to Atlantic white cedar propagation[41] (See Supporting Information for project design schematics).

Prior to reconfiguration, the HBR valley reach had been dammed for the purpose of water supply in the 1960s and 1970s. The dam had breached, exposing a layer of fine sediment that had accumulated at the bottom of the pond that was capped with a layer of sand as part of the project design. The WIL project valley was previously impounded by two in-stream ponds that captured surface runoff from an adjacent highway and upstream development. The pond dams were reconfigured to create two bypass ponds connected to the mainstem channel at their upper ends. Neither of the ponds has an outlet structure, exchanging flows with the mainstem channel through the connection at their upper ends or by overtopping their sand berms.

Study Design and Sampling Strategy. Both restoration projects were constructed several years prior to our monitoring work, therefore, we assessed their effectiveness at trapping and retaining TSS transported from upstream by using a mass balance approach, where inputs upstream of the reconfigured stream reaches were compared with outputs downstream. To determine loads upstream and downstream, we installed sampling stations at the top and bottom of each restored stream reach to measure streamflow and TSS concentrations.

We assessed the performance of the reconfigured reaches over a period of three water years, from October 1, 2008 to September

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30, 2011, when water samples were collected once every 2 weeks during baseflow conditions and at least once per season during stormflows. Baseflow occurs when there is no direct precipitation runoff contribution to stream discharge. Hence, baseflow samples were collected two or more days after the end of a rainfall runoff event. Stormflow samples were collected over entire hydrographs (i.e., during the rising and falling limbs of a storm event). Stormflow is defined herein as any period when streamflow was above the average baseflow level.

Baseflow and stormflow samples were collected using 1 L acid-washed polyethylene bottles. Baseflow samples were collected manually using a protocol for wadable streams adapted from the USGS,[42] whereas stormflow samples were collected using automated samplers (ISCO model 6712). The ISCO samplers were configured to collect up to 24 samples per event at 5−15 min intervals.

The automated samplers were initiated by actuators when stream stage was near 2 cm above baseflow levels, and sampling continued until a return to baseflow levels was achieved. For long-duration events, full ISCO bottles were replaced so sampling could continue throughout the entire storm hydrograph. During warm months, the ISCO samplers were filled with ice to limit biological activity in the water samples.

Once retrieved from the field, the water samples were transported to the laboratory in a dark cooler and stored at 4 °C prior to being processed. All water samples were filtered in the lab within 24 h, and concentrations of TSS were determined using the EPA Gravimetry Method 160.2 and Standard Method 208 E (http://nasl.cbl.umces.edu); the Method Detection Limit (MDL) was 2.4 mg L^{-1} TSS, and the quantitation limit was set at 0.0005 mg L^{-1} TSS.

The method to determine TSS concentrations involved filtering a known volume of water through preweighed 47 mm glass-fiber filters (GF/F Whatman, 0.7 μm nominal pore size) in increments of 100 mL using vacuum pressure no greater than 10 in. Hg. When the filter was saturated, it was folded in half, stored in a labeled glassine envelope and frozen. Prior to analysis, the filters were dried at 105 °C and then placed in a desiccator. Once samples reached room temperature, they were individually weighed. Total suspended solids concentrations (mg L^{-1}) were calculated as the weight of the filter after collection of the sample divided by the volume of water filtered.

To determine stream discharge, water depth (stage height) was recorded continuously at 5−15 min intervals at the up- and downstream sampling stations of each stream using pressure sensors with data loggers. The sensors were placed inside a 2 in. (1 in. = 25.4 mm) inner diameter PVC stilling well installed in the channel. The well had holes drilled near the sensor to increase response time and reduce possible stage artifacts associated with higher stream velocities. The water pressure sensors were paired with a barometric pressure sensor that recorded data at 5 min intervals to correct for atmospheric pressure effects on the stage measurements.

Instantaneous streamflow was measured near the monitoring stations immediately after collection of baseflow samples, and also during a wide range of stage depths during storm events. Water depth and streamflow velocity were determined using a measuring rod and an electromagnetic flow meter (Marsh McBirney Flo-Mate 2000), respectively.

At the HBR reach and upstream of WIL, instantaneous stream discharge was determined using the cross-sectional method.[43] At HBR, discharge was measured in the open channel, while at WIL discharge was measured in a 1-m concrete culvert using a velocity-area method.[44] The downstream station of WIL had a compound weir with a 120° V-notch capable of conveying up to 0.34 m^3 s^{-1}, and a 2.44 m rectangle section above it capable of conveying flows up to 0.67 m^3 s^{-1}; flows 12 in. above the compound structure could convey 2.98 m^3 s^{-1}. In the last year of the study, instantaneous flow downstream of HBR was measured using a 9 in. Parshall flume.

Data Computation. The instantaneous discharge and stage data collected at each sampling station were used to develop stage-discharge relationships[43] by plotting instantaneous discharge against log-transformed stage data recorded in continuous time intervals to produce a linear function. Power functions are commonly used to build rating curves based on the asymptotic trends as stage goes to zero. Logarithms of the power function produce a linear relation that can be used to convert instantaneous readings of stream stage into discharge values. Once the continuously recorded stage data were converted into discharge time series, we calculated annual discharge and total discharge for individual storm events for each hydrometric station by adding discharge values for each 5−15 min interval over the desired time period. Storm events were determined by the period when discharge was above the average baseflow value.

Loads were calculated for individual time intervals as the product of TSS concentrations and discharge. For the time intervals when flow was at or below the maximum level measured during baseflow, we calculated loads using flow-weighted mean concentrations (FWMC) (eq 1) of water samples collected during baseflow (i.e., during the biweekly samplings) as

$$\mathrm{FWMC} = \left(\sum C_i Q_i\right) / \Sigma Q_i \tag{1}$$

where C_i is the concentration (mg L^{-1}), Q_i is the discharge (L s^{-1}) for the interval i when a water sample was collected, and the denominator is the sum of observed discharges ($\sum Q_i$).

For the intervals when discharge values were above the maximum observed during baseflow, we calculated loads using a log−log regression curve from the relation between discharge and TSS loads measured in samples collected during stormflow. In order to reduce bias and account for the hysteresis between sediment loads and discharge commonly observed over the duration of a single runoff event, we used separate discharge-load regression curves for the rising and falling limbs of the hydrographs.[45]

After TSS load time-series were estimated for each sampling station, we determined loads (kg yr^{-1}) over the three-year period, separately for each water year (October−September) and each storm event sampled (kg $event^{-1}$). The difference (Δ) between loads entering (INPUT) and exiting (OUTPUT) a study reach was used to determine net sediment storage or export (eq 2). Net storage was assumed to have occurred when the load below the reconfigured reach (OUTPUT) was significantly lower than that above it (INPUT). In such instances, Δ LOAD was negative.

$$\Delta\mathrm{LOAD} = \mathrm{OUTPUT} - \mathrm{INPUT} \tag{2}$$

Uncertainty Analysis. Uncertainties inherent to water quality data collected in small watersheds can be substantial.[46] These uncertainties typically derive from common procedures used for water quality data collection, such as discharge measurements and sample collection.[46] We used the Data Uncertainty Estimation Tool for Hydrology and Water Quality (DUET-H/WQ) model to determine the cumulative probable uncertainties associated with TSS load estimates for each study

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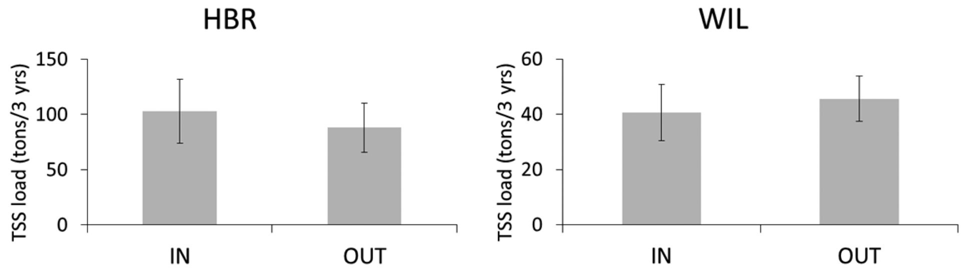

Figure 1. Total load of TSS entering (IN) and exiting (OUT) the reconfigured stream reach at Howard's Branch (HBR) and Wilelinor Tributary (WIL) during the study period (3 years). The uncertainty values associated with load estimates are indicated by error bars.

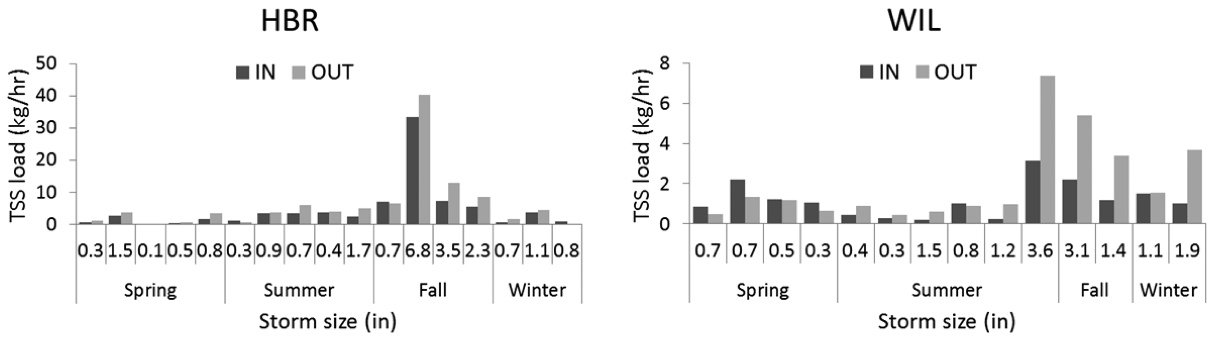

Figure 2. Comparison of TSS loads upstream (IN) and downstream (OUT) of the reconfigured reaches at Howard's Branch (HBR) and Wilelinor Tributary (WIL) during individual storm events sampled over the study period. The stormflow sampling events are grouped by season regardless of the sampling year.

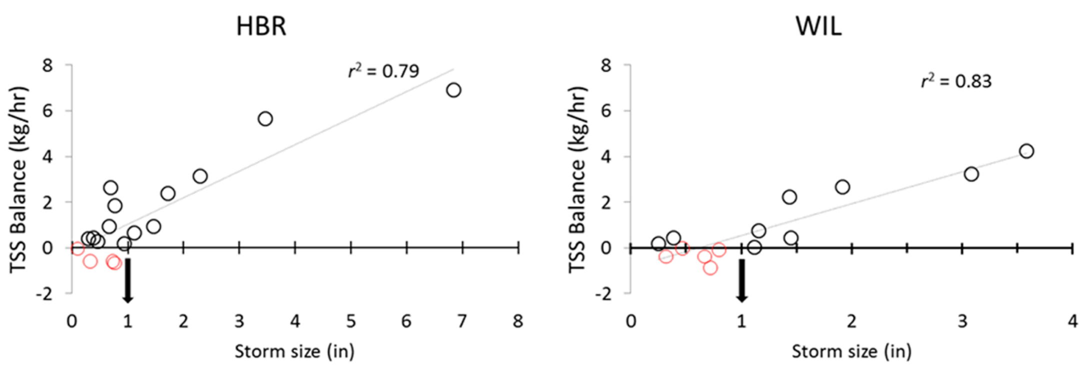

Figure 3. Balance of TSS from input and output along the reconfigured reaches at Howard's Branch (HBR) and Wilelinor Tributary (WIL) for storm events sampled versus storm size. The black circles indicate net export of TSS during a storm event and the red circles represent net retention. The black arrow indicates the point where all stormflow sampling events resulted in TSS export rather than retention.

site.[47] The foundational mathematical component is the root-mean-square error propagation method.[48]

■ RESULTS

Potential TSS Load Reductions (Storage vs Export). A total of 132 samples were collected at HBR during baseflow conditions and 960 individual samples during stormflow (>17 storm events at both stations) over the 3-year sampling period. At WIL, 110 baseflow and 860 stormflow samples (>14 storm events at both stations) were collected around the same period. The total TSS loads entering (input) HBR and WIL over the 3-yr period was 103 ± 26 tons and 41 ± 10 tons, respectively. The amount of TSS exported from the HBR reach downstream (output) was about 15% lower than the load upstream (input), while the export from WIL increased (Figure 1). However, differences were not significant for either reach because they were within the range of cumulative errors from load estimates. For HBR, uncertainties in load estimates were on the order of 28% and 25% for inputs and outputs, respectively. For WIL, these uncertainties were 26% for inputs and 20% for outputs.

Variability in TSS Loads and Retention Rates. Over the study period, TSS loads in the reconfigured reaches were overwhelmingly dominated by stormflow inputs (Figure S6, Supporting Information), whereas baseflow loads contributed less than 15% of the total loads entering the reaches. There was substantial variability in the amounts of TSS entering (input) and exiting (output) each reconfigured reach during the different stormflow events sampled (Figure 2). At HBR, TSS inputs during individual storm events ranged between 0.2 and 33 kg hr^{-1}, whereas outputs ranged between 0.1 and 40 kg hr^{-1}. At WIL, inputs and outputs during storm events ranged between 0.2 and 3.1 kg hr^{-1}, and 0.4 and 8.3 kg hr^{-1}, respectively. The largest loads were observed during stormflow events in the late summer and early fall. During these events, TSS output was always higher than input.

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As TSS inputs and outputs varied among storm events, the mass balances per storm event varied as well, from approximately 0.7−7 kg hr^{-1} for HBR and 0.9−5 kg hr^{-1} for WIL (Figure 3). The magnitude of loads during storm events was clearly associated with storm size. In both streams, only storms smaller than 1 in. resulted in TSS net retention. The larger storms resulted in the net export of TSS, and the magnitude of the export was significantly related to storm size.

The relative contribution of stormflow to annual discharge upstream of the HBR and WIL reconfigured reaches was about 40% and 80%, respectively (data not shown). Therefore, while annual discharge at HBR had a larger proportion of baseflow than stormflow, that of WIL was the opposite.

At HBR, concentrations of TSS in baseflow decreased from upstream to downstream from about 9 mg L^{-1} to 7.5 mg L^{-1}. Concentrations in stormflow (FWMC) also decreased, from about 120 mg L^{-1} upstream to 60 mg L^{-1} downstream. At WIL, average baseflow concentrations decreased along the reconfigured reach from about 6 mg L^{-1} to 4 mg L^{-1}, but increased during stormflow events from 26 mg L^{-1} upstream to 53 mg L^{-1} downstream.

Load Comparison. We recognize that the lack of prereconfiguration data prevents us from quantifying the effectiveness of these projects at reducing preconfiguration loads. Nevertheless, input−output load reduction estimates from this study indicate that our stream reaches did not export lower quantities of TSS compared to those observed in several nearby Coastal Plain streams (Figure 4). The comparison indicates that

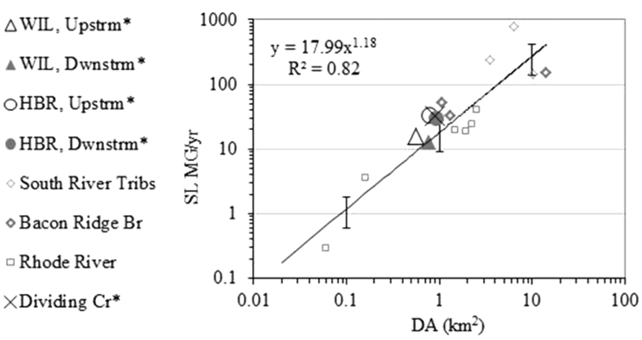

Figure 4. Total suspended solids (TSS) loads (denoted by *) calculated at the upstream and downstream ends of the WIL and HBR valley sites after project construction, and suspended sediment loads from several nearby locations.[49] The TSS load for Dividing Creek was estimated from unpublished data (2012−2013). Error bars show 50% error relative to the trend line.

although the valley reconfigurations may reduce loads, they do not drive the TSS export rate below the range of contemporary stream valleys in the region that have not been reconfigured. On the other hand, the reconfigurations likely helped stabilize TSS excess loads from the breached dam at HBR and from an eroding pond at WIL prior to project implementation.

DISCUSSION

Stream restoration represents a growing public investment for nonpoint source pollution mitigation and is viewed as a potential option for reducing sediment loads to aquatic ecosystems.[38,50,51] Consequently, there is a demand for scientifically defensible assessments of how these systems perform and whether they are effective at reducing pollutant loads transported downstream. Not only are quantitative assessments important to verify that water quality goals and objectives are achieved and sustained, but also to provide feedback to restoration practitioners and water resources managers about the appropriateness of designs and implementation plans.

In this study, we show that the two reconfigured lowland Coastal Plain stream valleys transformed into stream−wetland complexes had TSS loads similar to those of other degraded streams nearby in the study region. Moreover, loads exported out of the reaches (output) did not differ significantly from loads entering the reaches (inputs), so any changes in TSS loads observed during the study period were too small in relation to the magnitude of cumulative errors of load estimates to be significant. However, while these results may make it difficult to conclusively evaluate the performance of these reconfigured streams at retaining TSS transported from upstream in the watershed and reducing loads downstream, they provide valuable information.

Most importantly, our results indicate that any TSS retention that occurred in these greatly modified reaches is relatively small in comparison to reductions needed to considerably lessen TSS loadings into tidal waters. They also show that accurately quantifying TSS retention for stream restoration projects can be difficult because of the cumulative errors commonly associated with load estimates in small order streams.[46] Monitoring programs designed to estimate pollutant load reductions in restored streams must therefore use methods to minimize cumulative errors, including flow-rated structures (such as the weir and flume used at WIL and HBR, respectively) and automated concentration sampling equipment that is capable of measuring over the entire duration of runoff events.[46] At best, uncertainties in runoff and water quality measurements in monitoring studies should be carefully estimated[47,52] in order to guarantee that load reductions associated with stream restoration projects are scientifically defensible.[47]

At HBR, low banks and a broad, flat floodplain adjacent to the stream channel upstream of the reconfigured reach complicated the measurement of high flows and created uncertainties in load estimates. However, not accounting for these potential uncertainties, our calculations indicate that this system retained more TSS than it exported (although the amount retained annually was only about 17% of the upstream load). By contrast, load calculations for WIL indicate that the channel either exported or retained TSS entering the reconfigured reach, while not accounting for potential measurement uncertainties indicates that the channel exported more TSS than it retained for the duration of the study period.

We calculated uncertainties in our load estimates because of the potential for underperformance in relation to expectation and cost of pollutant reduction efficiency associated with stream restoration and the importance of considering this in decision making. However, it is important to recognize that cumulative errors result in a worst-case scenario and that the actual errors are likely considerable smaller due the tendency for positive and negative errors to cancel one another, particularly when aggregating multimetric and multiyear data sets.[53] As an alternative and for comparison, using the more traditional statistic of standard deviation in place of cumulative errors considerably constrains the uncertainty in our load estimates (i.e., 6.1 and 14.2 tons for HBR and WIL, respectively). Substituting the cumulative errors in Figure 1 with these standard deviation values (not shown) indicates that the input-output comparison for HBR is marginally significant, whereas that of WIL remains insignificant ($p > 0.05$).

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An analysis of TSS loads during individual stormflow events revealed that the capacity of these reconfigured stream valleys to trap and retain TSS can vary considerably. This variability depends, in part, on the season and size of the storm event. In the reconfigured reaches, storms that were 1 in. or smaller in size resulted in both the net retention and export of TSS. However, when storms were larger than 1 in., no net retention was observed among the storm events sampled, suggesting that larger storms usually result in the net export of TSS. An increase in loads during the larger storms was more pronounced at WIL than at HBR.

Despite the moderate number of storms sampled for stormflow in our study, they included a wide range of sizes representing the distribution of rain events common in the region. For example, our study included two tropical storms and a hurricane, which tend to occur in the summer and beginning of fall in the region. Therefore, the importance of storm size as a factor influencing TSS retention in the reconfigured reaches is not an artifact of our sample size.

Other factors controlling estimated retention of TSS in these reaches include the relative importance of stormflow versus baseflow in annual discharge and, to a lesser extent, TSS concentrations in stormflow and baseflow, and whether or not they increased or decreased downstream of the reconfigured reaches. For example, at HBR, baseflow accounted for about 60% of the annual discharge in the reconfigured reach, whereas FWMC in baseflow were slightly lower downstream than upstream (probably because of TSS retention during smaller storms). By contrast, at WIL, annual discharge was dominated by stormflow while the FWMC in stormflow practically doubled from upstream to downstream of the reconfigured reach. As a result, TSS loads downstream of the reach increased substantially during storm events, especially those >1-in.

We expected WIL to have a better capacity to accumulate sediment for longer periods of time than HBR because the larger and deeper ponds likely create a more steady system for TSS retention. However, impounding nutrient-rich stormwater in large ponds can affect nutrient and decomposition dynamics[54−57] and enhance primary production. For example, nutrients can be transformed from dissolved inorganic into organic forms, not only changing ecosystem metabolism[58,59] but also the amount of particulate material in suspension. Most of this material would be transported downstream during large storm events, increasing TSS and organic matter loads to tidal waters. If the organic material produced within these ponds is more labile than the natural material transported in streams from the watershed, oxygen consumption in water downstream may increase[55] thereby impacting ecological processes in the Bay.

Rates of organic matter and nutrient processing can be used as functional indicators for assessing stream ecosystem health.[58] Therefore, even if including large ponds in stream restorations help retain nutrients in organic matter and reduce loads transported downstream, changes in organic matter and nutrient processing in stream ecosystems can cause a shift in ecosystem functioning[59] and possibly the loss of ecosystem services. Furthermore, long-term impoundment of nutrient-rich streamwater in ponds can cause anoxia in bottom waters and enhance hyporheic denitrification,[60] although the effective zone of significant denitrification in streams often differs from the size of the hyporheic zone.[61] Thus, increasing whole-stream denitrification can only be achieved if a higher proportion of stream discharge passes through reactive areas of the hyporheic zone,[61] and in large, deep ponds, this is unlikely to happen.

The contact of anoxic water with sediment can also enhance the release of orthophosphate to the water column and increase primary productivity. Furthermore, anoxia in the bottom layers of ponds and lakes can lead to the accumulation of ammonium by both organic matter mineralization and limited nitrification. If higher loads of orthophosphate and ammonium are exported into the Bay, they can aggravate eutrophication, especially because ammonium is the preferred form of N utilized by phytoplankton.[62]

The reconfigured reach at HBR has a series of shallow pools and wetland areas that may augment TSS retention during storm runoff events, especially when they are small. However, while these pools and wetland areas may create conditions under which sediment retention can occur, the long-term efficiency of modified channels may ultimately be determined by natural and anthropogenic factors controlling yields of suspended solids in the headwaters[63] or above the reconfigured reach.[64]

Loads of TSS entering the reconfigured HBR reach were relatively high in comparison to loads at WIL. The catchment drained by HBR has fairly steep slopes and easily erodible soil materials in the headwater region. Therefore, processes occurring in the catchment such as severe erosion at the top of headwater channels connected to stormwater drainage pipes common in the study area[8] probably contributed sediment to the reconfigured reach.

In addition, flocculates generated by iron (Fe) oxidizing bacteria (FOB) observed at HBR during the study period are a potential source of TSS within the restored reaches. Iron oxidizing bacteria flourish in environments with steady fluxes of reduced Fe (II) from groundwater seeps and O_2 supplied from oxygenated water,[65,66] such as at the interface of stream and wetland features that compose wetland−stream complexes. While the natural formation of flocculate and mats from FOB are ubiquitous in the study region, these are prone to resuspension during stormflow events and can considerably increase TSS concentrations in reconfigured streams. Therefore, while stream−wetland complexes may reduce the transport of suspended sediments to downstream waters, they may concomitantly enhance the export of other types of suspended solid materials such as from FOB flocculate.

The most important drivers regulating the net export or retention of TSS in both stream reaches are rain size and intensity. Accordingly, climate change that results in an increase in the frequency of large storms may ultimately determine their sustainability and effectiveness at reducing TSS loads to downstream waters. For example, if the frequency of large and intense storm events in the Chesapeake Bay region increases with climate change,[67] the effectiveness of these engineered systems at trapping and retaining TSS will likely decrease in the future. Therefore, increased stormwater runoff in a wetter climate in addition to other factors that influence TSS dynamics in reconfigured streams, such as the supply of TSS upstream of the targeted reach, FOB, and primary production from impounded water, should be carefully evaluated in stream restoration projects in order to bolster their potential resiliency and long-term sustainability.

In conclusion, the modification of lowland valleys into stream−wetland complexes is currently perceived by many watershed managers as a viable and effective re-engineering technique that can be used to augment the retention of TSS transported from upstream runoff and erosion in developed catchments. While our data provide some evidence that at least one of these systems can reduce TSS loads to downstream

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waters, the capacity of these systems to store suspended solids is limited. It is however possible that the reconfigured streams are exporting less TSS than they were prerestoration if sediment erosion from within the channel or TSS inputs to the channel were significantly higher than they are today. We believe that this is unlikely since comparisons with other nearby streams indicate that both the upstream and downstream stations at our study sites were within the range of sediment loading variability in the region. However, the breached dams that existed at each of our study locations prior to reconfiguration may have created unusual conditions and produced locally elevated sources of suspended solids.

Further, estimating TSS loads in streams from concentration measurements can underestimate the transport of mineral suspended sediment. USGS data collected from a Coastal Plain stream in the region shows concentrations of TSS to be approximately 44−81% of suspended sediment concentrations in flows ranging from 10−10 000 L/s as shown using data collected from a nearby Coastal Plain USGS gaging station at Western Branch.[68] Large sized sand and gravels transported as bedload were also not sampled, but may account for up to 20% of the total load in small streams.[69] As a result, more coarse mineral sediment may have been transported into the valley reaches than measured using TSS sample analysis, and the coarse sediment sizes would have been more susceptible to trapping in the low gradient systems and require higher flow rates to be remobilized.[70] However, increasing the residence time of sediment loads within the restored reaches may decrease the capacity of these systems to store sediment and compromise the longevity of projects if sources from the channel upstream or from the catchment are not effectively managed.

Regardless of how these reconfigured reaches perform, the ecological implications of modifying lowland channels to address problems of excess sediment and nutrients originating from upstream locations in the watershed are complex (8) and may result in undesirable outcomes. Therefore, other measures such as the implementation of stormwater best management practices (BMPs) in the watershed should be part of the solution for reducing pollutant loads to Chesapeake Bay, either alone or in tandem with stream restoration projects since such practices will likely improve the effectiveness and long-term sustainability of stream restorations.

■ ASSOCIATED CONTENT

Supporting Information

Section S1; Figures S1−S6; Table S1. The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.5b00063.

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The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Notes

The authors declare no competing financial interest.

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■ ABBREVIATIONS

FOB iron (Fe) oxidizing bacteria
FWMC flow-weighted mean concentrations
HBR Howard's Branch
MDL method detection limit
TMDL total maximum daily load
TSS total suspended solids
WIL Wilelinor Tributary

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