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Biota and hydrology influence soil stability in constructed wetlands

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ABSTRACT

The impact of hydroperiod and vegetation on soil stability was investigated in wetland swales that treat urban stormwater. Critical shear stress was measured as a proxy for soil stabilization using a Cohesive Strength Meter in three parallel wetlands. Despite efforts to create three replicate wetlands by uniform construction and identical planting, each developed a distinct hydroperiod (low, intermediate, and high water-recession rates) and vegetation (varied biomass of cattails [*Typha* species]). Critical shear stress (τ_c) was highest in the high-recession, fast-draining wetland (7.8 Pa), followed by the intermediate-recession swale (6.1 Pa) and the low-recession, inundated swale (4.1 Pa). These values correlated with differential development of moss and algal mats, both of which were highly resistant to erosion (τ_c of 8.6 and 7.4 Pa, respectively). These epibenthic mats were patchy and developed primarily in the wetlands with high and intermediate water-recession rates but were limited in the low-recession wetland, with cattail shade, anaerobic conditions, and substrates consisting of organic matter (τ_c of 5.6 Pa), bare soil (3.0 Pa), and muck (1.8 Pa). Small inflows sustained ponding and associated cattails, which promoted shade and destabilized the surface soil of the low-recession system, as well as subareas within the better-drained wetlands. Epibenthic mats played an unexpected, disproportionate role in soil stabilization compared to vascular plants.

1. Introduction

Constructed wetlands are becoming a common ecological option for stormwater treatment, in part because the range of ecosystem services they can provide make them preferable to conventional treatment systems. When used to treat urban stormwater runoff, constructed wetlands are subjected to intermittent flows that vary in depth and velocity. This variance in flow regime impacts the hydroperiod, or the duration and frequency of inundation. This may, in turn, influence the treatment performance of wetlands, including sediment and nutrient removal, water retention, vegetation diversity support, and soil stability (Kadlec and Knight, 1996; Miller and Zedler, 2003; Greenway et al., 2007; Jenkins and Greenway, 2007; Boers and Zedler, 2008; Moustafa et al., 2011, 2012; Doherty et al., in revision).

The stabilization of soil is a balance between the hydrodynamic mechanisms that cause erosion and the forces that resist it (Grabowski et al., 2011). Vascular plants stabilize soil and prevent erosion via: (i) belowground biomass which aggregates soil, provides cohesion, and enhances microbial growth through a network of plant roots and root hairs (Gyssels et al., 2005; De Baets et al., 2007) and (ii) aboveground vegetation which slows the flow of water, thereby reducing the erosive forces acting on the soil surface (Gyssels and Poesen, 2003). Sediment detaches when the shear stress from flowing water exceeds a critical value that is influenced by the resistance of soil and plant structures.

Complex biological and physical components interact on a microscopic scale to create significant spatial variability in the properties (e.g. stability or erodibility) of cohesive soil and sediments (Tolhurst et al., 2006; Grabowski et al., 2011). Epibenthic mats of moss (bryophytes) and algae (various filamentous and mucilage-producing forms) utilize an extensive combination of physical, biological, and chemical processes to resist erosion (Paterson et al., 2000; Whitehouse et al., 2000; Andersen, 2001; Lundkvist et al., 2007), which may make them effective soil stabilizers (Tolhurst et al., 2006). In particular, mosses increase erosion thresholds by buffering the soil surface from direct shear stress of flowing water, and algae stabilize sediments by excreting extracellular polymeric substances (EPS) that bond soil particles (Hoagland et al., 1993). An increase in diatom biofilms has been shown to increase erosion thresholds (Sutherland et al., 1998; Tolhurst et al., 2008). Differences in erosion thresholds within intertidal mudflats correlate with the presence or absence of epibenthos (Andersen, 2001; Tolhurst et al., 2006).

While biological and physical components are responsible for soil stability, we know of no study that investigates how hydrologic

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regime and vascular vegetation together impact substrate development and stability in a constructed wetland. Soil texture and moisture content, presence or absence of vegetation, and hydroperiod have been shown to impact biological, physical, and chemical mechanisms in terrestrial applications and also impact stormwater treatment in constructed wetlands (Greenway, 2004). The ability of vegetation and epibenthos to stabilize soil, prevent erosion and resuspension of deposited sediment, and ultimately to improve water quality in constructed wetlands designed to treat urban runoff remains understudied.

Our goal was to understand how hydrology and vegetation development influence substrate stability in constructed wetlands. We studied three experimental wetlands (swales) that were constructed identically but developed different hydrologic regimes due to subsurface substrate heterogeneity. We hypothesized that (i) soil stability at the swale-scale would differ with hydrologic regime and (ii) swale vegetation and physical parameters would differ in their ability to explain erosion thresholds at the sub-meter ($0.25\,m^2$) scale.

2. Material and methods

2.1. Study site

The project site is located within the University of Wisconsin—Madison Arboretum in Madison, Dane County, Wisconsin. A Stormwater Management Research Facility (SMRF; latitude = 43°2′11.2″N, longitude = 89°25′28.5″W) was constructed to treat stormwater runoff from a 45.7-ha contributing urban watershed. Construction of the SMRF began in 2008 and was completed in November 2009. The site was mass-graded and covered with 15 cm of silt loam topsoil salvaged from the site during excavation.

The SMRF is one component of a treatment train which consists of a forebay and retention pond system that discharges into four trapezoidal wetland swales (each swale is 96-m long, 8.7-m wide at inlet end and 14.7-m wide at outlet end; slope: $0.06\,cm\,m^{-1}$) separated lengthwise by 0.3 m high earthen berms. Flow from all four wetland swales (Swale 0, I–III) discharges into a 7.6-m wide by 0.6-m deep collection swale which outlets to a trapezoidal concrete flume (runs parallel to the swales) that discharges into a second stormwater retention pond. A diversion structure with stoplogs allows incoming stormwater to be diverted in varied volumes toward the SMRF, or to bypass the system altogether and flow down the concrete flume toward the retention pond. The stoplogs were modified to limit incoming flow volumes to ensure that the swales were hydrologically isolated (did not overflow their berms) during the study period. Stormwater was directed into the swales on 1 March 2011. Prior to this date, all stormwater was diverted toward the concrete flume and retention pond.

Swales I–III were seeded in November 2009 with identical seed mixtures from a collection of 27 native wet prairie species at a rate of $590\,seeds\,m^{-2}$ (Prellwitz, 2013). Each swale was divided along the length of the swale into 16 equal area "sections", each seeded with a subset of 3 or 9 plant species. Swale 0 was subdivided and seeded in a different manner for another experiment and was not considered in this study. Water levels in the swales were measured with pressure transducers at the inlet and at the outlet of each swale (Doherty et al., in revision).

2.2. Critical shear stress measurements

As a proxy for soil stability, we measured critical shear stress (τ_c), or the shear stress required to initiate particle detachment, in situ with a Cohesive Strength Meter (CSM, Model MKIV 60 psi, Partrac of Glasgow, United Kingdom). To date, CSM research has been limited primarily to estuarine and intertidal sediments (Tolhurst et al., 2000, 2003; de Deckere et al., 2001; Defew et al., 2002; Friend et al., 2003; Watts et al., 2003; Chen et al., 2012). The CSM utilizes infrared optical sensors within a testing chamber to measure water transparency after the soil surface is subjected to water pulses at increasing pressures and correlates these values to sediment concentration and τ_c (see Tolhurst et al., 1999). The CSM is easily transported for in situ measurements, which are superior to estimates of τ_c based on soil samples brought back to the laboratory for flume experiments (Wilcock and McArdell, 1997; Houwing, 1999; Vousdoukas et al., 2011).

In 2010, CSM measurements were taken between 13 October and 18 October. The swale lengths were divided into four equivalent zones (four sections per zone). One section was randomly selected per zone per swale and measurements were taken within the extents of two randomly selected $0.25\,m^2$ quadrats in that section. In 2011, CSM measurements were taken between 15 September and 21 November. In Swales I and II, measurements were taken within two randomly selected quadrats in every other section (starting with the furthest upstream section). Due to homogeneity of vegetation and substrate in Swale III, a reduced number of sections representing the upstream-, middle-, and downstream-sections were measured for τ_c. Measurements were taken after peak productivity or vegetation senescence, which provided an entire growing season of root development between the 2010 and 2011 measurements.

For each CSM test, moderately loose surface particles were gently brushed from the measurement site. Particles that adhered to the soil surface were not disturbed. In particularly dry conditions that prohibited the insertion of the optical sensor head into the soil, the surface was hand-sprayed with distilled water to wet the soil surface enough to allow insertion (approximately 20 sprays). Distilled water was slowly injected via syringe into the optical sensor head prior to each measurement to initialize the light transmission reading. A CSM default test (S1–S19) was selected for appropriate incremental and maximum water pressure within the sensor head. The CSM measurements with an initial beam transmission reading less than 70% were discarded since this was indicative of surface particle disturbance prior to a test.

Multiple measurements ($n \geq 2$) were taken per $0.25\text{-}m^2$ quadrat to characterize critical shear stress. Representative soil substrates (as described in Section 3.1 of Section 3) visually observed within each quadrat were documented. At least two CSM measurements were taken per quadrat, with at least one within each representative soil substrate observed within the quadrat. Measurements were avoided in cracks, as this prohibited the optical sensor head from retaining water for the test duration. Samples were located approximately between vascular plants. Volumetric soil moisture content was measured near each CSM measurement site using a TH_2O Soil Moisture Meter with HH2 Moisture Meter readout unit, (±2%; Dynamax Inc., Houston, TX).

Pressure and beam transmission data were uploaded from the CSM, and multiple beam transmission measurements were averaged for each incremental pressure value (Black, 2007). Vertically applied jet pressures were converted to an equivalent horizontal bed shear stress using the equation developed by Tolhurst et al. (1999) and transmission values were converted to suspended sediment concentration using the equation by Black (2007). Both horizontal bed shear stress and suspended sediment concentration were plotted with respect to time.

The resultant two-series plot of sediment concentration versus time and horizontal shear stress versus time typically produced a soil erosion profile with three distinct regions: (1) an initial portion before sediment detachment occurred and particle