Approaches for Determining Swale Performance for Stormwater Runoff

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Abstract

Swales are "engineered vegetated ditches" that provide stable routing for stormwater runoff and a low-cost drainage option for highways, farms, industrial sites, and commercial areas. It is reported in the literature that swales mitigate runoff-carried pollutants, reduce runoff volume, and reduce peak stormwater runoff rate that can damage low-order streams and transfer pollutant loads carried in the runoff to receiving waters. EPA recognizes the reported capabilities of swales to reduce the environmental footprint while meeting the practical need to manage stormwater runoff. Further research, however, is needed to provide a more complete understanding of swales operations. This paper introduces EPA's swale research strategy, lessons learned during swale construction, and initial results of media and water balance trials. By developing a more complete understanding of the functions and capabilities of swales, it is hoped that the user community will be equipped to design and construct swales that efficiently reduce pollutant loading and protect receiving waters. Outcomes of this research are expected to help managers and regulators meet designated uses and goals outlined in the Clean Water Act, and maintain a continuing supply of high-quality water for human and aquatic life and economic growth.

Introduction

EPA defines grassed swales as shallow, channeled grassed depressions through which runoff is conveyed generally from impervious surfaces (U.S. EPA 1999). Grassed swales are an appropriate stormwater management practice and are commonly used in most regions of North America. Swales have several benefits. The grass in swales slows the flow of runoff water while porosity of the soil allows water to infiltrate. This results in two main mechanisms to remove pollutants, such as nutrients and heavy metals, in the runoff. First, the vegetation in the channel provides roughness, which slows the water and allows settling, aiding in the removal of particulates and particulate-associated pollutants from the stormwater runoff. Secondly, aerobic

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decomposition and chemical sorption that occur within the soil matrix as the stormwater infiltrates can reduce pollutant loads in the runoff. Check dams can be incorporated into the design of grassed swales to further reduce flow velocity and promote infiltration and sedimentation. Reduced runoff velocities and peak flow reduction help protect smaller streams down-gradient from the swale.

Typically, in urban and suburban settings, planners use grassed swales as an environmentally preferred solution or as an enhancement to curb-and-gutter storm sewer systems. The linear structure of swales favors their use in the treatment of runoff from highways, residential roadways and common areas in residential sub-divisions, along property boundaries, and in and around parking lots. Because of the reduced need for structural elements (e.g., curbs, gutters, and piping), swales are a low cost and low maintenance option to reduce pollutants in runoff.

Based on the perceived benefits, some communities are requiring developers to design swales into new residential areas as a less expensive and more environmentally friendly tool to manage stormwater than the traditional structural alternatives. The choice to install the swales can be part of a general strategy called Low Impact Development that incorporates watershed management practices as part of the planning.

EPA recognizes the potential pollutant removal and volume reduction capabilities of swales to minimize the environmental footprint, while meeting the practical needs of managing stormwater runoff. However, due to the stochastic nature of stormwater research and the inherent variability in collected data, field studies require long-term monitoring to achieve statistically valid results. Related issues of operating in the field, such as uncertainty of weather forecasting, site access, utilities, vandalism and other logistical difficulties collectively, add greatly to the costs of rigorous field experiments. To avoid these, the EPA selected the approach of doing controlled-condition research by constructing onsite research swales. This strategy enables the National Risk Management Research Laboratory (NRMRL) of EPA's Office of Research and Development to collect the high-quality data needed for engineering design, performance evaluation, and for direct measurement of information (i.e., infiltrate quantity and quality) that is often difficult to obtain. When necessary, researchers can alter onsite system dimensions, shape, and runoff rate and volume to engineering failure with no risk to the well-being of surrounding population, personal property, or environment. The location is safer than attempting research measurements along busy roadways during a rainstorm and avoids unnecessary risks to people and equipment. The controlled-condition experiments can reduce uncertainty by allowing collection of every stormwater runoff event and completely evaluating runoff characteristics (e.g., solids, heavy metals, and nutrient concentrations), permitting comprehensive statistical analyses. Both time and costs to obtain statistically valid results can be reduced in controlled experiments that reduce the variability compared to field experiments relying only on stochastic stormwater runoff events.

Experimental Methods

Swale design and construction

NRMRL constructed three separate 40-m long swales differing in slope during the summer of 2006. The steepest has a 5% slope, considered near the upper limit established by many regulators. The flattest swale has a slope of only 0.5%; less than the lowest slope recommended for many applications. The third swale has a 1% slope, representative of the range often cited as "preferred" (Figure 1). Each swale has a trapezoidal cross section that routes the runoff. NRMRL selected this initial shape because many regulators think this shape reduces the maintenance effort and simplifies hydraulic design and construction. After collecting data with this shape, NRMRL can alter the cross section, if needed.

Figure 1. Construction of the 5%, 1%, 0.5% swales (from left to right).

The subsurface of each swale was divided into four separate 10 m watertight segments or treatment cells along the length of the swale and four layers vertically. The bottom layer is an impermeable liner that isolates the segment and prevents uncontrolled loss of water that infiltrates through the surface. A 20-cm thick layer of well-washed gravel sits on the impermeable membrane. The gravel surrounds a slotted pipe that routes all infiltrating water to a common exit point. A porous fabric separates a 30-cm deep media layer from the gravel. The uppermost surface will be covered with grass.

The compartmentalization will enable researchers to develop or confirm computer models that predict infiltration rates and chemical reactions that may occur in the subsurface. This design also permits the comparison of water quality and quantity with length using observed differences between each 10-m segment (cell).

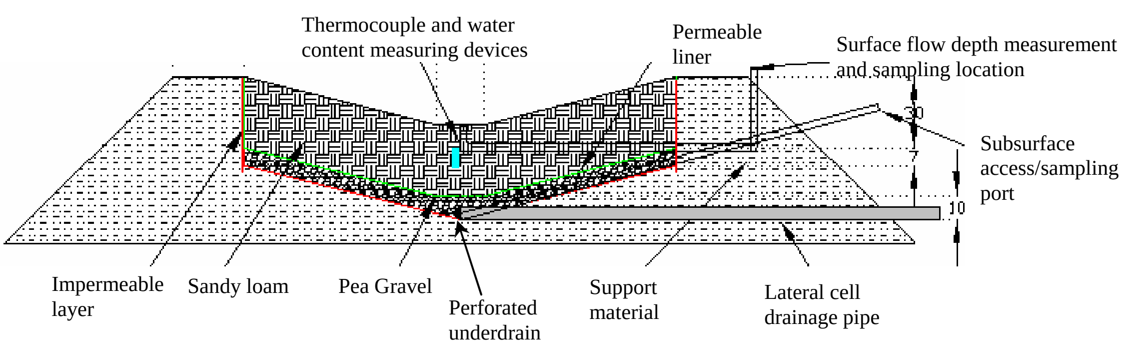

Figure 2. Schematic of swale cross-section.

To collect needed planning data before the establishment of grass, trial runs, termed shakedown tests, were completed using artificial turf with average blade widths of 0.95 cm (flattened), blade lengths of 5 cm, and stem densities of 4133 stem bundles per 0.25 m^2 on the 5% sloped swale (Figure 3). The use of artificial turf assures uniform properties along the swales and allows comparison with published results from other research evaluations using similar products.

Figure 3. Header box and artificial turf in the 5% swale.

Pipes about 15° above horizontal penetrate into the gravel layer to allow researchers to collect samples of the infiltrating water that can be immediately analyzed at the onsite laboratory, facilitating monitoring of short holding time stressors (e.g., microbials). Surface water in each swale can be collected using flush-mounted sampling pipes located at 2-m intervals along the length of each swale. The influent header box and effluent footer box were also designed for sample collection. Dedicated in-line meters record all flows entering and leaving the swales. The swales have electronic monitoring and logging for surface water depth and sensors to record the moisture content and temperature of the media. Water infiltrating into the gravel layer is monitored electronically for dissolved oxygen, temperature, pH, turbidity, conductivity, and oxidation-reduction potential.

Stormwater Runoff Collection and Routing

All water used in the experiments was stormwater runoff collected from an onsite stormwater outfall. When needed, a diversion pipe routed the runoff from the storm sewer to a 76-m^3 collection tank where it was stored until needed. Before use, the stormwater was mixed by cycling the volume through mixing eductors to promote a more homogeneous mixture with consistent properties, both spatially and temporally.

A centrifugal pump transfered the mixed water from the storage tank to the top of the swale. The transfer rate was adjustable to allow control of desired flowing water depth within the swales. All water exiting the swale was captured for measurement and analyses. Experiments lasted from 1 to 3 h depending on selected conditions. To date three trial shakedown tests have been conducted to try to establish a water balance and determine instrumentation and pumping capabilities.

Soil Media

The soil media used in infiltration management practices is recognized as a critical component that influences subsurface pollutant attenuation. Sorption by the media may be the most significant subsurface mechanism for removing particulate and soluble metals and nutrients from urban stormwater runoff. Media selection for use in the swales is an important requirement in that it should be amenable for plant growth, able to control infiltration rates and provide sorption sites for both heavy metals and nutrient contaminants. Several recommendations exist on the nature and type of media that should be used in swale and other bioretention BMPs. The recommendations are general, giving broad criteria for media characteristics to allow selection of locally available engineered media. Examples of media criteria include: a pH range of 5.2 – 6.5; organic matter (OM) content between 1% and 5%; sand-silt-clay contents between 60% – 90%, 5% – 20%, and 5% – 20%, respectively; P-index between 10 – 30 (Hunt and Lord, 2006); cation exchange capacity (CEC) greater than 10 meq/100g; and infiltration rates of 3-25 cm/h or greater (depending on site conditions and desired time of treatment through retention). The engineered media mix for baseball infields generally meets the guidelines for percent sand-silt-clay, infiltration rates, and is generally available across the United States. For this reason and because of the national standards that exists for this engineered soil, EPA selected three infield mixes for further testing.

Soil media isotherm sorption and column adsorption studies are ongoing to evaluate the selected soil media. The targeted stressors include total and dissolved heavy metals (copper (Cu), lead (Pb), zinc (Zn), chromium (Cr)) and macronutrients (total and soluble forms of phosphorous and nitrogen). The isotherm experiments investigate the reaction mechanisms happening at the media/solution interface. Column experiments help in understanding the matrix interactions for determining breakthrough time, media depth, and flow rates that might be experienced in typical swale and bioretention applications. Both studies are important in determining equilibrium behavior of competing heavy metals and nutrients and establish the concentration and timing for maximizing the sorption capacity of the media for the stressors of concern.

The infield mix was characterized to verify proportions of sand-silt-clay content (71%, 9%, and 20%, respectively); however, the pH was acidic (4.6), and OM content was less than 0.5%, a concern for supporting vegetation. Amendments of garden soil and cow manure were evaluated in experiments performed by EPA and Rutgers, the State University of New Jersey, for improving the OM content of the infield soil mix to meet the bioretention media guidelines. Similarly, experiments varying the proportion of dolomitic limestone (from 0% to 10% on a mass basis) were completed to determine quantities necessary to meet pH guidelines for bioretention media.

Surface Water Solids

Multiparameter water quality sondes were installed in the header and collection boxes during the shakedown tests. These sondes primarily measured turbidity, recorded at 15-s intervals. Turbidity was selected as a solids measurement because of its use in lakes and streams and for comparisons with other researchers that have reported significant turbidity reductions in runoff after flowing over test swales (Nara and Pitt 2005). Total suspended solids (TSS) were analyzed in samples collected at pre-determined timed intervals from surface-mounted sampling systems in each swale segment. TSS samples were also collected simultaneously in the header and collection boxes.

Results, Discussion, and Lessons Learned

Results and observations from preliminary tests offer some insight for construction and methods of analyses in swales. As the project matures, much more information will be available to evaluate grassed swale design and assessment.

Construction of Swales

During construction, several problems were encountered that could affect water quality. A substantial sediment load was encountered when the washed gravel that was purchased and placed in the swales was first rinsed. Gravel was washed for one hour using a 7.6-cm diameter fire hose that had a flow rate of approximately 600 lpm. The TSS concentration visually declined with time, but grab samples collected early in the washing process averaged 1800 mg/L. After the 1 h washing, filtrate from the gravel was relatively clear. During construction of infiltration devices at the Villanova Stormwater Park, researchers also had to wash "washed" gravel as part of the installation process to reduce initial sediment conditions (R. Traver, personal communication). The Center for Watershed Protection reported similar issues with purchased "washed gravel" (T. Schueler, personal communication).

Water Balance

Several shakedown tests were completed by pumping stormwater onto the swale. Flow rates and volumes were recorded using flow meters in delivery pipes and discharge pipes to evaluate whether a complete water balance could be done. The trial experiments used the 5% sloped swale lined with artificial turf. The preliminary data suggest that it will be possible to establish a water balance using empirical corrections to the measured flow rates. The uncertainty of the balance will be larger than anticipated.

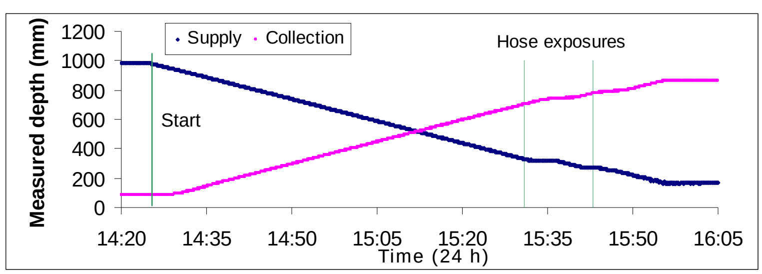

Figure 4. Measured depths in supply and collection tanks during a trial run.

Monitoring the depth in the supply and recovery tanks provide a usable estimate of flow rates. During the consistently controlled condition portion of a shakedown (see Figure 4), the measured levels changed linearly as expected for cylindrical tanks. The water level in the supply tank decreased at 14,325 mm/day. During the same period, the depth in the recovery tank increased at 14,397 mm/day (0.5% RPD). Figure 4 shows the time of runoff transit of the 5% swale by recording the delay in timing of depth measurements due to routing through the swales. This figure also indicates the measured response to change in pumping rate when the hose was exposed to air. Assuming uniform vertical cross section, the estimated average flow rate was 655 lpm, which is 4% lower than the corrected rate measured using the flow meters and within the estimated uncertainty of the corrected meter reading of the feed.

Soil Media

Results show that a 24-h equilibration resulted in considerable sorption of both Cu and Zn by the infield mix at a high soil:solution ratio (1:10), and at low concentrations (<1 mg/L) (Figure 5, only Cu shown).

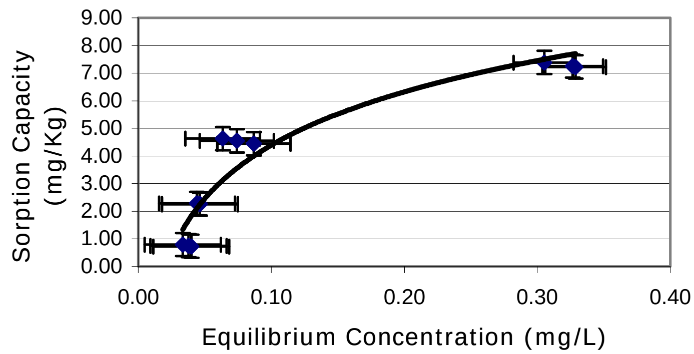

Figure 5. Copper isotherm data for the NJ infield mixture.

The chemical characteristics of engineered baseball infield mix soils are not homogeneous across the United States but are largely dependent on local conditions of quarry source material. When analyzing similar infield mixes from three NJ locations, two mixes were found to have a pH of 4.3-4.6, OM < 0.5%, and P-index < 2, while the other mix had a pH of 5.4. All three mixes required amendments to meet OM and P-index guidelines. Garden soil amendments of 6 g/100 g (wet weight) baseball mix and cow manure amendments of 5 g/100g (wet weight) baseball mix brought the OM and P-indices of these soils to within guideline specifications. Augmenting the infield mix with lime increased the equilibrium pH. Samples with a greater percentage of added lime reached an equilibrium pH faster than those with smaller amendments and had a higher final pH. The sample with 0.5% lime addition reached an equilibrium pH after more than 100 h, whereas samples with 10% lime additions reached equilibrium pH within 48 hours. It appears that for most infield engineered soil mixes, lime amendment of 0.5% or less is sufficient to raise the pH enough to meet bioretention soil guidelines. The amended pH is also within the desirable range for adsorption of heavy metals. However, by amending the infield mix to 5% OM (by wet weight) using garden soil, the resulting soil properties, including pH and CEC, were improved. The amendments resulted in a pH of 5.3, a P-index of >10.0, and a CEC greater than 10 meq/100g, bringing the mix to within range of the bioretention media guidelines and eliminated the need for lime amendments.

Stormwater Solids

The measured TSS concentrations in samples collected from the influent header box at 15-m intervals were reasonably consistent during the first part of the demonstration (Figure 6). Overall, the TSS concentrations were higher than typically encountered in stormwater runoff and previously observed at this outfall. This is probably due to known construction activities in the local watershed area. The TSS concentration measured in samples collected by an autosampler and using the sampling ports generally agreed with the header box samples. The increasing concentrations later in the experiment likely reflect incomplete mixing of the supply tank.

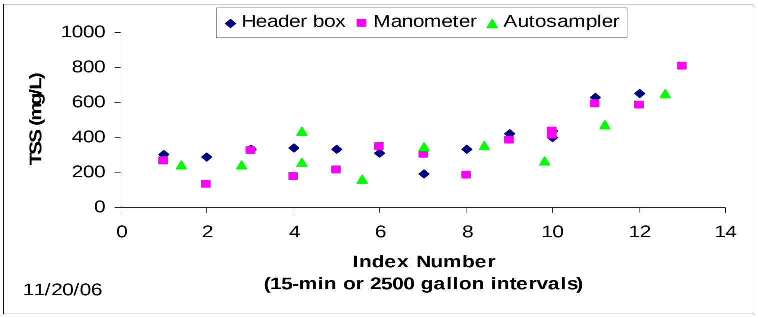

Figure 6. TSS concentrations measured in samples collected at 15-minute interval from the header box and manometers and samples collected at 9500-l (2500 g) intervals by the autosampler.

Turbidity measurements evaluated change in recorded turbidity between the inlet and outlet of the swale. The slotted protective cups covering the sensors in the sondes were filled with leaves after the first turbidity run. Therefore, the measured results during this demonstration are suspect.

Conclusion

Grassed swales are one of several tools to convey stormwater runoff from impervious surfaces. Many other perceived benefits are also associated with these systems. Reducing flow velocities, which allow increased sedimentation and increased infiltration, also contribute to decreased runoff volume and pollutant loading. Benefits of EPA's constructed swales include the ability to alter design shape, runoff volume, pollutant constituents, and media without risk to the well-being of surrounding population, personal property, or environment water quality. The addition of check dams with varying heights, materials, etc., to evaluate other design conditions is also a benefit. Lessons learned during constructioninclude the necessity to wash gravel even if sold as "washed gravel". Soil-media testing provided information on expected sorption of baseball infield mix and pointed out inconsistent chemical properties that may be common in other engineered soil mixes. This suggests soil testing is important when selecting an infiltration media. Monitoring the depth in the supply and recovery tanks provided a reliable estimate of swale flow rates. Overall, the controlled-condition research enables NRMRL to safely manage the research project and collect high-quality data needed to establish engineering design, in a manner that has less risk to people, equipment, and the environment.

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