Large-Scale Application of Biofiltration Swale Runoff Management Practices

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Abstract
Retaining rainfall where it lands is a fundamental benefit of Low Impact Development (LID). The Delaware Urban Runoff Management Model (DURMM) was developed to address the benefits of LID design. DURMM explicitly addresses the benefits of impervious area disconnection as well as swale flow routing that responds to flow retardance changes. Biofiltration swales are an effective LID BMP for treating urban runoff. By adding check dams, the detention storage provided can also reduce peak rates. This presentation explores how the DURMM runoff reduction approach can be integrated with detention routing procedures to project runoff volume and peak flow reductions provided by BMP facilities. This approach has been applied to a 1,200 unit project on 360 hectares located in Delaware, USA. Over 5 km of biofiltration swales have been designed, many of which have stone check dams placed every 30 to 35 meters to provide detention storage. The engineering involved in the design of such facilities uses hydrologic modeling based upon TR-20 routines, as adapted by the DURMM model. The hydraulic approach includes routing of flows through the check dams. This presentation summarizes the hydrological network, presents the hydrologic responses, along with selected hydrographs to demonstrate the potential of design approach.

Keywords
Biofiltration swales; check dams; DURMM; infiltration; LID; TR-20

INTRODUCTION
Delaware’s Green Technology (Lucas 2004a) approach integrates several elements of LID design that are rarely addressed by typical engineering practices, or available in other design manuals. These approaches have been incorporated into a spreadsheet model, the Delaware Urban Runoff Management Model (DURMM, Lucas 2004b). This model was formulated to overcome many of the deficiencies of other simpler event-based approaches. DURMM is now widely applied in Delaware, and is used extensively there by the engineering and regulatory community.

DURMM has been used to create LID designs that are on the ground now. This paper describes how the DURMM model was integrated with HydroCAD® routing software to design stormwater Better Management Practices (BMPs) for a 1,200 unit project on 360 hectares located in Delaware, USA. This project involved not only extensive use of biofiltration swales, but also several bioretention facilities and 6 large wet ponds. After a brief summary of the DURMM model, an overview of the project design and its routing and initial results is presented. A more detailed analysis of the potential of biofiltration swales using a simple process-based infiltration approach is then presented to examine the potential of routing infiltration dynamically during events.

METHODS
The DURMM model offers an approach to project reductions in runoff volumes due to impervious area disconnection (IAD). IAD is the conveyance of runoff from impervious source areas over pervious surfaces, providing opportunities for infiltration. The model also provides an innovative approach to retard flows by the use of shallow biofiltration swales, thus extending time of concentration (Tc). These volume and timing benefits are important elements of LID design.
DURMM adapts the Curve Number (CN) method (USDA-NRCS, 1985) to address the need for relatively simple hydrologic modeling approach for small storm events. While using the same allocation of discrete polygons defined by land cover and hydrologic soil group as is used in the CN method, DURMM hydrology for disturbed soils is based upon a derivation of the Hortonian infiltration equation, as formulated in the WinSLAMM model (Pitt, 1987; 2003). This results in more runoff from pervious areas during the small storm events comprising the majority of urban runoff, the underestimation of which is a major deficiency of the CN method.

The determination of segmental flow pathways used to determine $T_c$ is similar to that used in the CN method. However, DURMM employs a flow-weighted approach to routing the segmental flow pathways, as well as an iterative swale flow routing routine that accounts for the changes in Manning’s $n$ as function of flow depth, and includes submerged flow regimes. Application of this approach to biofiltration swales not only greatly increases the wetted area available for IAD, but also substantially increases the travel time, thus increasing $T_c$ and lowering peak flow rates.

DURMM projects IAD runoff losses using a rainfall excess approach based upon the CN method, which is applied to the wetted area computed by the swale flow routines. DURMM also has routines to compute detention storage in biofiltration swales and flow kinetics through stone check dams. This provides the input parameters for designs intended to meet required detention volumes distributed along biofiltration swales. In this manner, the relative precision of CN method input procedures has been complemented by the greater accuracy of the WinSLAMM hydrological algorithms, as well as flow-responsive $T_c$ computations.

**Biofiltration Swale BMPs**

Biofiltration Swales represent BMP in which filtering occurs as runoff travels at low flow depths through vegetation along a wide channel. Biofiltration swales are well suited for concentrated flow situations, where runoff has already been collected by piped conveyance systems. However, they are also very effective as a conveyance system in themselves, and they can employ shallow check dams to provide detention storage to meet the peak rate reduction criteria set forth in typical stormwater management regulations.

There seems to be a clear trend for a reduction in efficiency and increase in the minimum concentration with increasing depth and velocity of flow (Lucas 2004a). When used for conveyance, it is very important that vegetation not be submerged, since this causes the vegetation to bend over with the flow. For these reasons, biofiltration swales should be designed so that the average flow depth does not exceed 8-10 cm during the design quality storm event.

**Project Description**

The Bayberry Project in Delaware is the largest planned development in the state. The Village of Bayberry South comprises some 1,200 units located on a tract of 370 hectares. The land plan for this project involved a collection of neighborhoods situated on the bluffs overlooking the valleys draining to Shallcross Lake, a 19 hectare lake. The contributory watershed to this lake is 1,600 hectares, including the proposed 100 hectare Town Center, which also discharges through the project. As such, the potential impacts of the Town Center also had to be modeled as part of the overall routing.

Existing land cover on the property is dominated by row crop agriculture, which currently imposes substantial nutrient and total suspended sediment (TSS) loads upon the Lake. As such, it could be argued that any sort of suburban development would be beneficial. Applicable hydrological design criteria require that existing peak flows not be increased, and that BMPs be provided that would be
Large-Scale Application of Biofiltration Swale Runoff Management Practices

capable of providing 80% TSS removals. However, in addition to these required criteria, the intent of the design is the use of Green Technology BMPs to the maximum extent practical, and also to ensure that there would be no increase in runoff volume.

Due to effects of compaction, agricultural runoff volumes are already quite high, so the volume criterion is easily met. However, the relatively long flow path attenuates the existing peak rates of runoff, so peak rate controls were necessary. Given the location of much of the development immediately above steep slopes, the only viable alternative for providing peak rate attenuation and water quality improvement was to use biofiltration swales in the narrow strips of level ground between the developed areas and the bluffs. In combination with the proposed wet ponds, these BMPs were designed to provide the required water quality and quantity improvements.

**Routing Diagram**

Figure 1 illustrates how the various hydrologic nodes were routed in the HydroCAD® routing software. This software employs USDA-NRCS Technical Release 20 (TR-20) routines that are based upon the CN method. The CN method is the most widely applied hydrological routing approach used in the USA. However, as mentioned above, the CN method has shortcomings for small events, and cannot address the effects of IAD, so DURMM routines were used to develop the Tc and event CN for each subarea. Subareas are shown in the hexagon nodes (in green) in Figure 1.

![Figure 1: HydroCAD® Routing Diagram](https://iwaponline.com/wpt/article-pdf/2/2/wpt2007049/131082/49.pdf)
DURMM routines were also used to develop the Manning’s $n$ for the biofiltration swales that did not employ check dams. These are shown as the square orange reach nodes immediately downstream from most of the subareas. The loss of runoff due to IAD in these swales is incorporated as a reduction of its contributory subarea $CN$. Otherwise, no infiltration was allocated to these swales, even though the average infiltration rate in the site averaged over 12 cm/hr. The other reaches below the confluence of contributory subareas and biofiltration swales were modeled to replicate the geometry of existing channels draining into Shallcross Lake.

Ponds and junctions are shown as triangular nodes. The pale blue nodes are ponds with appreciable storage. These include the six water amenity ponds (circled in orange dashes), as well as the bioretention facilities and biofiltration swale check dam nodes. The bioretention facilities were segregated into ponded surface storage (blue circles) and bioretention media (dotted blue circles) to model facility response as runoff ponds up on the surface and discharges through outlets while simultaneously infiltrating into the media and then out the underdrains.

The dark grey triangular nodes represent conveyance manholes. They are inserted to account for the junction losses that occur in such structures. These junctions convey flows from the northwest pond (in upper left) as primary flows directed into the overall reach system. Secondary flow from this pond (in red dashed line) was routed to maintain inflows into the largest pond at the southwest (in lower left) through another series of junctions. The latter pond replenishes an infiltration facility (shown in dashed green circle). This facility and the bioretention media nodes were the only facilities for which infiltration was explicitly modeled in this study.

The remaining pond nodes represent the pools created by the presence of check dams and/or outlet structures at the end of the swales. These are used to convey swale runoff under roadways or into the final discharge locations at the bottom of the bluffs. By using such facilities, the energy of the flow is contained within engineered structures. This substantially reduces the erosive flows that presently destabilize the channels that presently convey runoff over the bluffs.

The biofiltration swale check dams are comprised of stone-filled gabion structures in which most of the fill stone is unscreened, so it is effectively impermeable. A central opening of clean stone at a specific width provides flow through the dams. Flow through these openings is routed as a special outlet in HydroCAD® based upon the routines described in detail in Lucas (2004a). Flow over the check dams is routed by typical trapezoidal weir equations.

**Initial Results**

The dynamic routing option in HydroCAD® accounts for the reduction in hydraulic gradient created by tailwater. Using this option, it was found that junction and outlet losses required so much head that the resulting storage in the water amenity ponds largely attenuated composite peak flows by themselves. As such, the low gradient of the conveyance system ended up controlling flows. As a result, check dams were needed only in locations of high discharge, or where the receiving reach segment bank conditions were unstable.

This resulted in some 31 check dams extended over a kilometer of detention biofiltration swales. The remaining 4.5 kilometers of biofiltration swales were found to meet the discharge criteria by virtue of their effect upon hydrograph timing alone. As a result, the stormwater management system displayed in Figure 1 was able to meet the required peak flow and volume criteria, as well as providing enough retention time in the biofiltration swales for water quality improvement.
Infiltration Opportunities in Biofiltration Swales

While the preceding analysis documented the effectiveness of the overall approach, recall that infiltration losses in the biofiltration swales were not computed during the dynamic hydrologic routing. However, substantial runoff losses have been documented in flows through conveyance swales located on permeable soils (Wanielseta and Yousef, 1993). Runoff losses accounted for a substantial portion of the mass load reductions in biofiltration swales (Johnson et al., 2003; Caltrans, 2004), so the infiltration potential of biofiltration swales has considerable documented potential.

Note that the wetted area of biofiltration swales is considerably greater than simple conveyance swales, while the underlying soils are unsaturated at the onset of a storm event. Even as soils become saturated, the saturated depth during frequent events thus remains fairly low. Furthermore, when check dams are used to detain runoff, the wetted area, duration of wetting and hydraulic head is increased. These preceding factors would substantially increase the rate of infiltration from biofiltration swales. However, there are few, if any, public-domain models that dynamically address how these elements affect infiltration rates.

To address the potential afforded by biofiltration swales, a revised Green-Ampt infiltration approach can project the runoff reductions due to detention along biofiltration swales. The dynamic infiltration rate in swales with check dams can be described by the following equation:

\[ f(t) = K_{sat} \frac{H(t) + L(t) + S_{av}}{L(t)} \]

where \( K_{sat} \) is saturated hydraulic conductivity, \( H(t) \) is the ponding depth, \( L(t) \) is the length of the wetting front, and \( S_{av} \) is the average capillary suction head at the wetting front, or \( \psi_0/2 \). \( \psi_0 \) is the matric potential at the wetting front. Refer to Lucas (in press) for the derivation of this equation.

These routines can be incorporated into a dynamic model of infiltration routing in bioretention swales with check dams. As a simplification of this dynamic approach, it is possible to highlight the effect of these factors by applying fixed infiltration rates to biofiltration swales and those swales with check dams, and running HydroCAD® to determine the results. Since HydroCAD® computes exfiltration as a function of wetted area, the effect of area is dynamically addressed.

To demonstrate the potential of dynamically routing infiltration losses from swales, most of the swales were extracted from the overall model to eliminate the effect of the pond and reaches, and linked to discharge at one point of analysis. These 4.4 km of swales convey runoff from 91.5 hectares of mostly developed areas. This represents 48 meters of swale per hectare of contributory area. Given a top width of 12.9m, the swales represent slightly over 6% of the contributory area. Three scenarios were prepared; the first scenario had the swales shortened to one-tenth their length without infiltration, as if they were pipes. The second scenario applied an infiltration rate of 5.1 cm/hr for the swales, plus the 10 outlet nodes. Given that the average rate in the sandy soils throughout the site was over 12 cm/hr, and that suction wetting effects were ignored, this is a conservative rate.

The third scenario added 124 check dam nodes to replace the swales. The infiltration rate was increased by 50% to 7.6 cm/hr in swales with check dams to approximate the increase in infiltration rate as a result of the effect of the \( H(t) \) and \( L(t) \) terms in (1). This is based upon an average ponding depth of 45 cm over an average wetting front depth of 90 cm. This simplification understates the increase for small events and overstates the increase for large events. These runs were applied to the 2-inch (5.1 cm), as well the 3.3-inch (8.4 cm), 5.2-inch (13.2 cm) and 7.5-inch (18.5 cm) storm events. These depths represent the 9-month, 2-year, 10-year and 100-year recurrence intervals.
RESULTS AND DISCUSSION

Figures 2 through 5 and Tables 1 through 4 present the results of this analysis. The piped conveyance runs represent the response of a typical piped conveyance system. This run provides data on the incoming volume and peak rate of runoff. The swale runs display the effect of the biofiltration swales upon hydrograph timing and volume reduction. As such, these runs represent the effect of IAD as applied to the wetted area of the swales. The runs for swales with check dams display the supplemental effect of the check dams upon the swale response.

The swale conveyance response shows how conveyance by the swales even without detention results in considerable runoff losses, as well as a substantial delay and attenuation of the hydrograph peak. At a 9-month recurrence interval, the volume is attenuated by 34.3%. Given that over 80% of annual runoff is generated by smaller events with less runoff, annual losses would be even greater. The delay in peak timing exceeds half an hour in the 2.0 inch event. This results in a very substantial attenuation of peak flows approaching 73%.

The response of the swales with check dams demonstrates the benefits of detention created by the check dams. The delays in timing are nearly an hour and the peaks are reduced beyond that provided by the swales, with reductions approaching 85%. Furthermore, the runoff volume is attenuated by 69.1%. Since annual runoff reduction would be an even greater percentage, such a substantial volume reduction emphasizes the remarkable potential for runoff and pollutant mass load reductions by using biofiltration swales with check dams.

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<th>Summary of Results, 5.1 cm</th>
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Figure 2 and Table 1: Runoff Response- 5.1 cm (2.0-in.), 24-hr Rainfall

<table>
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<th>Summary of Results, 8.4 cm</th>
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Figure 3 and Table 2: Runoff Response- 8.4 cm (3.3-in.), 24-hr Rainfall
A similar response is seen for the swale scenario in the 8.4 cm event, albeit less pronounced. At this 2-year recurrence interval, the delay in peak timing is still over 20 minutes. Given a runoff volume attenuation of 22.1%, this results in a peak flow attenuation approaching 53%. However, the effect of check dam detention results in delays in timing of nearly an hour, so peak flows are reduced even more, with reductions approaching 87%. The volume reduction is also still very high in this event, exceeding 57%. Events of this frequency are typically considered channel forming events, so such a substantial attenuation has important implications for the bank stability of receiving watercourses.

The peak flow attenuation provided by the swales in the 10-year event is over 38%, declining to 31% in the 100-year event. The runoff volume reductions without check dams are relatively low, being 15.2% and 11.4%, respectively. These responses reflect the higher runoff volumes and flow rates relative to the swale surface area, as well as the decreased retardance that occurs at higher flow depths.

The peak flow attenuation due to the swales with check dams in these large events is also less evident. Once the check dams are overtopped, the delay in the larger events is less pronounced. Rapid overtopping in the 100-year event results in virtually no attenuation compared to swales by themselves. This is probably due to dynamic pond routing assuming very rapid propagation of the flow waves from pool to pool. However, given their long and shallow geometry, the speed of...
propagation should more closely correspond to that of flow through the swales in a manner analogous to Muskingum-Cunge routing, so it seems probable that peak delays are understated.

Even so, note that the runoff volumes are still substantially attenuated, by 42.7% in the 10-year event, and by over 33% in the 100-year event. These reductions occur at peak depths less than a meter. If the swales were longer, or wider, there would be more attenuation of flows and volumes.

**CONCLUSIONS**
Considering that the area in swales represents only 6% of their contributory area, these results call attention to the potential for biofiltration swales with check dams to meet hydrologic objectives of reducing runoff peak rates and volumes from development. As previously stated, one of the most important elements of LID is retaining rainfall where it lands, and biofiltration swales with check dams provide a considerable benefit in terms of reducing pollutant loads by virtue of their runoff reductions alone. In view of the fact that the concentrations are also substantially reduced (Lucas 2004a), their cumulative benefits in terms of annual mass load reductions would be very substantial.

Furthermore, the considerable attenuation of flow peaks and volumes in the two year event will greatly reduce erosive stresses during the frequent runoff events that are most responsible for stream instability in urban watersheds. Given that events up to the 2-year event represent some 95 percent of annual rainfall in Delaware, these findings have very important implications for effective management of this deleterious impact of urban runoff.

Considering that the installed cost of piped systems are in the same range as swales, this suggests that biofiltration swales are not only very effective from a hydrological standpoint, they can be very cost-effective as well. Often, such swales can be integrated into the adjacent open space and buffers that are required in most development projects as part of regulatory design standards anyway. As such, the marginal land cost of such swales is minimal. This is in marked contrast to the cost and expense of discrete “end of pipe” detention facilities.

The preceding discussion has established a framework for dynamic computation of infiltration losses from distributed detention facilities. This framework is particularly suited to Green Technology BMPS such as biofiltration swales that have a relatively large surface area in relation to their source area. This approach provides BMP designers with a tool that dynamically quantifies the extent of volume reductions provided by distributed infiltration approaches during the storm event. In this manner, a key element of LID design can now be more rigorously defined.

**REFERENCES**
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