Assessing the Influence of Operational Controls on Flow Behavior in a Constructed Stormwater Wetland through Residence Time Analysis

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Land development activity can result in land use changes that generate high runoff flows from rain events. When improperly managed, urban stormwater runoff contributes to flooding, exacerbates erosion, physically alters ecosystems, and transports pollutants from paved surfaces into waterbodies (1-3). Green stormwater infrastructure (GSI) represents a sustainable, innovative approach to manage stormwater runoff utilizing physical, biological, and chemical functions of vegetation and soil media within engineered systems (4,5). Dynamic design and operation of these systems can improve flood mitigation, pollutant capture, and cost efficiency in the context of changing hydrologic demand (6,7).

In this study we assessed existing and proposed dynamic control devices' influence on GSI performance. We utilized rhodamine dye tracer testing to analyze residence time in two segments of the Villanova Constructed Stormwater Wetland (CSW), meanders M1 and M3, shown in Figure 1. For each tracer test, the nonreactive rhodamine dye was deployed from an upstream location, and dye concentrations were measured at 5-minute intervals by Cyclops-7 Loggers positioned at the beginning and end of the meander. The resulting dye concentration curves reveal information about the flow behavior of the water traveling through the meander (Fig 2). Residence time is a key performance factor because longer residence implies reduced downstream flows and more contact and reaction time for water quality improvements (8).

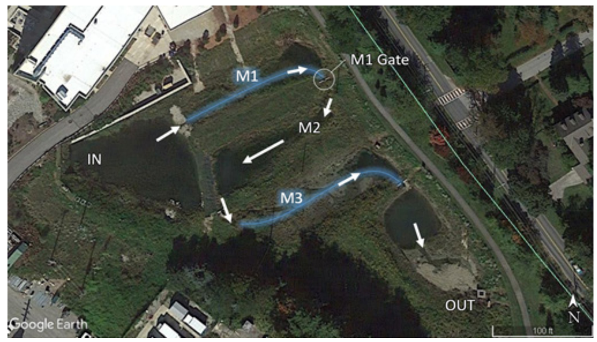

Figure 1. Villanova's CSW with flow direction arrows (9). Residence time was analyzed for two channel segments, Meander 1 (M1) and Meander 3 (M3), highlighted in blue.

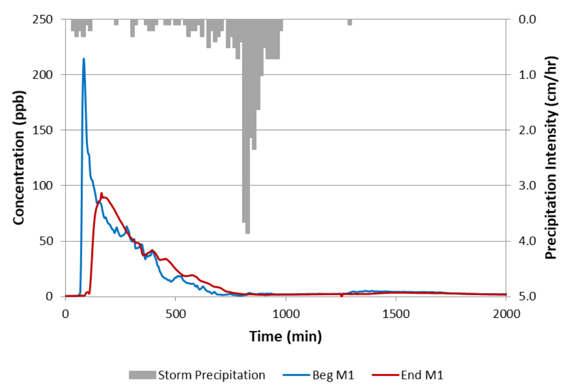

Figure 2. Dye concentration curves (parts per billion) and rainfall intensity (centimeters per hour) from a 6.60 cm storm event that occurred on 4/15/18. The blue and red curves represent dye concentrations recorded at the beginning and end of Meander 1, respectively.

The CSW receives runoff from Villanova's campus and routes it through a meandering channel with inlet and outlet forebays before discharging to the headwaters of Mill Creek. At the end of Meander 1 (M1) is a dynamic sluice gate that can be adjusted remotely to constrict flow and induce ponding upstream of the gate (Figure 1). To examine the influence of dynamic control under storm conditions, dye concentration curves from three storm events occurring after the gate installation were compared with prior tests. In between storms, the CSW maintains dry-weather channel flow known as baseflow and continues to provide time-dependent water quality improvements (8). To examine baseflow performance, the residence time analysis conducted for Meander 3 (M3) investigated whether baseflow velocities might support a proposed channel bottom retrofit for enhanced nutrient capture (10). Additionally, whereas M1 lies directly upstream of the control gate, M3 is located at a greater distance and thus reflects how the gate's hydraulic influence is experienced beyond the immediate vicinity of the control point.

Concentration curves for the dynamically operated M1 channel featured delayed peaks compared to tests prior to the M1 gate installation. From the CSW inlet to the M1 gate, three 2018 storms had an average time to peak concentration of 4.1 hr, compared to 2.4 hr observed across eight storms occurring in 2014 before the gate was installed. Though two-sample t testing indicates that the increase is not statistically significant, these preliminary trends serve to inform future studies of the M1 gate. Moreover, as this work continues, the power of the study will grow with the available dataset. A comparison of M1 flow statistics before and after gate installation is presented in Table 1. Among the three 2018 tests, mean residence time within M1 decreased as storm depth increased, indicating that the gate's operational logic may have mitigated changing hydrologic inputs, but that it did not fully overcome the increased loading from larger storms. Further study is needed to understand how the gate's physical and logical characteristics influence the residence time response to rainfall depth, as well as rainfall duration, intensity, and distribution. For the second analysis segment, the mean M3 residence time was 7.0 hr, which acts as a constraint on reaction time. This residence time corresponds to an average flow velocity of 0.16 cm/s. These flow parameters are important design considerations for proposed channel retrofits promoting increased nutrient capture through hyporheic exchange, the exchange of surface and subsurface water (10).

Table 1. Summary of flow characteristics before and after M1 gate installation. Time to peak measures the elapsed time between dye release at the CSW Inlet and peak dye concentration recorded at the end of M1, downstream of the M1 gate. Mean residence time represents the average flow time from beginning to end of M1. Only two of the eight tracer tests performed before gate installation had sensors at both the beginning and end of M1, so calculations for that category were limited to a sample size of n = 2.

	Before M1 Gate Installed	After M1 Gate Installed
Time to Peak (hr)	**2.4 (n=8)**	**4.1 (n = 3)**
Mean Residence Time (hr)	**3.0 (n = 2)**	**3.4 (n = 3)**

This study represents a preliminary step in addressing how flow can be most effectively controlled through constructed stormwater wetland GSI. Many water quality functions within a stormwater wetland are time-dependent processes that could be enhanced through maintaining longer residence times within critical channel segments (8). More broadly for GSI, the possibility for real-time monitoring and control has significant promise in leading the transition to more adaptive stormwater management solutions. With operational controls, these systems can be engineered to function more efficiently across varying baseflow and storm conditions.

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