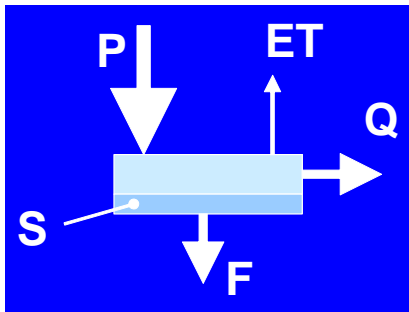


Modeling the Effectiveness of Traditional and Innovative Stormwater Management Strategies in the Chagrin River Watershed: Part 1 - Development Site Scale

September 2009

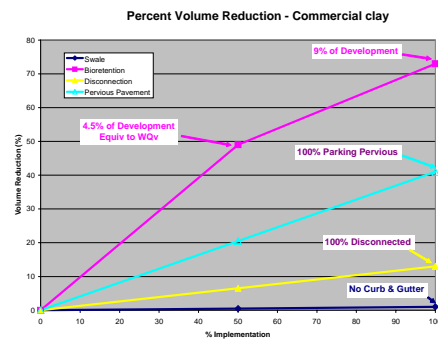
Jay Dorsey, ODNR-DSWR; Rachel Webb, CRWP; Jon Witter, Ohio NEMO; Dan Mecklenburg, ODNR-DSWR; Amy Brennan, CRWP



Center Street Redevelopment Project, Mentor, Ohio



Bioretention Project - Sterncrest Road, Orange Village, Ohio



Chagrin River Watershed Partners, Inc.
P.O. Box 229, Willoughby, Ohio 44094
(440) 975-3870, www.crwpp.org

Project Partners

This report was prepared by the Chagrin River Watershed Partners, Inc. (CRWP), Ohio Non-point Source Education for Municipal Officials (NEMO) program, and Ohio Department of Natural Resources— Division of Soil and Water Resources (ODNR-DSWR). Funding and support for this project was provided by CICEET, the Cooperative Institute for Coastal and Estuarine Environmental Technology. A partnership of the National Oceanic and Atmospheric Administration and the University of New Hampshire, CICEET develops tools for clean water and healthy coasts nationwide. Additional support for this report was provided by the Members of CRWP through their annual Member dues.

CRWP is a non-profit technical organization formed by the townships, villages, cities, counties, and park districts of the Chagrin watershed to develop and implement innovative solutions to address current, and minimize new, flooding, erosion, and water quality costs and to control the increasing infrastructure costs associated with urban/suburban development. CRWP provides Members with advice and assistance on zoning and subdivision codes, implementation of these codes, development plan review, and other best practice implementation at Member direction.

ODNR was formed by the Ohio Legislature in 1949 and is charged with developing and implementing long-term planning and programming related to the development and conservation of the states' natural resources and participating in regulatory matters associated with environmental hazards. ODNR has many diverse programs and owns and manages 590,000 acres including 74 state parks, 20 state forests, 133 nature preserves, and 138 wildlife areas. The Division of Soil and Water Resources provides leadership and services to conserve, protect, and enhance soil, water, and land resources.

The *Ohio NEMO* program was started in 1999 to help local governments better manage non-point source pollution while accommodating growth. The program is built on the belief that well informed land use planning is critical for the protection of environmental quality. Since land use planning takes place primarily at the local level, Ohio NEMO focuses their efforts on working with local decision makers and their support personnel. More recently, Ohio NEMO has focused on technical issues and developing local capacity to use GIS and modeling tools to provide quantitative analyses of potential environmental impacts due to land use decisions.

Table of Contents

Acronyms and Abbreviations..... 4

Abstract..... 5

Introduction..... 6

Approach..... 11

Model Selection..... 11

Representative Sites..... 13

Regulations that Affect Stormwater System Design and Performance..... 13

Scenarios Modeled & Input Data..... 13

Results and Discussion..... 21

Runoff Volume..... 23

Runoff Water Quality..... 35

Peak Discharge Rate..... 39

Implementation Issues..... 40

Evaluation of WinSLAMM as a Modeling/Planning Tool..... 41

Conclusions and Recommendations..... 47

Acronyms and Abbreviations

ASCE	American Society of Civil Engineers
BMP	Best Management Practice
C&G	Curb and Gutter
CGP	Construction General Permit
CN	Curve Number
CRWP	Chagrin River Watershed Partners, Inc.
CSM	Critical Storm Method
CWA	Clean Water Act
CWP	Center for Watershed Protection
DEM	Digital Elevation Model
DSWR	Ohio Dept. of Natural Resources, Division of Soil and Water Resources
FABE	Food, Agricultural and Biological Engineering Department, Ohio State University
GIS	Geographic Information System
HSG	Hydrologic Soil Group
LID	Low Impact Development
LLR	Large Lot Residential Development
MDE	Maryland Department of the Environment
MDR	Medium Density Residential Development
NEMO	Nonpoint Education for Municipal Officials
NEORS	Northeast Ohio Regional Sewer District
NPDES	National Pollutant Discharge Elimination System
NRCS	Natural Resources Conservation Service, U.S. Department of Agriculture
NURP	Nationwide Urban Runoff Program
ODNR	Ohio Department of Natural Resources
OEPA	Ohio Environmental Protection Agency
OSU	Ohio State University
SLAMM	Source Loading and Management Model
SWMM	Storm Water Management Model
TR-20	Technical Release 20, Computer Program for Project Formulation
TR-55	Technical Release 55, Urban Hydrology for Small Watersheds
USDA	U.S. Department of Agriculture
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geologic Survey
WEF	Water Environment Federation
WQv	Water Quality Volume

Modeling the Effectiveness of Traditional and Innovative Stormwater Management Strategies in the Chagrin River Watershed: Part 1 - Development Site Scale¹

Jay Dorsey, ODNR-DSWR; Rachel Webb, CRWP; Jon Witter, Ohio NEMO; Dan Mecklenburg, ODNR-DSWR; Amy Brennan, CRWP^{2,3}

Abstract

WinSLAMM (Source Loading and Management Model) was used to evaluate the effectiveness of alternative stormwater management approaches, relative to those currently favored by local and state regulations, in reducing runoff volume and controlling annual sediment loads. The practices evaluated included impervious area disconnection, open swale drainage, bioretention and pervious pavement. These practices, especially when used together, can more effectively manage runoff volume with several combinations approaching pre-development runoff volume. Controlling runoff volume is key to minimizing damage and costs associated with flooding and severe stream erosion, and to achieving water quality standards.

WinSLAMM predicts that low impact stormwater practices individually can reduce site-scale annual runoff volume from a few percent to over 50%, while a well-designed suite of low impact practices can reduce annual runoff volume by 80% for residential or commercial development. Impervious area disconnection and bioretention show the most promise for residential areas, whereas pervious pavement and bioretention show the most promise for commercial sites.

Currently, there is little impetus for developers or their engineers to include these practices in the design of new developments. Widespread implementation of these alternatives requires reconsideration of local zoning, subdivision and stormwater regulations, as well as methods for promoting and accounting for their use. This report makes land use specific recommendations for promoting alternative approaches, highlights issues with implementation of these alternatives, and evaluates WinSLAMM as a stormwater planning and research tool.

¹ This study was supported by two grants:

(1) "Improving Stream Protection and Assistance to Phase II Communities through Advanced Storm Water Standards" (ODNR, 2004); funding and support provided by OWDA, the Ohio Water Development Authority.

(2) "Improving Land Use in the Lake Erie Basin through Better Planning, Improved Regulations, and Stormwater Modeling" (CRWP, 2006); funding and support provided by CICEET, the Cooperative Institute for Coastal and Estuarine Environmental Technology. A partnership of the National Oceanic and Atmospheric Administration and the University of New Hampshire, CICEET develops tools for clean water and healthy coasts nationwide.

² Ohio Department of Natural Resources, Division of Soil and Water Resources (ODNR-DSWR); Chagrin River Watershed Partners (CRWP); and Ohio NEMO Program, Ohio State University, Department of Food, Agricultural and Biological Engineering.

³ Acknowledgments: This project would not have been possible without the contributions of Brian Ashurst, City of Mentor; Justin Czekaj, City of Aurora; Joan Milhoan, City of Solon; Kyle Dreyfuss-Wells, NEORS (formerly CRWP).

Introduction

The stormwater management paradigm has evolved as our understanding of the environmental and economic impacts of stormwater management strategies has improved (Pitt, 2005b; Reese, 2007). Over the centuries, stormwater management morphed from open drainage systems (ditches) to remove stormwater and wastewater, to combined sewer pipes to handle both stormwater and wastewater, to separate sewers for wastewater (sanitary) and stormwater. It might be said that the focus, historically, was on cleanliness and convenience at the point of stormwater generation.

During the 1970s and 1980s, concerns about downstream flooding led to stormwater structures (mostly detention ponds) that control the peak rate of discharge from individual developments during extreme storm events, typically larger than 2 inches. This approach resulted in an entire generation of engineers and planners trained to connect rooftops, streets and parking lots directly into storm sewers to quickly direct rainfall away from where it is not wanted (yards, streets, parking lots) to the stormwater pond where it is “managed” (see e.g., ASCE, 1992). Wide curb and gutter streets, downspouts directly connected to storm sewers, catch basins located within parking lots with curbed and landscaped “islands”, and underground drainage networks are a result of regulations (zoning, subdivision and stormwater) developed during this era. This paradigm continues to be a primary driver of stormwater management decisions made by local governments in the Lake Erie basin.

By the late 1980s and early 1990s, it became apparent that efficient stormwater drainage/conveyance systems and end-of-pipe detention ponds were not “managing” all of the issues related to stormwater (Schueler, 1987). The Clean Water Act (shorthand for a number of pieces of legislation from 1970s and 1980s) helped expand the focus on stream and lake water quality beyond the industrial dischargers to “non-point sources” of pollution. The Nationwide Urban Runoff Program (NURP; USEPA, 1982) was a great first step in quantifying and documenting the effectiveness of end-of-pipe stormwater controls for managing water quality. Another 25+ years of research has resulted in an extensive stormwater runoff quality database. Burton and Pitt (2001) are amongst the many who have documented the water quality impacts of stormwater runoff.

Another body of research and literature has developed around stormwater impacts on receiving channel stability (see e.g., Booth, 1990; Booth and Jackson, 1997; Mecklenburg and Ward, 2002). In essence, stream channel size and shape is a direct result of the interaction between the amount of surface runoff, the stream slope, and sediment characteristics. If more runoff volume is added to a stream or stream slope is increased, more and bigger sediment will move, resulting in channel incision.

Large detention ponds with flood control outlets do little to mitigate the impacts on downstream channel stability that result from increased imperviousness and runoff. As a result, historic stormwater management programs and guidelines have caused degraded, unstable receiving streams. Degraded (i.e., incised or entrenched) receiving streams are less efficient at processing nutrients and assimilating suspended sediments resulting in poor in-stream habitat and water quality. In addition, unstable stream systems often pose threats to roads, bridges and other infrastructure that may require costly remediation measures. These impacts are common in the Chagrin watershed and throughout the Lake Erie basin.

It should be noted that, although the knowledge base about ecological consequences of channel incision and hydromodification has increased significantly within the scientific community over the last 20 years (see e.g., Konrad and Booth, 2005; USEPA, 2007b), these issues are not well understood by practicing stormwater engineers and local decision makers.

Another interesting note about the end-of-pipe detention basin as flood control paradigm is that studies going back to the 1970s (see e.g., McCuen, 1974, 1979; Duru, 1981; Urbanas and Glidden, 1983; Traver and Chadderton, 1983; Emerson et al., 2003) have highlighted that, although detention basins may manage peak discharge at the outlet to the development site, the cumulative effects at the watershed scale are much more complex and may exacerbate flooding problems under some scenarios. In spite of this, few communities have measured or modeled the impacts of their stormwater management strategies at a watershed scale.

To address the multiple concerns related to stormwater management, a more comprehensive set of design criteria have been developed and applied by different state and local governments. One approach, developed and promoted by the Center for Watershed Protection, is the Unified Sizing Criteria approach (see e.g., Ch. 2 of Maryland Stormwater Manual; MDE, 2000) that incorporates water quality, groundwater recharge, channel protection and flood protection criteria.

Through review of national research literature and guidance, and consultation with the Ohio Department of Natural Resources, Division of Soil and Water Resources (DSWR) and other partners, the Ohio Environmental Protection Agency (Ohio EPA) chose to focus their initial state-level post-construction stormwater requirements (Ohio EPA, April 2003) on water quality and the protection of channel stability in receiving streams.

The post-construction requirement in the Ohio EPA NPDES⁴ Construction General Permit (CGP), known as the water quality volume (WQv), reflects the dominant na-

⁴National Pollutant Discharge Elimination System.

tional guidance on the capture and treatment of stormwater runoff for some “water quality event” that ranges from 0.5" to 1" depending on local rainfall characteristics (ASCE, 1998; USEPA, 2004). Most states that have adopted state-level post-construction water quality standards include a WQv requirement, and this standard consistently has been promoted by USEPA in NPDES-targeted stormwater management guidance (e.g., USEPA, 2004; Muthukrishnan et al., 2004).

In Ohio, the choice of 0.75 inches as the WQv rainfall capture depth and the requirement that the extended detention (24-48 hr) drawdown come from a “brimful” condition allows this single requirement to function both as a water quality requirement and a channel protection requirement. In essence, the WQv sizing and drawdown requirements result in capture, extended detention and treatment of routed rainfall depths of between 0.85 and 1.5 inches.

Ohio EPA included in the CGP (p23; Ohio EPA, 2008) a number of structural best management practices (BMPs) that have a proven track record for stormwater treatment for water quality, and are capable of the extended detention necessary to help maintain channel stability. These practices are required for all developments that disturb 5 acres or more, and are highly recommended for all developments that disturb more than 1 acre but less than 5 acres.

Table 1. Ohio EPA Accepted Structural Post-Construction BMPs (OEPA, 2008; Construction General Permit Table 2)

Best Management Practice	Drain Time of WQv
Infiltration Basin [^]	24 - 48 hours
Enhanced Water Quality Swale	24 hours
Dry Extended Detention Basin [*]	48 hours
Wet Extended Detention Basin ^{**}	24 hours
Constructed Wetland (above permanent pool) ⁺	24 hours
Sand & Other Media Filtration	40 hours
Bioretention Cell [^]	40 hours
Pocket Wetland [#]	24 hours
Vegetated Filter Strip	24 hours

Not surprisingly, the most common means of meeting the WQv requirement in Ohio is a detention basin. This is understandable on at least two counts: (1) given the “detention basin is stormwater management” paradigm described above, designers and developers have limited knowledge of the alternatives; and (2) local regulations for most development sites require one of the aforementioned peak discharge control detention ponds, into which the WQv readily can be incorporated.

Historically, very little thought was given to preserving open space or managing stormwater at its source, resulting in curb and gutter drainage networks that quickly deliver high volumes of stormwater runoff to large detention basins. However, guid-

ance developed over the last 10 years has seen a significant shift in emphasis toward more ecologically oriented development approaches variously called smart growth, low impact development, green infrastructure, water sensitive urban design, integrated site design, and environmental site design (CWP, 1998; Prince George's County, 1999a, 1999b; Coffman, no date; USEPA, 2005a; Bitting and Kloss, 2008; MDE, 2008)⁵. In essence, these approaches protect, enhance or mimic natural processes to maximize the degree of stormwater management functions and services provided by the landscape (Wulliman and Thomas, 2005). Two recent publications (Belan and Otto, 2004; DePhilip et al., 2006) promote this approach for the Great Lakes watersheds.

This shift in paradigm carries with it a number of issues related to that transition. These will be discussed in some detail later in this report, but a several related issues are worth noting up front: (1) complexity of the stormwater management system; (2) engineer and reviewer knowledge/experience/ability; (3) guidance and tools for analysis and design; (4) incentives for implementation; and (5) removal of barriers to implementation.

For 40 years or more, engineers were able to describe and model stormwater runoff with relatively simple tools such as the rational method, the modified rational method and Natural Resources Conservation Service (NRCS) curve number method, and the guidance reflected this paradigm (see e.g., NRCS, 1986; ASCE, 1992; McCuen, 1998). With the shift in focus from extreme rainfall events (2" or 3" or more) to the entire rainfall spectrum, an entire new level of understanding and ability is required to analyze, design and construct the new developments and their stormwater systems.

The 99% of rainfall events less than 2" have been labeled Small Storm Hydrology, and the context and challenges for management outlined, by Pitt (1987, 1999, 2003a). The need for different types of hydrologic, hydraulic and water quality analyses has led to development of a suite of analytical tools such as WinSLAMM⁶, Water Balance Model, and BMP DSS⁷, as well as new uses for more traditional tools such as SWMM (Elliott and Trowsdale, 2006; Huber et al., 2006; Zhen et al., 2006; Stephens and Dumont, 2008). In addition, hydraulic analyses are being carried beyond the development site in the form of flow duration analyses to predict impacts on bedload dynamics and channel stability (see e.g., Rohrer and Roesner, 2005; Aquafor Beech Limited, 2006).

Up to this point in Ohio there has been little incentive (e.g., a pat on the back) for developers or design engineers to incorporate low impact development features. The in-

⁵This report uses "low impact development" (LID) for the suite of ecologically-oriented strategies and practices.

⁶WinSLAMM – windows version of the Source Loading and Management Model

⁷BMP DSS – BMP Decision Support System

centive must come either from the carrot (cost savings, positive press, etc.) or from the stick (regulations). Several states are taking the “stick” approach. For example, Maryland, Minnesota, and Wisconsin have some form of groundwater recharge or infiltration criteria, forcing engineers to incorporate LID practices into their designs.

Several states (including Minnesota and Pennsylvania) have provided a “carrot” by providing credits toward meeting some aspect of their stormwater criteria through the use of LID practices (MPCA, 2005; PaDEP, 2006). However, the biggest incentive will come from cost savings achieved through the LID approach. Examples of these savings are being documented by U.S. EPA and others (see e.g., USEPA, 2007a). Also, tools such as the BMP Decision Support System (Zhen et al., 2006) that include cost optimization allow designers and reviewers to evaluate a wide menu of practices to find the mix that best fits the development type and watershed setting.

Meeting the multiple objectives of flood control, water quality protection, and channel stability is a difficult task. Little quantitative analysis specific to the Lake Erie basin exists to support local governments as they attempt to improve stormwater management plans including best management practice selection. Evaluating the many factors that influence water quantity, water quality, and stream stability is complex and not easily accomplished by direct measurements.

Evaluating hydrologic and environmental responses that might occur as a result of land use changes and stormwater management choices can be greatly facilitated with decision tools such as computer simulation models. This approach is particularly useful in evaluating the effect of existing or proposed zoning, subdivision and stormwater regulations, or the range of stormwater management strategies.

In order to enhance the effectiveness of land use planning, to support improved stormwater regulations, and to provide guidance for local reviewers and engineers in best management practice selection, the Source Loading and Management Model (WinSLAMM; Pitt and Voorhees, 2002) was tested for its ability to evaluate the potential of various stormwater management criteria and practices to meet comprehensive goals of flood control, channel stability, and water quality protection.⁸

⁸Disclaimer - The purpose of this study was not to calibrate or validate WinSLAMM parameters for the Chagrin River watershed, an exercise that would have required extensive rainfall-runoff-pollutant data sets at the source area and development site scale. The small storm runoff hydrology of impervious surfaces is not location-dependent, and the original tests from Milwaukee and Toronto that led to development of the model should provide a reasonable representation for Ohio climate and conditions (R. Pitt, personal communication; Pitt, 1987, 2003b, 2008). A clay soil type was selected for all pervious areas to be conservative and not overstate the benefits of low impact practices. A logical next step past this study would be to find or develop one or more detailed rainfall-runoff or rainfall-runoff-pollutant data sets to verify WinSLAMM input parameters for northeast Ohio conditions. Further discussion can be found in the “Evaluation of WinSLAMM” and “Next Steps” sections.

Approach

The following section outlines the approach taken to evaluate different development types, local regulations and BMP choices including:

- ▶ selection of appropriate models;
- ▶ identification and definition of representative sites;
- ▶ review of current regulations that affect stormwater system design and performance; and
- ▶ description of scenarios modeled and development of input data sets.

Model Selection

Model selection was driven by several factors including:

- ▶ hydrologic and water quality performance to be evaluated;
- ▶ management scenarios to be modeled;
- ▶ capabilities and limitations of the modeling tool;
- ▶ ease of use;
- ▶ cost; and
- ▶ prior experience with models.

For the purpose of the project, it was decided a priori to focus the site-level performance or “effectiveness” on two criteria: 1) annual runoff volume; and 2) suspended solids. In addition, it was necessary to generate development site scale discharge hydrographs as inputs to the watershed-scale model.⁹

Thus, the project focused on finding an urban hydrology model capable of simulating the impact of various management strategies, such as downspout disconnection, curb and gutter versus swale drainage, bioretention and pervious pavement, on runoff volume and water quality for individual developments. An earlier evaluation of models by ODNR-DSWR narrowed the field of models to the Storm Water Management Model (SWMM) and Source Loading and Management Model (SLAMM)¹⁰. These computer models were developed to model both quantity and quality of stormwater runoff in urban and urbanizing environments. SWMM, developed under the sponsorship of the U.S. Environmental Protection Agency, has become the industry standard for modeling and designing complex drainage networks (Rossman, 2008). SLAMM was developed to more accurately quantify runoff volumes and pollutant concentrations for the smaller storm events not typically addressed by models used for drainage system de-

⁹The watershed-scale model was used to examine the viability of using rehabilitation of entrenched streams as an alternative approach to accomplish comprehensive stormwater management objectives (CRWP, 2006).

¹⁰Since the WinSLAMM model was selected, two excellent, if now a bit dated, reviews of models capable of LID modeling were published (Elliott, A.H., and S.A. Trowsdale, 2006; Huber et al., 2006).

sign (Pitt and Voorhees, 2002). The decision was made to use WinSLAMM, the most current version of SLAMM, because of specific application to the study objectives, ease of use and cost¹¹.

WinSLAMM is a semi-empirical hydrologic and water quality model “developed to better understand the relationships between sources of urban runoff pollutants and runoff quality” (Pitt and Voorhees, 2002). Model theory is covered in great detail in Pitt’s Ph.D. dissertation (Pitt, 1987). Though WinSLAMM can model runoff from a single event or a time series (i.e., continuous), the heart of WinSLAMM is per event hydrology based on simple volumetric runoff coefficient relationships for each source area. The model contains source area specific pollutant build-up and wash-off algorithms. The model has the capability to model water quantity and water quality impacts of wet detention basins, swale drainage, impervious area disconnections, bioretention and pervious pavement. A simple schematic of model structure is presented in Figure 1.

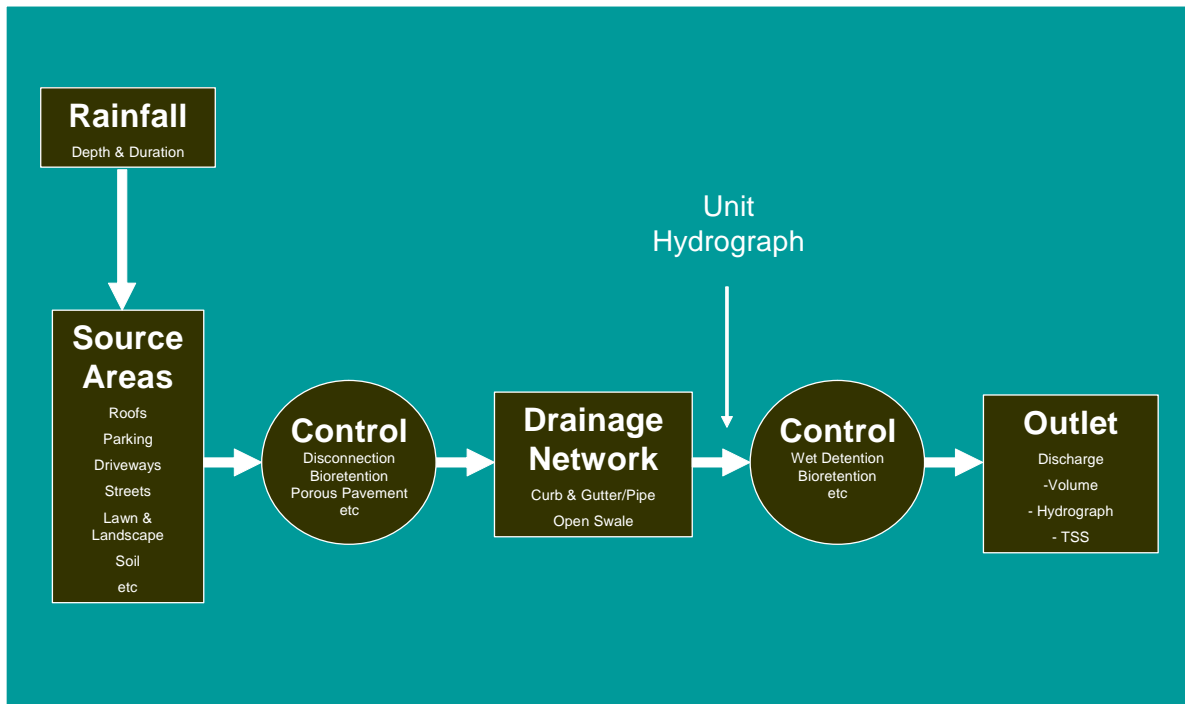


Figure 1. WinSLAMM Model Structure

More detail on WinSLAMM is given below. Development of WinSLAMM input data sets is described later in this section. The results of the modeling exercise, and commentary on the functionality of the WinSLAMM model are covered in later sections.

¹¹During the course of this research, SWMM, USGS regression equations, spreadsheets, rational method, and NRCS curve number method also were used to model aspects of the developments (e.g., to size or model the sewer network, drainage swales or detention basins).

Representative Sites

Identification of “representative” landscapes and developments was considered critical in order for the modeling results and conclusions to be transferable to other parts of the Lake Erie basin. Common types and characteristics were noted on field visits to a range of commercial and residential developments in several Chagrin Watershed communities (Solon, Mentor, Aurora, Moreland Hills, Pepper Pike, Mayfield Heights).

In December 2007, CRWP, Ohio NEMO and ODNR-DSWR met with representatives of the cities of Aurora, Mentor and Solon. From this meeting, it was determined the site-scale modeling would:

- ▶ develop “generic” residential and commercial developments based on zoning and stormwater requirements for the city of Solon;
- ▶ collect, compare and contrast zoning and stormwater requirements from Aurora and Mentor to assess applicability of modeling results to other communities; and
- ▶ given adequate time and resources, also consider large lot township zoning and development.

Regulations that Affect Stormwater System Design and Performance

Stormwater management decisions and outcomes are affected by a wide variety of explicit/direct and hidden/indirect development requirements including minimum lot sizes, minimum house sizes, minimum street width or parking space requirements. To be able to accurately model stormwater outcomes in a community requires consideration of land use plans, zoning maps and regulations, subdivision regulations, and stormwater regulations. Beyond the code, conversation with the staff that implement these regulations gives insight into specifics of implementation and enforcement.

Stormwater, subdivision and zoning regulations were collected for Aurora, Mentor, Solon and Geauga County (Bainbridge Township). Solon subdivision, zoning, and stormwater regulations were reviewed in-depth for rules, restrictions and requirements that influence development stormwater system characteristics. The same exercise, at a more perfunctory level was conducted for Aurora and Mentor. Those regulations are summarized in Appendix A-1.

Scenarios Modeled & Input Data

The following three development types were modeled:

1. Commercial development (85% impervious area) representing a commercial strip or shopping center with outlots;
2. Medium density residential subdivision (30% impervious area) with 0.4 acre lots, representing typical new development lot minimums in the participating municipalities; and

3. Low density or “large lot” residential (12% impervious area) with 2 acre lots, representing township development as well as certain residential zoning (e.g., Aurora R-1) in participating municipalities.

Each development was set at 20 acres for the following reasons:

- ▶ new residential and commercial developments in the watershed range in size from a few acres to more than 50 acres;
- ▶ upon discussing drainage areas within new development, several local engineers mentioned 20 acres as being “typical”; and
- ▶ 20 acre development blocks were readily scalable into larger 80 ac, 320 acre, etc. subwatersheds for watershed-scale modeling purposes¹².

The inputs needed to populate the WinSLAMM modeled are listed in Table 2.

Table 2. WinSLAMM model inputs.

Input	Options
Rainfall Data	time series or event
Soil Type	sandy (HSG-A), silty (HSG-B), or clayey (HSG-C or HSG-D)
Land Use Source Areas	percent of development in roofs, driveways, sidewalks, parking areas, streets, lawns/landscaping, etc.
Drainage	curb & gutter or swale
BMP Controls	wet detention, bioretention, or pervious pavement
Pollutant Build-up and Wash-off Files	provided for Midwestern U.S. conditions
Unit Hydrograph Characteristics	peak/average ratio for compound triangular unit hydrograph

The rest of this section will discuss development of rainfall data, and detail selection or development of appropriate input data.

Rainfall Data

Two types of rainfall data were needed for this study: 1) design events representing different durations from 3 to 24 hours and recurrence intervals from 0.1 to 100 years; 2) recorded rain gage data for a “typical” year.

¹²A sensitivity analysis was performed comparing 20, 40 and 80 acre blocks to determine impact on model impacts. Influence on runoff volume and 80 acre (i.e., a single 80 acre, 2x40 acre, or 4x20 acre) discharge hydrographs was deemed inconsequential for purposes of this study. The potential effect of development size on pond size and geometry (especially pond surface area) could significantly affect removal efficiency of suspended solids.

Design Event Data - Three sources summarizing the historic rainfall record are in common use in Ohio: TP-40 (Hershfield, 1961), Bulletin 71 (Huff and Angel, 1992), and NOAA Atlas 14 (NWS-NOAA, 2004). The NOAA Atlas 14 data is the most accurate, up-to-date, and location-specific rainfall data and easily accessed through the NWS Precipitation Frequency Data Server. The recurrence intervals available in Atlas 14 are 1 to 100 years. For smaller recurrence intervals, Huff and Angel (1992) was used.

For this study, two sets of design events were used. Local stormwater regulations typically include some form of peak discharge control. In this modeling exercise, the peak discharge approach utilized was the Critical Storm Method (CSM; ODNR, 1980), the peak discharge requirement in Aurora and Mentor stormwater regulations. The CSM requires rainfall depths for the 1 through 100 year, 24 hour events. For this study, NOAA Atlas 14 data for a location near Solon was used.

To be able to analyze the range of effects of valley storage on stream discharge and depth (see companion study), a wide variety of rainfall depths and storm durations was evaluated. A 44-event design storm series was created with 11 events each with durations of 3, 6, 12 and 24 hours. The recurrence intervals for the 11 events were 100, 50, 25, 12.5, 6.2, 3.1, 1.6, 0.8, 0.4, 0.2 and 0.1 years¹³. The 1.6 through 100 year RI events are derived from Atlas 14. The 0.1 through 0.8 year events were derived from Huff and Angel (1992). The resulting “Chagrin Design Storm” data set is as follows:

Table 3. Rainfall depths for the 0.1 through 100 year, 3, 6, 12 and 24-hr Events.

	Duration (hr)			
RI (years)	3	6	12	24
0.1	0.55	0.64	0.74	0.85
0.2	0.76	0.89	1.02	1.18
0.4	0.97	1.13	1.31	1.51
0.8	1.21	1.42	1.64	1.90
1.6	1.39	1.66	1.95	2.27
3.1	1.66	1.98	2.29	2.68
6.2	2.00	2.36	2.73	3.18
12.5	2.32	2.74	3.17	3.67
25	2.69	3.21	3.70	4.26
50	3.07	3.68	4.24	4.86
100	3.46	4.18	4.82	5.49

¹³Note: This design storm series was developed by taking the 100 year recurrence interval (RI), and then halving the RI ten times (50 = 100/2, 25 = 50/2, 0.1 = 0.2/2) as described in Mecklenburg and Ward (2002).

Typical Year Rainfall Data - The best way to compare different development scenarios at the site scale is to look at the performance in terms of runoff volume and solids pollutant load over a “typical” year of real rainfall data from the area. Several sets of long-term recorded rain gage data (Burton, Cleveland Easterly, Painesville Highway Department and Ravenna) collected within 25 miles of the Chagrin watershed were available through the Midwest Regional Climate Center.

Review of annual and seasonal rainfall averages suggested that the Burton gage data would be the most representative of the majority of the Chagrin watershed¹⁴. Forty one (41) years of rainfall data (1950-1990) were processed and formatted for input to WinSLAMM (start date, start time, end date, end time, event depth). The inter-event period was set at six (6) hours. After the data was processed and formatted, it was evaluated for complete years of rainfall data (i.e., no periods of non-recording or bad data). Twenty (20) years of data were “discarded” for incompleteness. The remaining years were evaluated for closeness to the following characteristics - mean annual rainfall, mean monthly rainfall, event frequency distribution. Burton rainfall year 1980 was determined to be most representative of those characteristics and is henceforth labeled “typical”¹⁵.

Site Characteristics

The development of representative site characteristics for input data was evolutionary, starting from initial discussions and site visits, through review of local regulations, preliminary geographical information system (GIS) analysis of candidate subdivisions, to selecting and ground-truthing representative sites. Though a similar process was conducted for the representative commercial and low density residential, the development of medium density residential site characteristics is detailed here¹⁶.

A project-specific Chagrin GIS was developed from data provided by CRWP and the three participating communities that included high-resolution aerial photos, digital elevation models (DEMs), soils data and parcel data.

¹⁴It should be noted that there is a significant gradient in annual rainfall from Lake Erie to the East Branch headwaters. It is likely that individual storm characteristics (intensity, duration) would also vary most from Burton data the closer to Lake Erie. This should be taken into consideration when selecting precipitation data for continuous hydrologic modeling in the northern one-third of the watershed.

¹⁵There is no such thing as a “typical” rainfall year, but other terms seemed just as inaccurate.

¹⁶The process followed here, for the most part, is outlined in detail in the WinSLAMM user’s guide Section 5, “Using WinSLAMM” (Pitt, 2003b). A case study that uses this approach for the Little Shades Creek Watershed in Alabama is presented in “Site Development Characteristics for Stormwater Modeling” (Bochis and Pitt, 2005).

Soils -A review of the watershed soils showed a predominance of glacial till-derived hydrologic soil group (HSG) C & D soils (Mahoning, Ellsworth, Wadsworth, Rittman, etc.) with a few more-permeable HSG-B soils (e.g., Chili) in developable upland areas¹⁷. Valley bottoms are dominated by HSG-B & C soils (Holly, Tioga, Chagrin, Orrville, Euclid) developed in alluvium on floodplains and low terraces. For this study, clay soils were selected in WinSLAMM to represent the predominant HSG-C & D soils in upland areas.

Land Use/Source Areas - For each development type of interest (commercial, medium-density residential, large lot residential) the following process was followed:

- ▶ review zoning and subdivision regulations for requirements that will affect source area size and dimensions (lot size, house size, setbacks, street width, cul-de-sac diameter, open space requirements, etc.);
- ▶ use aerial photos in GIS to delineate representative developments;
- ▶ visit sites and complete WinSLAMM field data form;
- ▶ compare findings to other communities through regulations, discussion, and research results; and
- ▶ create “generic” development scenario.

To develop the Medium Density Residential¹⁸ (MDR) prototype, the R-1-C zoning in Solon (24,000 ft² or 0.55 acre) was selected and compared to similar zoning categories for Mentor (R-3 = 18,000 ft² or 0.41 acre; 22,000 ft² or 0.5 acre) and Aurora (R-3 = 17,420 ft² or 0.40 acre). It was decided to find representative Solon subdivisions with between 1.8 and 2.5 lots per acre (i.e., 0.40 to 0.55 acre lots).

A GIS delineation of two Solon MDR subdivisions produced very similar results in terms of lot size (S1 = 2.4 lots/ac; S2 = 2.2 lots/ac) and source area percentages. The source areas for the delineated subdivisions were compared to Low Density and Medium Density Residential Standard Land Use files provided with the WinSLAMM software that represent average values found for these types of developments in other areas. For ease of input and translation to other communities, a lot size of 0.4 acres was assumed with a total impervious area of 30%. For details, see Appendix A-2.

Similar analyses were conducted for commercial and large lot residential developments. The source area percentages for the three representative development types can be seen in Table 4.

¹⁷Soils are classified by the Natural Resource Conservation Service into four Hydrologic Soil Groups (HSG) based on the soil's runoff potential. The four Hydrologic Soils Groups are A, B, C and D. Group A soils have the smallest runoff potential and Group D the greatest. Details of this classification can be found in Technical Release 55 (TR-55), 'Urban Hydrology for Small Watersheds' (NRCS, 1986).

¹⁸For the purpose of this study, Medium Density Residential represents single-family residential developments with 1-4 lots/acre.

Table 4. Source Area Percentages for Representative Large Lot Residential (LLR), Medium Density Residential (MDR) and Commercial Sites.

Source Area	Model LLR (2.0 ac lots) Area (%)	Model MDR (0.4 ac lots) Area (%)	Model Commercial Area (%)
Roofs	3.5	12.5	20.0
Parking	0	0	40.0
Driveways	3.5	7.0	2.0
Sidewalks	0.5	2.0	3.0
Streets	4.5	8.5	20.0
Total Impervious	12.0	30.0	85.0
Lawns/landscaping	88.0	70.0	15.0
Total	100	100	100

Drainage/Conveyance Network - One variable that may significantly affect stormwater runoff volume, runoff rate, and water quality is the type of drainage network that conveys water from source areas to the discharge point in a BMP or at the edge of the development. WinSLAMM allows selection of either curb and gutter (C&G or CG) or open swale drainage. The curb and gutter assumes connection to a storm sewer network that delivers the runoff to the BMP or discharge point.

No storm sewer sizing takes place in WinSLAMM. For this exercise, the 10-year event and rational formula were used to size storm sewers and drainage swales needed for determining time of concentration estimates used in sizing peak discharge control structures (see discussion under BMP Controls below).

BMP Controls - Stormwater best management practice (BMP) controls are necessary on most new developments in Ohio to meet either the state's WQv requirement (Ohio EPA, 2008) or local peak discharge control requirements. The following stormwater BMP controls were considered in this study:

- ▶ no control;
- ▶ wet detention basin - for WQv, peak discharge control, or both;
- ▶ bioretention; and
- ▶ pervious pavement (commercial site only).

Although "true" dry ponds without micropools were an allowable option for meeting the WQv requirement at the time this study was conducted (Ohio EPA, 2003), they were not used for the site level analysis because WinSLAMM is not designed to model a detention basin without permanent pool. In the most recent construction stormwater permit (Ohio EPA, 2008), Ohio EPA specified that a permanent micropool was re-

quired in all dry ponds. Model scenarios were added to test water quality performance of a dry pond with permanent micropool.

BMPs were designed (“sized”) according to standard guidance (e.g., NRCS, 1986; ASCE, 1992; McCuen, 1998) and the pertinent state (Ohio EPA, 2003; ODNR, 2006) or local requirements. A spreadsheet was generated to size WQv wet detention basin and outlet to meet Ohio EPA NPDES CGP requirements¹⁹. The NRCS TR-55/TR-20 (NRCS, 1965; NRCS, 1986) methodology (through a proprietary software package) was used to size the detention basin and outlet to meet local Critical Storm Method requirements. The bioretention practices were designed and simulated in accordance with the Rainwater and Land Development manual (ODNR, 2006). Pervious pavement was simulated to fully infiltrate the WQv from the parking lot only, and based on University of New Hampshire Stormwater Center guidance (UNHSC, 2007).

Pollutant Build-up and Wash-off - To estimate the end-of-development loading of particulate solids from the different development scenarios requires pollutant build-up and wash-off information for each source area such as roofs, driveways, parking lots, streets, and lawn/landscaped areas. In the absence of measured data for the Chagrin watershed, input data files representative of the Midwestern U.S. were used (R. Pitt, personal communication; file descriptions are posted at the USGS Wisconsin Water Science Center website <http://wi.water.usgs.gov/slamm/>).

Unit Hydrograph - The WinSLAMM model applies a compound unit hydrograph to the per event runoff volume to model the rate of discharge into the stormwater BMP or, for models with no control, the rate of discharge leaving the site. WinSLAMM is able to specify a peakiness factor to the unit hydrograph. This was set to 3.8 per recommendation of the model developers (J. Voorhees, personal communication).

Model Runs

The scenarios modeled using WinSLAMM to evaluate site-level runoff volume and sediment loadings for one year of rainfall (1980 data for Burton rain gage) are summarized in Table 5.

Table 5 Key

- ▶ Connected Impervious % - refers to the percentage of total site impervious area (i.e., roofs, driveways, sidewalks, parking areas, and streets) that drains directly to the drainage network without passing across a pervious (i.e., lawn or landscape) area as sheet flow. Disconnected impervious refers to impervious areas that discharge as sheet flow to a lawn or landscape area (e.g., roof downspout to a splashblock).
- ▶ Pond – all of the ponds are wet detention basin designs except for the pond noted as “dry pond”.
- ▶ Bioretention or Bio (%) - refers to the size, as a percentage of the total development site, dedicated to bioretention. For example, bioretention (1.5%) under the medium density residential scenario would have a surface area equal to 1.5% of the 20 acre site, or 0.3 acres.
- ▶ Pervious pavement or PP – in these scenarios, the entire parking lot area uses a pervious pavement design.

¹⁹C = 0.858i³ - 0.78i² + 0.774i + 0.04 (OEPA, 2008); orifice size by Method 2 #22, p19 (OEPA, 2007).

Table 5. WinSLAMM Model Scenarios.

Land Use	Soil Type	Drainage	Connected Impervious %	Control/Detention	Notes
Undeveloped	clay	swale	0	none	
Large Lot Residential	clay	curb & gutter	100	none	
Large Lot Residential	clay	curb & gutter	100	pond	
Large Lot Residential	clay	curb & gutter	100	bioretention (1%)	
Large Lot Residential	clay	curb & gutter	100	bioretention (2.4%)	
Large Lot Residential	clay	curb & gutter	0	none	
Large Lot Residential	clay	curb & gutter	0	bioretention (1%)	
Large Lot Residential	clay	curb & gutter	0	bioretention (2.4%)	
Large Lot Residential	clay	swale	100	none	
Large Lot Residential	clay	swale	0	none	
Large Lot Residential	clay	swale	0	bioretention (1%)	
Large Lot Residential	clay	swale	0	bioretention (2.4%)	
Medium Density Residential	clay	curb & gutter	100	none	
Medium Density Residential	clay	curb & gutter	100	wet pond	
Medium Density Residential	clay	curb & gutter	100	dry pond	w/micropool
Medium Density Residential	clay	curb & gutter	100	bioretention (1.5%)	
Medium Density Residential	clay	curb & gutter	100	bioretention (6%)	
Medium Density Residential	clay	curb & gutter	60	none	downspouts only
Medium Density Residential	clay	curb & gutter	0	none	
Medium Density Residential	clay	swale	100	none	
Medium Density Residential	clay	swale	0	none	
Medium Density Residential	clay	swale	0	bioretention (1.5%)	
Medium Density Residential	clay	swale	0	bioretention (6%)	
Commercial	clay	curb & gutter	100	none	
Commercial	clay	curb & gutter	100	pond	
Commercial	clay	curb & gutter	100	bioretention (4.5%)	
Commercial	clay	curb & gutter	100	bioretention (9%)	
Commercial	clay	curb & gutter	100	pervious pavement	
Commercial	clay	curb & gutter	100	PP & bio (4.5%)	
Commercial	clay	curb & gutter	100	PP & bio (9%)	
Commercial	clay	curb & gutter	0	none	
Commercial	clay	swale	100	none	
Commercial	clay	swale	0	none	
Commercial	clay	swale	0	bioretention (4.5%)	
Commercial	clay	swale	0	bioretention (9%)	

Results and Discussion

A total of 35 development scenarios were modeled using WinSLAMM to generate annual runoff volume and annual particulate solids load estimates. Results are presented in Tables 6, 7, and 8²⁰.

Table 6. WinSLAMM Modeling Results for Medium Density Residential (MDR) - Burton 1980 Rainfall.

Scenario	Runoff Depth	Runoff Volume Reduction	Rv ²¹	Particulate Solids	Solids Reduction
	(in/ac/yr)	%		(lb/ac/yr)	%
No Controls	12.2	N/A	0.29	315	N/A
Pond (Wet/Dry)	12.2	0	0.29	44/111	86/65
Swales	11.3	7	0.27	248	22
Downspouts Disconnected	8.3	32	0.20	283	10
All Disconnected	5.8	53	0.14	205	35
Swales & Disconnected	5.0	59	0.12	150	53
Bioretention 1.5% (WQv)	8.0	34	0.22	128	60
Bioretention 6%	3.0	76	0.12	29	91
Swales Disc & Bioret- 1.5%	2.5	79	0.08	42	87
Swales Disc & Bioret- 6%	0.7	94	0.02	6	98
Undeveloped	1.4	88	0.03	4	99

²⁰ Disclaimer - Though results are based on local and state regulations, and recommended guidance, there are many model variables (individual development characteristics, topography, soils, outlet availability, ...) specific to a given site and development that will cause results to vary significantly. These model estimates are used to illustrate relative comparisons for these scenarios/inputs and should not be considered representative of all conditions or scenarios. As a reminder, the purpose of this study was not to calibrate or validate WinSLAMM parameters for the Chagrin River watershed, an exercise that would have required extensive rainfall-runoff-pollutant data sets at the source area and development site scale. A logical next step past this study would be to find or develop one or more detailed rainfall-runoff or rainfall-runoff-pollutant data sets to verify WinSLAMM input parameters for northeast Ohio conditions. Further discussion can be found in "Evaluation of WinSLAMM" section.

²¹ Rv is the annual volumetric runoff coefficient, the fraction of total precipitation leaving the development site as stormwater discharge. Rv allows easy comparison between different land uses, source areas, or suites of stormwater practices. For example, for typical medium density residential development following local guidelines (connected downspouts, curb & gutter drainage system and detention pond) the annual runoff volume would increase over 800% $[(0.29-0.03)/0.03]$.

Table 7. WinSLAMM Modeling Results for Large Lot Residential (LLR) - Burton 1980 Rainfall.

Scenario	Runoff Depth	Runoff Volume Reduction	Rv	Particulate Solids	Solids Reduction
	(in/ac/yr)	%		(lb/ac/yr)	%
No Control	6.2	N/A	0.15	210	N/A
Dry Pond [#]	6.2	0	0.15	49	77
Swales	5.7	8	0.14	163	23
All Disconnected	3.7	40	0.09	159	24
Swales & Disconnected	3.2	48	0.08	116	45
Bioretention 1% (WQv)	3.9	38	0.09	83	61
Disconnected & Bioret-1%	2.1	67	0.05	51	76
Disconnected & Bioret-2.4%	1.2	81	0.03	21	90
Swale Disc & Bioret-1%	1.8	70	0.04	39	82
Swale Disc & Bioret-2.4%	1.1	83	0.03	16	93
Undeveloped	1.4	80	0.03	4	98

Table 8. WinSLAMM Modeling Results for Commercial - Burton 1980 Rainfall.

Scenario	Runoff Depth	Runoff Volume Reduction	Rv	Particulate Solids	Solids Reduction
	(in/ac/yr)	%		(lb/ac/yr)	%
No Controls	26.3	N/A	0.63	647	N/A
Wet Pond	26.3	0	0.63	63	90
Swales	26.1	1	0.63	542	16
All Disconnected	22.8	13	0.55	567	12
Swales & Disconnected	22.5	14	0.54	474	27
Pervious Pavement	15.4	41	0.37	332	50
Bioretention 4.5% (WQv)	13.3	49	0.32	149	77
Swale Disc & Bioret-4.5%	11.7	55	0.28	116	82
Bioretention 9%	7.0	73	0.17	57	91
Perv Pave & Bioret-4.5%	5.1	81	0.12	50	92
Perv Pave & Bioret-9%	1.9	93	0.05	15	98
Undeveloped	1.4	96	0.03	4	99

Runoff Volume

In its simplest form, site hydrology can be represented by the following figure:

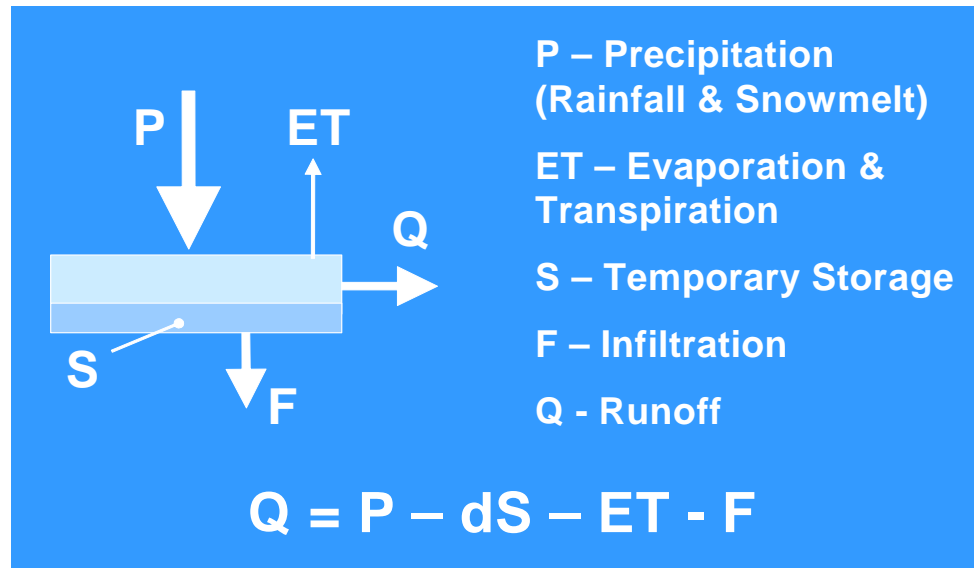


Figure 2. Simplistic Storm Event Hydrologic Budget at the Earth's Surface.

If rainfall infiltrates the soil, it is unavailable for surface runoff. The keys to maximizing infiltration are to:

- ▶ minimize the impervious area necessary for the type of development; maximize pervious areas;
- ▶ “disconnect” impervious areas from the drainage network, i.e., direct any runoff leaving impervious areas onto pervious areas such as lawn or landscaped areas;
- ▶ maintain or enhance the infiltration capacity of the site's pervious areas;
- ▶ slow the flow or conveyance rate of runoff, providing more opportunity for infiltration along the flow path; and
- ▶ provide additional temporary storage (S) on pervious areas and in infiltration BMPs such as bioretention and pervious pavement.

WinSLAMM is able to model each of these management approaches in varying degrees.

²²Evaporation and transpiration (ET) during a runoff event are relatively small. Over the course of a year, however, evapotranspiration of retained (infiltrated or stored) water is significant. See more on Ohio's hydrologic cycle at: <http://ohiodnr.com/Portals/7/pubs/pdfs/fctsht18.pdf>.

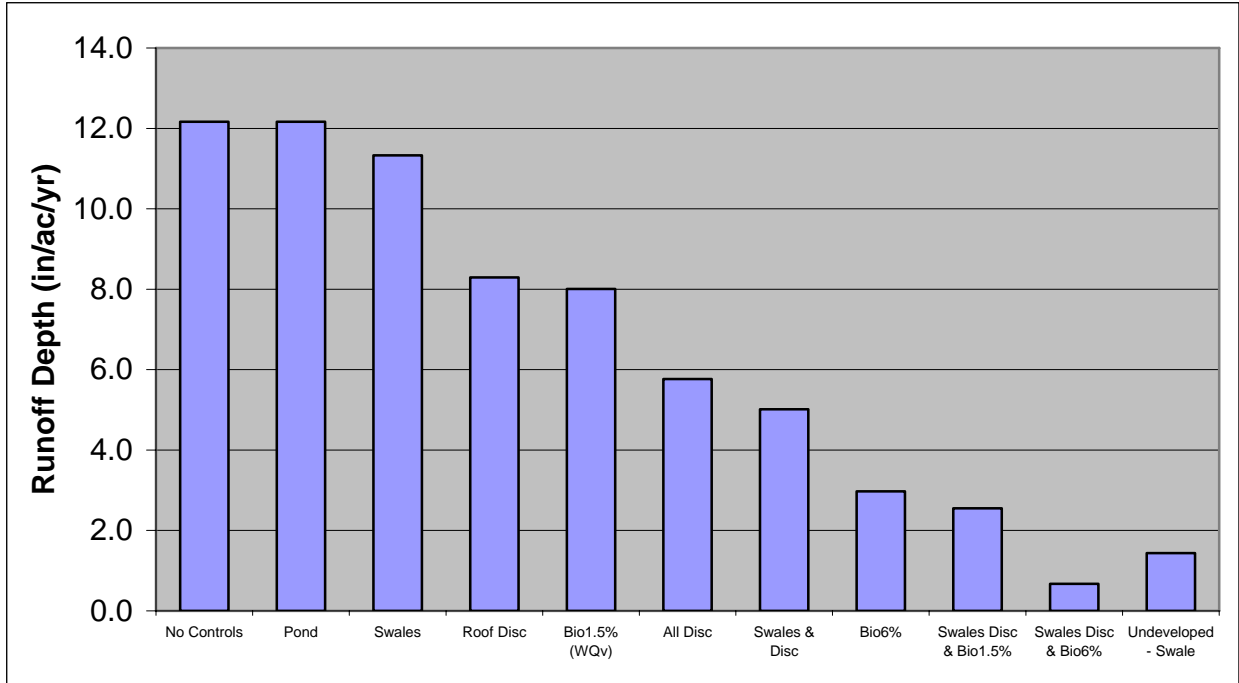


Figure 3. WinSLAMM Annual Runoff Volume for Medium Density Residential (MDR) Scenarios - Burton 1980 Rainfall.

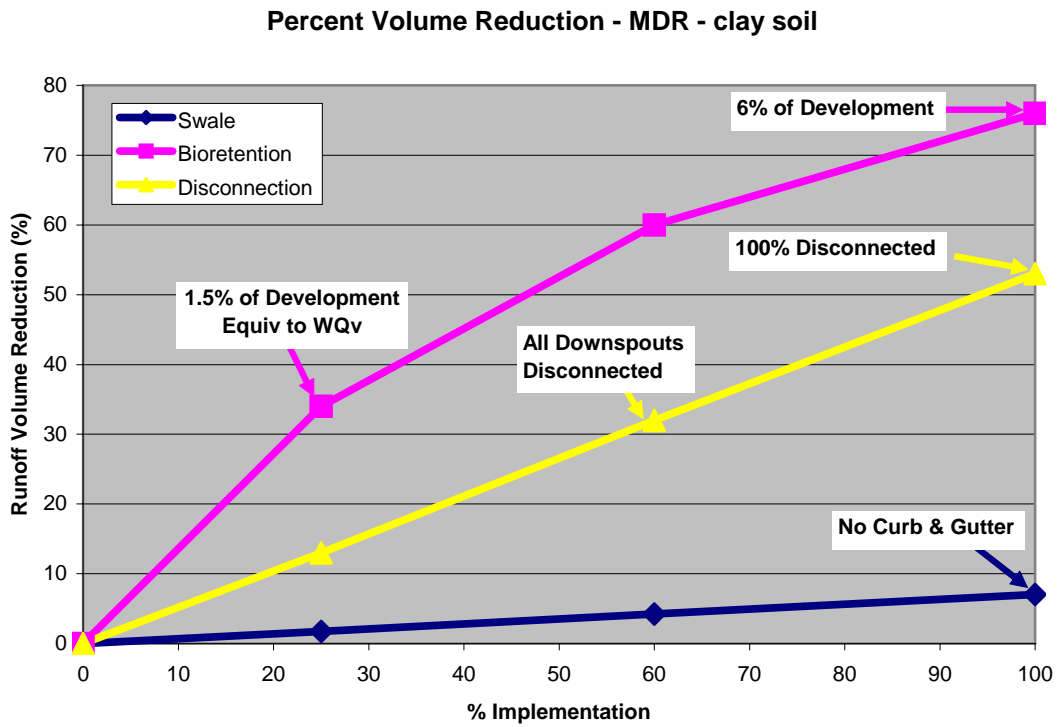


Figure 4. WinSLAMM Runoff Volume Reduction Strategies for Medium Density Residential (MDR) - Burton 1980 Rainfall.

Medium Density Residential (0.4 acre lots, total impervious area 30%)

The estimated volume reduction by applying several of these stormwater management strategies for a medium density residential (MDR) development are presented in Figures 3 and 4.

The results in Figure 3 are organized in order from highest annual runoff volume (no controls) to lowest (undeveloped)²³. Review of Table 6, Figure 3, and Figure 4 reveals several key points:

- ▶ runoff volume is not significantly reduced by detention basins with permanent pools²⁴;
- ▶ for this particular site design on tight clay soils, switching from curb & gutter and storm sewers to swale (open ditch) drainage results in about a 7% volume reduction; the amount of infiltration can be increased by any combination of widening the swale bottom, decreasing ditch slope, or improving the infiltration rate through soil amendments (sand, peat, compost) or mechanical means; the reduction would be significantly higher for HSG-A or HSG-B soils;
- ▶ even for tight clay soils, impervious area disconnection significantly reduces runoff volume; disconnecting only downspouts resulted in a 32% volume reduction; disconnecting all impervious areas resulted in a 53% volume reduction; the reduction would be significantly higher for HSG-A or HSG-B soils ;
- ▶ bioretention BMPs designed to meet the WQv requirement (13,350 ft² total surface area or 1.5% of the 20-acre site), and in which a one-foot deep exfiltration²⁵ reservoir was included below the underdrain, would reduce runoff volume about 34%; WinSLAMM predicts that increasing the total surface area of the bioretention BMPs to 6% of the 20 acre site (53,400 ft² total surface area) would reduce annual runoff volume about 76%;
- ▶ combining infiltration strategies results in improved volume reduction; for example, combining swale drainage and 100% impervious area disconnection would result in approximately 60% volume reduction; to swales & disconnection, add bioretention BMPs to meet the WQv requirement and annual runoff volume is reduced about 80%.

²³Runoff volume is more meaningful when considered as runoff volume per unit area which is equivalent to runoff depth.

²⁴WinSLAMM does not have the capability of modeling true (i.e., no wet forebay or permanent micro-pool) dry detention basins that would experience some level of runoff volume reduction through infiltration and evapotranspiration.

²⁵Exfiltration refers to infiltration from the bottom and sides of the bioretention basin into the native soil.

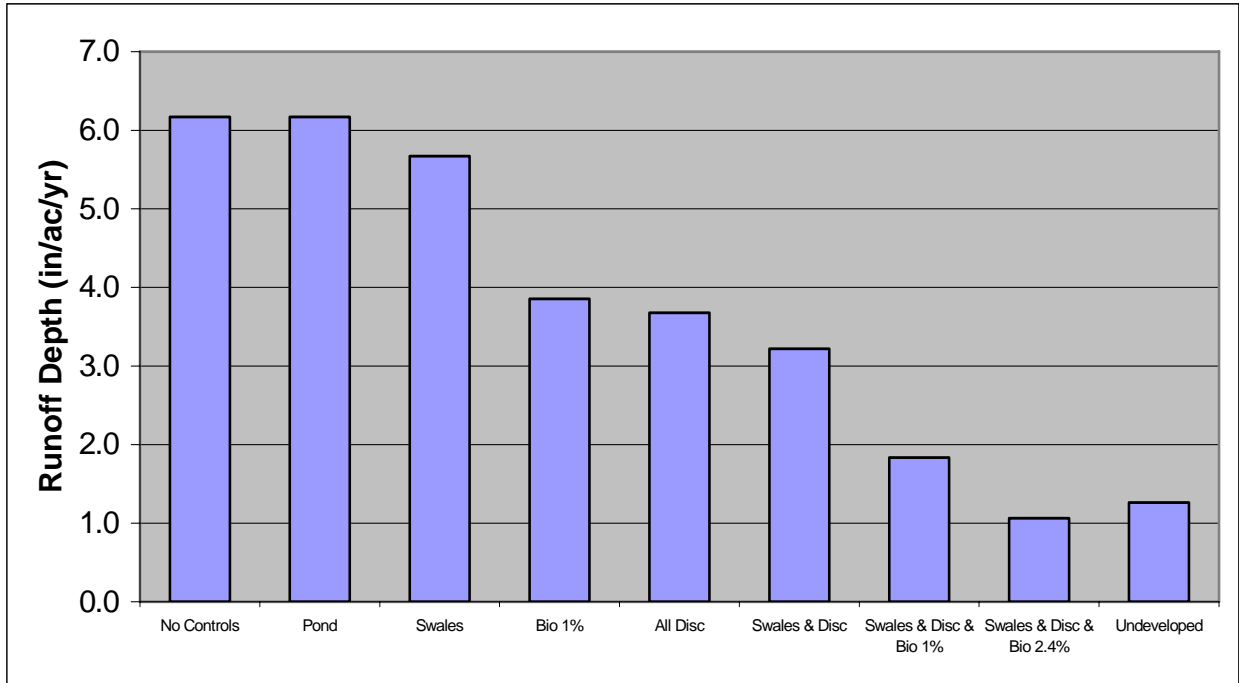


Figure 5. WinSLAMM Annual Runoff Volume for Large Lot Residential (LLR) Scenarios - Burton 1980 Rainfall.

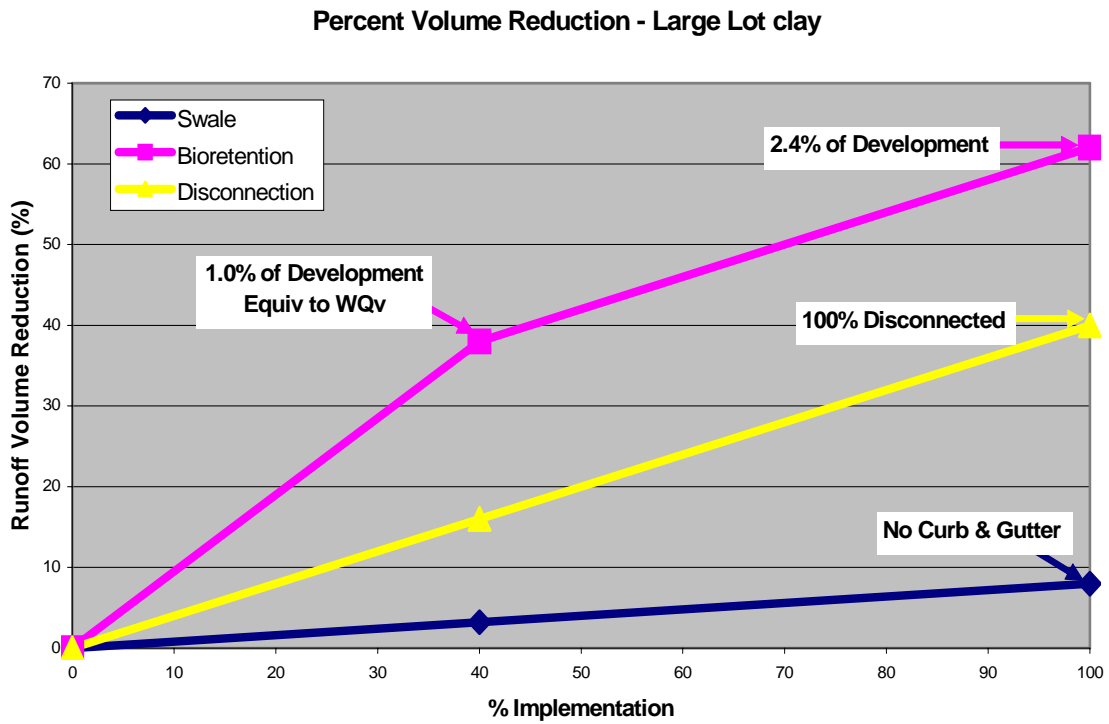


Figure 6. WinSLAMM Runoff Volume Reduction Strategies for Large Lot Residential (LLR) - Burton 1980 Rainfall.

Large Lot Residential (2 acre lots, total impervious area 12%)

The estimated volume reduction by applying various stormwater management strategies for large lot residential (LLR) development are presented in Figures 5 and 6²⁶.

The results in Figure 5 are organized in order from highest annual runoff volume (no controls) to lowest (undeveloped). Review of Table 7, Figure 5, and Figure 6 shows:

- ▶ runoff volume is not significantly reduced by detention basins with permanent pools;
- ▶ switching from curb & gutter and storm sewers to swale (open ditch) drainage results in about a 8% volume reduction; the amount of infiltration can be increased by any combination of widening the swale bottom, decreasing ditch slope, or improving the infiltration rate through soil amendments (sand, peat, compost) or mechanical means; the reduction would be significantly higher for HSG-A or HSG-B soils;
- ▶ disconnecting all impervious areas resulted in a 40% volume reduction; the reduction would be significantly higher for HSG-A or HSG-B soils;
- ▶ bioretention BMPs designed to meet the WQv requirement (8750 ft² total surface area or 1.0% of the 20-acre site), and in which a one-foot deep exfiltration reservoir was included below the underdrain, would reduce runoff volume about 38%; WinSLAMM predicts that increasing the total surface area of the bioretention BMPs to 2.4% of the 20 acre site (21,000 ft² total surface area) would reduce annual runoff volume about 76%;
- ▶ combining infiltration strategies results in improved volume reduction; for example, combining swale drainage and 100% impervious area disconnection would result in approximately 48% volume reduction; to swales & disconnection, add bioretention BMPs to meet the WQv requirement and annual runoff volume is reduced about 70%; by taking advantage of the full suite of low impact strategies (swales, disconnection, and bioretention covering 2.4% of the site), the annual runoff volume from this site would be very close to pre-development levels .

²⁶This study assumed that 75% of the LLR development site (15 ac) was not disturbed during construction, with the remaining 25% (5 ac) disturbed (graded, etc.) during home site development and road, utilities and home construction. This information was needed for post-development site characterization for pond sizing.

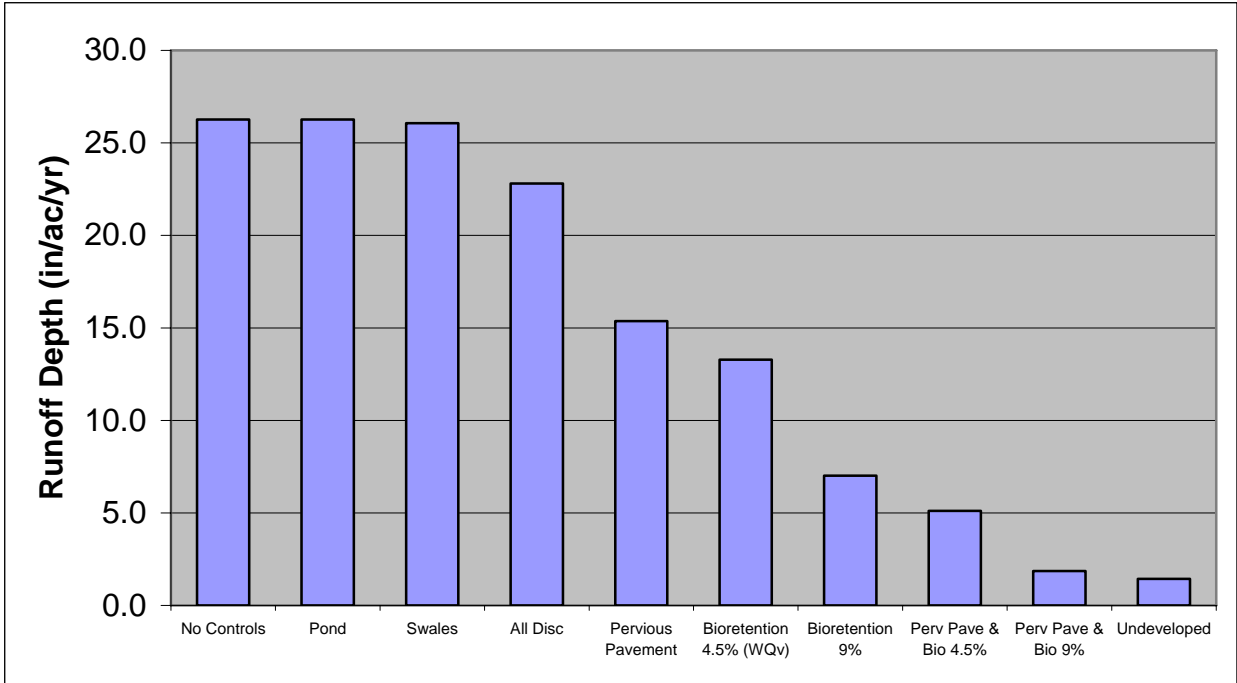


Figure 7. WinSLAMM Annual Runoff Volume for Commercial Scenarios - Burton 1980 Rainfall.

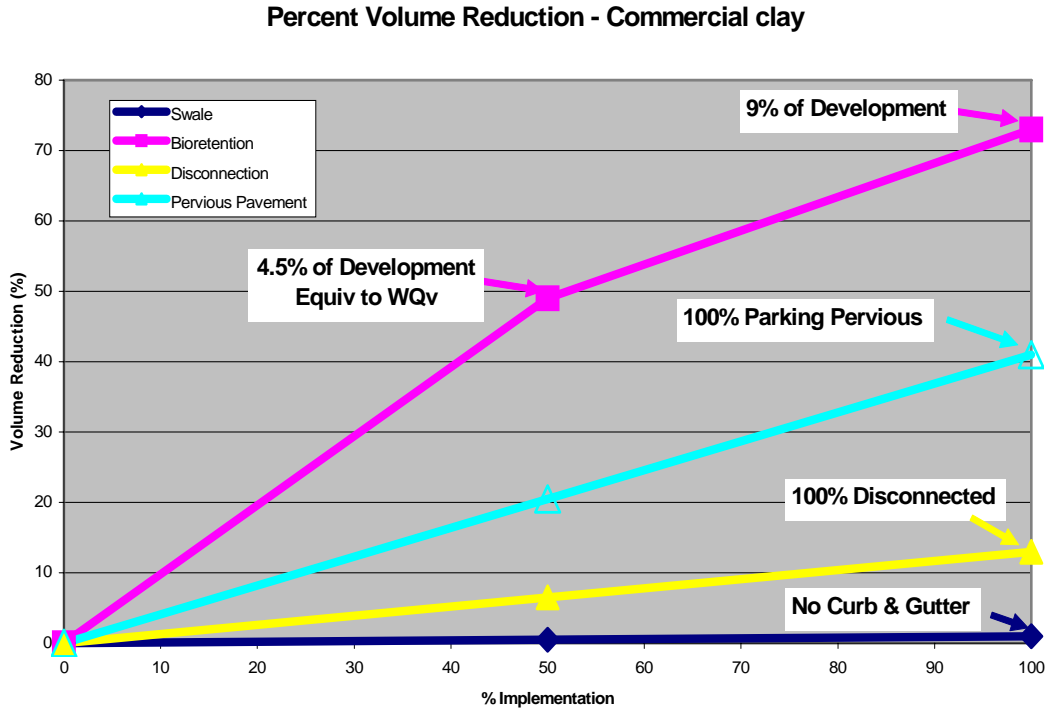


Figure 8. WinSLAMM Runoff Volume Reduction Strategies for Commercial - Burton 1980 Rainfall.

Commercial (total impervious area 85%)

The estimated volume reduction by applying various stormwater management strategies for strip commercial development are presented in Figures 7 and 8.

The results in Figure 7 are organized in order from highest annual runoff volume (no controls) to lowest (undeveloped). Review of Table 8, Figure 7, and Figure 8 highlight the following:

- ▶ runoff volume is not significantly reduced by wet detention ponds;
- ▶ because of the increased site impervious (with coincidental increase in runoff volume and reduction in pervious open areas), switching from curb & gutter and storm sewers to swale drainage (~1% volume reduction) and impervious area disconnection (13% volume reduction) provide limited opportunity for volume reduction for commercial sites on tight soils; the reduction would be significantly higher for HSG-A or HSG-B soils
- ▶ bioretention BMPs designed to meet the WQv requirement (39,200 ft² total surface area or 4.5% of the 20-acre site), and in which a 18" deep exfiltration reservoir was included below the underdrain, would reduce runoff volume about 49%; WinSLAMM predicts that increasing the total surface area of the bioretention BMPs to 9% of the 20 acre site (78,400 ft² total surface area) would reduce annual runoff volume about 73%;
- ▶ designing the entire parking lot as pervious pavement with a 4" aggregate reservoir below the underdrain results in an annual runoff volume reduction of 41% for the entire commercial site, infiltrating over 90% of all rain falling on the pavement;
- ▶ combining infiltration strategies results in improved volume reduction; for example, combining 100% impervious area disconnection with bioretention sized to meet the WQv requirement and annual runoff volume is reduced about 55%; combining pervious pavement and bioretention can reduce annual runoff volume by over 80%.

Discussion

Traditionally, the management of runoff "quantity" for flood control or to prevent stream erosion focused on controlling the peak discharge *rate* from a development site at some pre-development level. As was noted in the introduction, peak discharge controls based on large storm events provide dubious benefits for flood management (McCuen, 1974, 1979; Duru, 1981; Urbonas and Glidden, 1983; Traver and Chadderton, 1983; Emerson et al., 2003) and do not prevent stream channel incision (MacRae, 1997; Booth and Jackson, 1997; Mecklenburg and Ward, 2002; Aquafor Beech Ltd, 2006).

Many of our most troubling and costly stormwater impacts—severe stream channel erosion, flooding, loss of stream habitat, and degraded water quality—are largely attributable to the increase in runoff volume associated with development (Pitt, 2002;

WSTB, 2008). Therefore, we would expect the effective management of runoff volume to go a long way toward addressing these impacts.

When considering management of runoff volume, opportunities are dictated by the type of development (and thus the amount of impervious area), site and soil characteristics, and the size and distribution of rainfall events. Before considering site conditions and management options, it is instructive to weigh the size and frequency of rainfall events in relation to our stormwater management goals.

Figure 9 shows the cumulative frequency of occurrence for rainfall events of different depths (inches) for the Burton, Ohio rain gage for the year 1980. The chart shows that over 60% of events were 0.2" or less, and over 80% of events were 0.5" or less. Conversely, the large rainfall events (>2") for which we traditionally have designed our stormwater management systems represent about 1% of all events.

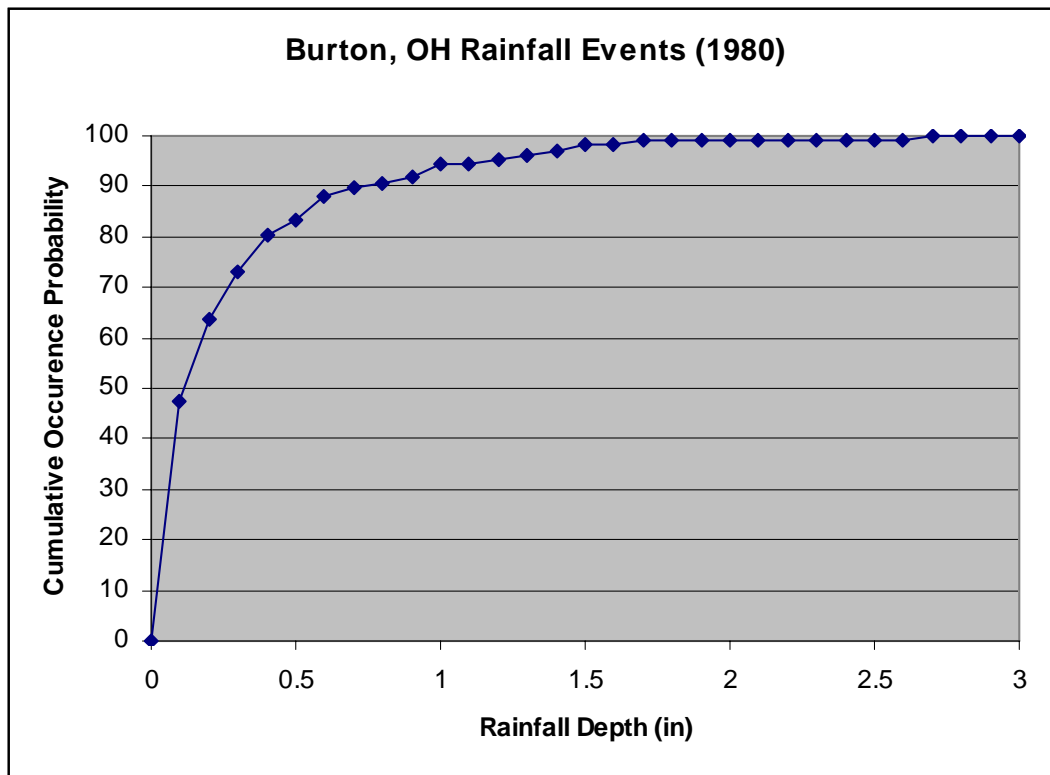


Figure 9. Cumulative Frequency of Occurrence for Rainfall, Burton, 1980.

This common distribution of rainfall events has led to recommendations for tiered strategies toward managing stormwater runoff (Schueler et al., 1992; Claytor and Schueler, 1996; Pitt, 1999, 2003a; Graham et al., 2004; Stephens and Dumont, 2008). Pitt (2003a) recommends for “common rains” less than about 0.5” in depth²⁷:

“In most areas, runoff from these rains should be totally captured and either re-used for on-site beneficial uses or infiltrated in upland areas.”²⁸

Similarly, Stephens and Dumont (2008) recommend that the 75% of annual runoff volume produced by “light showers” be captured and infiltrated on site.

The results from this modeling exercise highlight approaches that would allow the community, designer, and developer to meet such goals. They break down into these strategies:

- ▶ disconnect impervious areas from the gray infrastructure (i.e., curb, gutter, and storm sewer) drainage network;
- ▶ maintain or enhance surface soil quality;
- ▶ introduce areas, such as bioretention and rain gardens, with engineered soils that maximize infiltration;
- ▶ create storage below the underdrain system in bioretention and pervious pavement to promote deep infiltration;
- ▶ to the maximum practical extent, use swale drainage instead of curb, gutter and pipe drainage;
- ▶ replace detention basins with BMPs such as pervious pavement and bioretention that promote infiltration;
- ▶ combine these strategies to maximize results.

Several studies highlight real-world examples of use of LID practices to reduce runoff volume. For example, the City of Burnsville, Minnesota, installed 17 rain gardens (another name for bioretention) in a 25-lot, 5.3 acre residential neighborhood to reduce runoff. In a paired watershed study, the watershed with the bioretention practices (0.41” of runoff) exhibited a 93 percent reduction in total runoff volume when compared to the untreated control watershed (5.58” of runoff) for 48 rainfall events totaling 19.0 inches during 2004-2005 (Barr Engineering, 2006).

In a study located here in the Chagrin River watershed, the Chagrin River Watershed Partners, Inc. found that bioretention practices were able to fully infiltrate 15 of 21 rainfall events (71%) that exceeded 0.75” during 2008-2009 (R. Webb, personal communication). All events smaller than 0.75” were fully infiltrated. This demonstration project addressed ongoing local flooding issues while minimizing impact to the existing stormwater management infrastructure.

²⁷This consideration of the spectrum of rainfall events, and appropriate management based on frequency and impacts of different size events, has been termed “small storm hydrology” and extensively considered by Pitt (1987, 1999, 2003a).

²⁸At some point, our society will likely realize what a valuable resource fresh water is and stop treating it as waste (see e.g., Jarrett et al, 2003). Based on observation of the current human condition, this seems unlikely until water begins to become a scarce resource.

Sabourin and Wilson (2008) reported on the performance of enhanced swales that have characteristics of both the swales and bioretention systems described in this report. The study used a paired watershed approach to compare enhanced swale drainage to the traditional curb, gutter and concrete storm sewer approach. For four rainfall events ranging between 0.46 inches and 0.98 inches, the runoff volumes from the enhanced swale watershed were only 14 to 27% of watershed with conventional drainage. Peak flows were 14 to 53% of those for the conventional systems. The concentration of pollutants in runoff was similar between the sites, but because of the reduced volume, pollutant yields were reduced significantly. TSS was reduced 81-95% by this enhanced swale system, without the use of a detention basin.

Kaufman and Wurtz (1997) reported both hydraulic and economic benefits of a downspout diversion program intended to lessen the burden on combined sewers and wastewater treatment in Flint, Michigan. The program disconnected the downspouts for the approximately 6200 customers in the 6.5 sq. mi. Beecher Water District. The authors reported a 29 percent reduction in mean stormwater flow volumes across all rainfall depths.

These other studies confirm the level of runoff volume reduction suggested by this study are possible. As we use these approaches to reduce runoff volume, the site and watershed scale hydrology and hydraulics will be altered radically from what we are used to from developed landscapes. This is likely to be positive in terms of downstream flood reduction, more stable receiving streams and better surface water quality. However, we must be careful to consider the impacts of more on-site runoff retention and infiltration to avoid ancillary issues that may cause unintended economic, environmental, aesthetic or health costs that could prevent sustainable implementation of LID stormwater systems.

In the rush to fix stormwater problems, especially those associated with increased runoff volumes, LID practices often are presented as the answer to all our stormwater ills. This undiluted promotion of LID practices often ignores the complexity of site and watershed scale hydrology, biology and water chemistry that got us the poor performance of traditional stormwater designs in the first place.

A few considerations worth noting include:

- ▶ On-site surface and subsurface drainage systems necessarily will have to become more sophisticated to manage stormwater in close proximity to people and property. Issues include: infiltration of stormwater on sites with slip-prone soils; design, construction and maintenance of infiltration practices and site drainage to minimize long-term surface ponding; better landowner education; appropriate protection of and access to stormwater infrastructure through

easements and deed restrictions; and development or identification of responsible management entities with knowledge, experience and tools to properly maintain or rehabilitate stormwater infrastructure.

- ▶ Effects of stormwater infiltration on groundwater hydrology and quality should receive equal consideration to surface water impacts. Few in the Midwestern United States recognize the extent, quality, or value of our groundwater resources, how susceptible those resources are to poor management of pollutant sources (including stormwater), or the high cost to remediate or treat degraded groundwater (Freeze and Cherry, 1979; Lloyd and Lyke, 1995). A couple excellent reviews of the research literature about groundwater contamination by stormwater are available (Pitt et al., 1996; Weiss et al., 2008), but additional work is still needed on: short- and long-term groundwater impacts of specific infiltration BMPs, and stormwater treatment systems; and stormwater effects on local and regional groundwater hydrology.
- ▶ Measurement and modeling how LID stormwater systems fit into overall watershed scale hydrology and ecological function is still in its infancy. A number of tools and approaches have been developed to help assess hydrologic or geomorphic performance at a watershed scale including: LID oriented models such as BMP DSS (Zhen et al., 2006) and the Water Balance Model (Stephens and Dumont, 2008); volume management as part of an overall watershed-scale hydrologic and hydraulic analysis (Emerson et al., 2003); flow duration analyses or flow exceedance analyses (MacRae, 1997; Rohrer and Roesner, 2005; Aquafor Beech Limited, 2006; Pitt, 2007; Roesner and Rohrer, No Date); full-spectrum detention analyses (Wulliman and Urbonas, 2005); and measures of geomorphic stability (Doyle et al., 2000; Bledsoe, 2002). These approaches and tools will be added to more traditional tools such as SWMM and HEC-RAS to assess watershed-scale impacts of stormwater practices, drainage network design and management, and valley storage on downstream flooding and geomorphic stability and predictability.

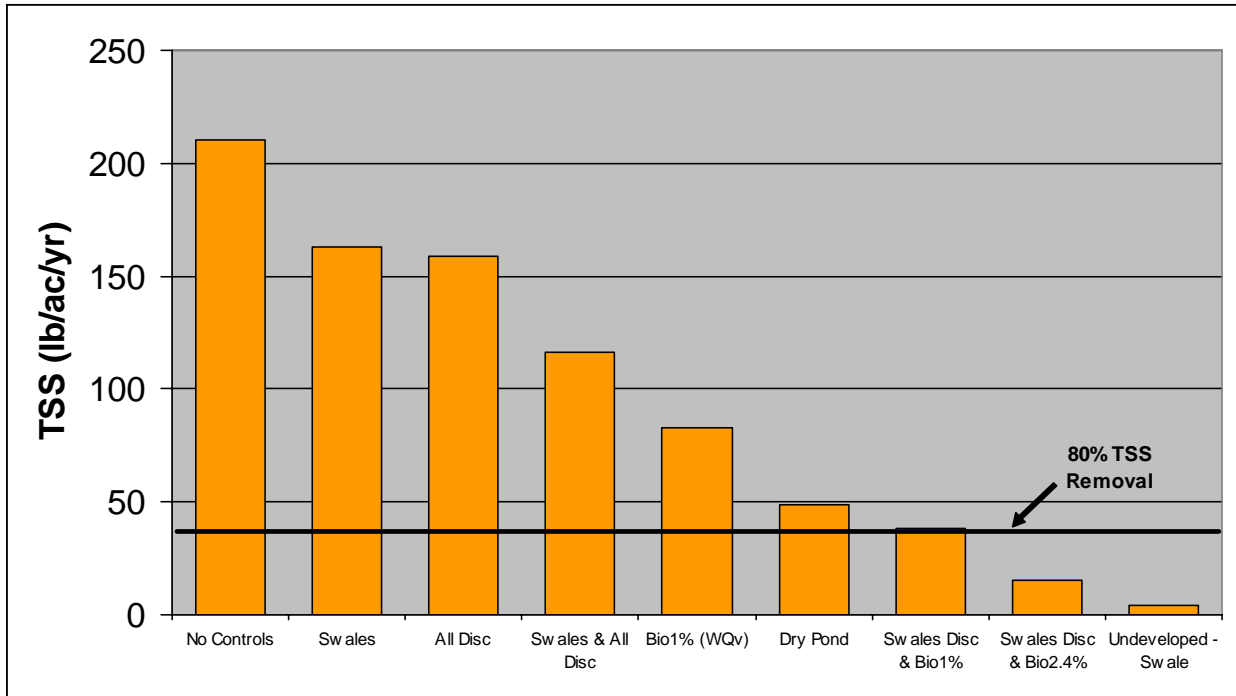


Figure 10. WinSLAMM Annual Particulate Solids Yields for Large Lot Residential Scenarios - Burton 1980 Rainfall.

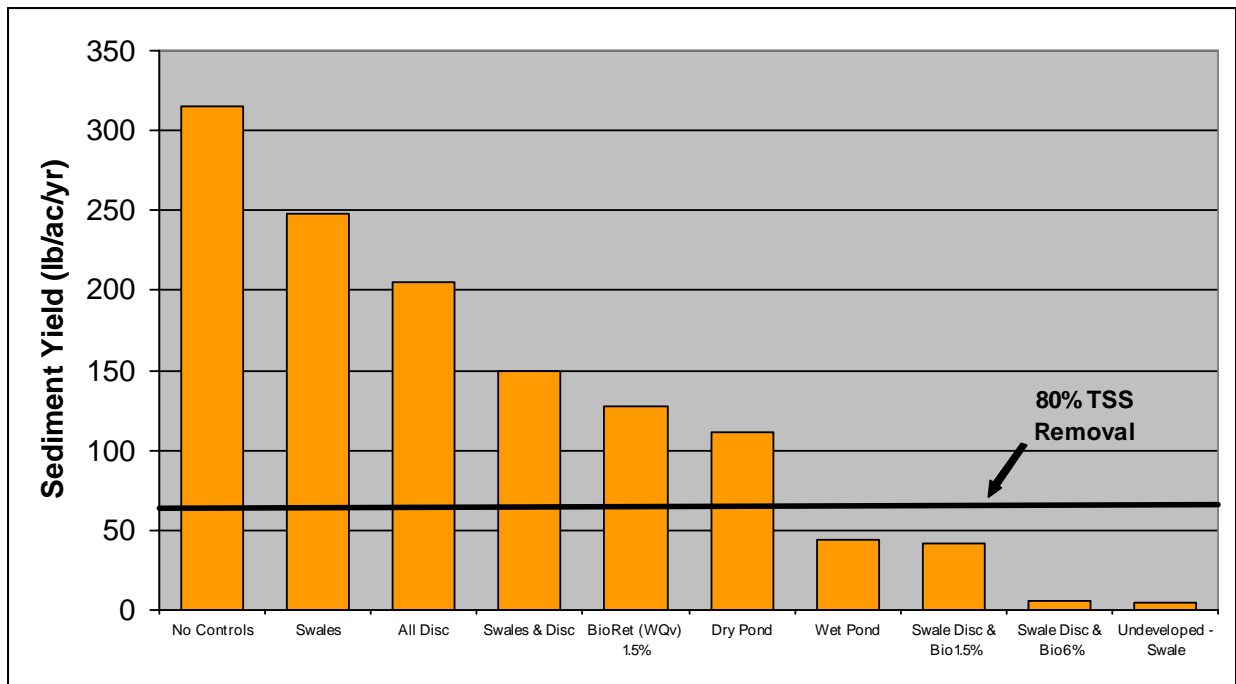


Figure 11. WinSLAMM Annual Particulate Solids Yields for Medium Density Residential Scenarios - Burton 1980 Rainfall.

Runoff Water Quality

Figures 10, 11, and 12 show WinSLAMM predicted annual sediment yields for LLR, MDR and Commercial, respectively. The results are organized in order from highest annual sediment yields (no controls) to lowest (undeveloped). Review of these figures and Tables 6-8 highlight the following:

- ▶ WinSLAMM predicts that impervious area disconnections and swale drainage reduce sediment yields between 16 and 35% alone, or up to 45% in combination, primarily through reduction in runoff volume; that means these green infrastructure approaches can play a significant role in achieving water quality targets as part of an integrated stormwater management plan, especially for development with ample pervious areas;
- ▶ well-designed and maintained wet detention ponds are proven sediment reduction BMPs, typically reducing sediment yields more than 80%; properly designed dry ponds, with a wet forebay and permanent micropool, designed to meet both the WQv and CSM peak discharge requirements can reduce sediment yields by 60-80% - dry ponds without permanent pools will not achieve this level of performance;
- ▶ WinSLAMM predicts bioretention BMPs designed to meet the WQv requirement would reduce sediment yields between 60 and 77%; by bumping the bioretention BMP area to 20% of site impervious area, WinSLAMM predicts sediment yields would be reduced about 90%;

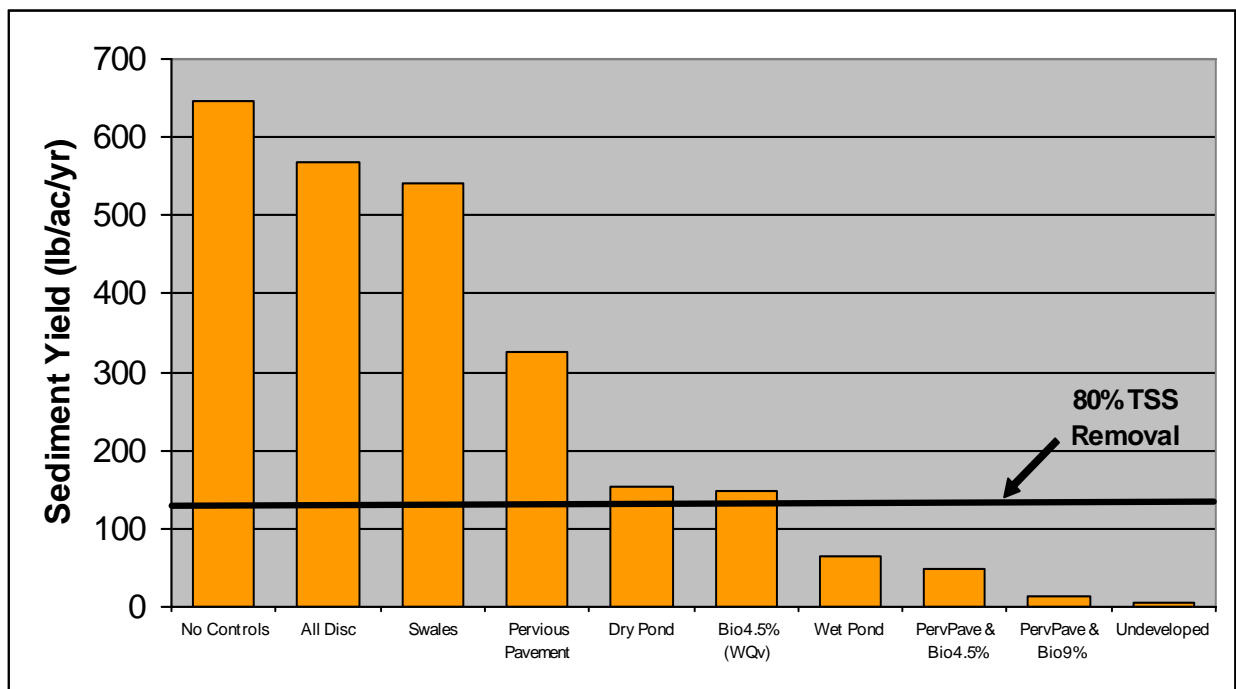


Figure 12. WinSLAMM Annual Particulate Solids Yields for Commercial Scenarios - Burton 1980 Rainfall.

- for the commercial site, using pervious pavement for the entire parking lot would result in about a 50% reduction in sediment yield from the entire development site – note that this scenario did not treat any other source area (roofs, sidewalks, drives, lawn/landscape areas); pervious pavement is an excellent water quality treatment and runoff volume reduction strategy when used with other BMPs necessary to meet WQv and CSM requirements from the rest of the development site;
- combining infiltration strategies results in improved water quality; in the residential scenarios, combining impervious area disconnection, swale drainage and bioretention sized to meet the WQv requirement resulted in over 80% reduction in sediment yield; for the commercial site, combining pervious pavement and bioretention sized to meet the WQv requirement results in sediment yield reduction of 92%.

These sediment removal results are consistent with those reported in the literature (USEPA, 2004; CWP, 2007).

Discussion

Stormwater quality controls reduce the mass of pollutants in discharge. The primary factors in determining runoff water quality are: 1) pollutant sources – the presence or build-up of pollutants where rain falls or runoff flows; 2) the volume of stormwater runoff; and 3) pollutant reduction treatment mechanisms, or unit processes, between where rain falls and runoff (or discharge) leaves the site. This discussion will focus on the latter two factors²⁹.

Natural landscapes are full of features that reduce runoff volume, and place stormwater in extended contact with soil and vegetation. The reduction of runoff volume comes from the high infiltration capacity of natural soils (attributable to low bulk density, good soil structure, well-developed macroporosity), the sorptive capacity of the surface leaf litter and high organic matter topsoil, temporary storage provided by puddles and other discontinuities in the soil surface, and hydraulic roughness of flow pathways. All these attributes of natural landscapes are diminished through the development process – by soil compaction and loss of soil structure, by removing topsoil and surface litter, by uniformly grading for efficient surface drainage and minimal puddling, by creating smooth, hydraulically efficient flow paths.

Within a stormwater management system, the treatment mechanisms, or unit processes, that affect sediment removal include: infiltration/volume reduction, flow attenuation, filtration, and sedimentation (NCHRP, 2006)³⁰. In the traditional pipe-and-pond approach, the impervious surface, curb and gutter, and pipe parts of the flow-path provide insignificant levels of these processes. The entire burden for sediment re-

²⁹For a comprehensive overview of source controls, see *Urban Runoff Quality Management* (ASCE, 1998).

moval is placed at the end of the pipe, the last small segment of flow path before stormwater is discharged from the site.

Appropriately designed, constructed and maintained wet extended detention basins can be very effective at sedimentation, and thus sediment removal, especially if the extended detention volume is shallow with a large surface area (USEPA, 2004; CWP, 2007). Dry extended detention basins are another matter. If designed, constructed and maintained for water quality treatment, they can be effective for that purpose. However, dry ponds are typically designed to meet the minimum regulatory requirements at minimum cost. Usually this results in a stormwater BMP with minimal levels of the unit processes outlined above and substandard reduction in sediment yields.

Stormwater management *systems* are most effective when they incorporate additive and complementary unit processes. For example, parking lot runoff can be designed to sheet flow across a filter strip in which infiltration, filtration and sedimentation occur into a bioretention area in which the primary mechanism is filtration, but which also provides infiltration and sedimentation. Shifting the primary drainage pathway from curb, gutter, and storm sewer to swales transforms a drainage network with few or no unit processes to one with extensive filtering, and some infiltration and sedimentation.

The LID approach to managing stormwater focuses on creating the most functional landscape within the constraints of the development type, location and site conditions. Like natural systems, this approach:

- ▶ uses multiple treatment mechanisms with additive or complementary unit processes, preferably in series³¹;
- ▶ creates hydraulic inefficiency in the flow pathways – disconnects impervious areas from gray infrastructure, promotes sheet flow instead of concentrated flow, uses open swales versus curb & gutter;
- ▶ maintains or enhances the infiltration capacity of the soil;
- ▶ maximizes stormwater contact with soil and vegetation.

The results here show that building a LID stormwater treatment system around impervious area disconnections, open swale drainage, and bioretention provides excellent

³⁰These are the primary physical and hydrologic processes that affect sediment dynamics. Other stormwater contaminants such as nutrients, petroleum hydrocarbons and metals are affected by these processes, but also by chemical and biological unit processes such as plant and microbial uptake, oxidation, reduction, sorption, and coagulation. For a more comprehensive treatment of unit processes in stormwater control, see *Evaluation of Best Management Practices for Highway Runoff Control* (NCHRP, 2006)..

³¹Such a system of practices is often referred to as a “treatment train”, that can be defined as a series of BMPs each designated to address different aspects of stormwater runoff control with the goal of attenuating stormwater discharge rate, and maximizing/optimizing volume control and pollutant removal.

sediment removal while also providing the additional hydrologic benefits described in the previous section. The water quality treatment benefits provided by this more functional landscape would be extended to other pollutants of concern such as nutrients, metals and petroleum hydrocarbons³². A commercial site with over 50% impervious area probably requires pervious pavement to maintain the same level of treatment.

³²The University of New Hampshire Stormwater Center has reported pollutant removal performance for a wide range of conventional, manufactured and LID stormwater BMPs for TSS, petroleum hydrocarbons, inorganic nitrogen, metals and phosphorus (Roseen et al., 2006, UNHSC, 2007b).

Peak Discharge Rate

WinSLAMM is not the right tool for modeling peak flow rates for large rainfall events and was not used for that purpose. However, as mentioned above, developers expect incentives to implement LID practices. It is worthwhile then, to use the NRCS curve number (CN) method to explore incentives that may be provided by LID. One such incentive is a peak discharge “credit” that results from the hydrologic benefits provided by LID. In particular, low-impact development practices:

- increase the amount of infiltration, thus reducing the site’s Curve Number and runoff volume for design storms
 - make drainage flowpaths less efficient, thus increasing the time of concentration.
- These hydrologic “credits” result in smaller post-development flow peaks and smaller, cheaper “flood control” BMPs.

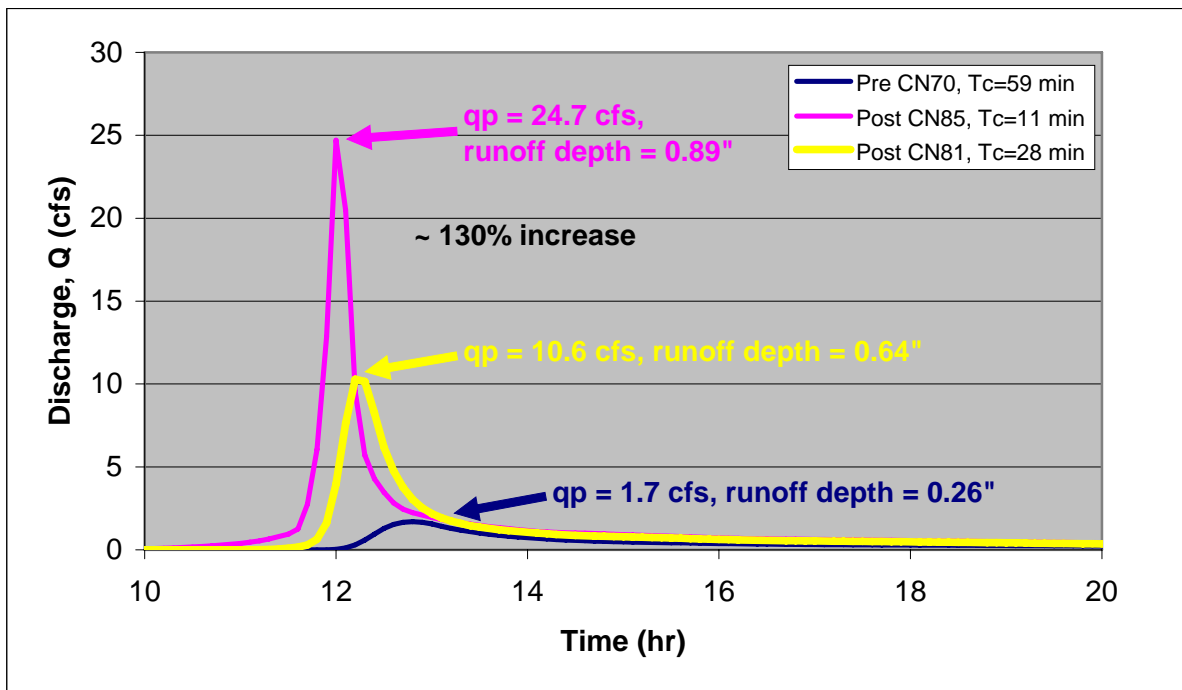


Figure 13. Runoff Hydrographs for Medium Density Residential (3 lots/acre) Development for 1-yr, 24-hr Rainfall Event (2.05”).

As an example, for a 20-acre residential subdivision with 0.33 acre lots it would be possible to reduce detention storage requirements by 20% and to gain 1 or 2 additional lots by applying a suite of low impact development strategies including selective grading, swale drainage and impervious area disconnection (see Figure 13). The potential benefit to the developer from the lots gained, infrastructure costs and construction costs could exceed \$50,000 while providing the runoff volume and water quality benefits noted above.

Implementation Issues

Development primarily is driven by financial considerations. The stormwater management system is only one of many development components - including buildings, streets, utilities, landscaping, public spaces, etc. - that, together, result in a desirable asset for the developer and community. Traditionally, concerns such as convenience, aesthetics, traffic patterns, and emergency access have taken precedence over the stormwater infrastructure.

Many of the impacts and costs associated with current stormwater management designs occur off-site and are not felt by the developer or property owner. A couple factors allow these externalized costs to go unchecked. There is a lack of understanding of watershed hydrology and stream morphology among key decision makers, so they may not understand stormwater's role in downstream flooding and stream erosion. In addition, stormwater impacts are cumulative. It is difficult to attribute stormwater impacts or the costs associated with them to a specific development. Costs for replacement of bridges, culverts and other infrastructure are borne by taxpayers ignorant of this hidden expense. Costs for flooding or severe streambank erosion are borne by downstream property owners who have little recourse to recoup expenses for damages short of uncertain and costly lawsuits.

How can more effective stormwater management systems be encouraged? A number of issues related to implementation of low impact stormwater management approaches are worthy of discussion here:

1. Understanding of stormwater impacts and their sources;
2. The complexity of the stormwater management system including engineer and reviewer understanding, and guidance and tools for analysis and design;
3. Removal of barriers and "disincentives" to implementation;
4. Incentives for implementation.

Understanding Stormwater Impacts and Their Sources

A body of stormwater research literature has begun to more completely describe hydrologic and water quality impacts of urbanization and stormwater runoff (Booth, 1990; Booth and Jackson, 1997; Burton and Pitt, 2001; Pitt, 2002, Conrad and Booth, 2005; Aquafor Beech Limited, 2006; NRC, 2008). Especially important are the emphases on small storm hydrology (Pitt, 1987, 1999, 2003a; Claytor and Schueler, 1996), runoff volume reduction (Emerson et al., No date; Hirschman et al., 2008), hydrologic impacts on geomorphic stability (Doyle et al., 2000; Rohrer et al., No date), and flow duration or flow exceedance (MacRae, 1997; Wulliman and Urbonas, 2005; Rohrer and Roesner, 2005; Davis et al.; No date). These studies all highlight the benefit of the LID approach, that is, encouraging integrated stormwater BMPs that slow the flow of water and infiltrate as much stormwater as site conditions will allow. Communicating that

in a meaningful way to local decision makers is challenging. Short of regulatory requirements at the state or federal level, a better accounting of off-site stormwater impact costs to a community and its taxpayers are probably needed to move local officials to action.

Complexity of Stormwater Management Systems

“Gray infrastructure” stormwater systems - those that are all connected, curb & gutter, pipe and end-of-pipe controls - are relatively simple to engineer. Stormwater management issues and impacts are pushed to the end of the development site and, in many cases, off-site. Little or no consideration is given to protection or maintenance of the many functions and services provided by the pre-development landscape. The pipes-and-pond, cookie cutter approach allows site planners to simply allocate space for stormwater conveyances and controls without integrating stormwater management into overall site planning and layout.

The benefits from low impact development and green infrastructure are significant, as noted above, because the developer and engineer take responsibility for managing water on-site rather than passing the impacts downstream. However, managing stormwater on-site requires a different level of commitment in stormwater planning and design. There is no such thing as cookie cutter. The stormwater management system must be adapted to site conditions - topography, soils, subsurface limitations such as shallow bedrock or shallow groundwater table, availability of outlet, etc. This requires a more thorough site investigation, as well as knowledge about how to work with site conditions.

LID works best when the stormwater management system is an integrated part of the site layout. This requires up-front consideration of the stormwater system during layout of lots, streets and utilities. LID protects existing flow pathways and drainage features (and their many landscape functions and services) to the maximum extent possible, planning the site and stormwater system to incorporate these features. This requires site planners, landscape architects, and design engineers to all be involved from inception. Planned open space (such as landscaping requirements or parking lot islands) becomes an integral part of the stormwater management system as opposed to simply meeting a code requirement.

This integration of stormwater components throughout a development may also create challenges for long-term ownership and maintenance of the stormwater management system, especially when multiple property owners are involved. Clear guidance on system location, function and maintenance must be laid out by the design engineer, incorporated in a long-term stormwater management plan, and appropriately and legally documented through covenants or deed restrictions.

Understanding and appropriately designing site drainage - both surface and subsurface drainage - becomes especially important to avoid standing water issues (aesthetics, mosquito breeding, complaints, undoing of stormwater features). Areas with steep slopes and slip-prone soils require special consideration of infiltration practices and subsurface drainage to avoid seepage, hillslope slippage and land slides.

The increased level of system complexity requires greater depth and breadth of knowledge, both for project designers and project reviewers. The collective knowledge and experience base with these systems has improved markedly over the past few years and the library of guidance material for LID practices is constantly expanding (Ferguson, 1994, 2005; CWP, 1998; Prince George's County, 1999a, 1999b; Coffman, no date; Livingston, 2000; Quigley and Lawrence, 2000; Belan and Otto, 2004; Hinman, 2005; USEPA, 2005a, 2007a; UNHSC, 2007a; Bitting and Kloss, 2008; MDE, 2008; NRC, 2008). Training opportunities related to design of individual BMP alternatives (such as pervious pavement and bioretention) and integrated LID stormwater system design are becoming more available. However, as with any new technology, direct experience is the best teacher. Developers, designers, reviewers, construction contractors, owners, and maintainers of these systems each face a steep learning curve.

The depth of knowledge and attention to detail has to be carried through the construction process as well. The alternative stormwater management systems depend on maintenance of soil quality and optimal soil infiltration characteristics. More specific guidance is required on timing and optimal site conditions for construction, as well as more oversight during the construction process.

Getting appropriate training and becoming proficient at using available tools and models to design LID stormwater systems requires an investment of time and money by the developer and the design engineer. Several engineering firms with an Ohio presence have begun making this investment and will be ahead of the curve when Ohio's state and local regulations reflect the technical understanding of stormwater impacts and follow national trends toward runoff reduction requirements. In addition, several developers have begun to seek special designations such as LEED certification [footnote] to show their commitment to environmental responsibility; for the time-being, being "green" is sexy.

Not only design engineers, but those who review and permit post-construction stormwater systems must be able to evaluate both the meeting of post-construction requirements (such as peak discharge control and WQv) and appropriateness to site and watershed conditions. Effectiveness of the review (in terms of time efficiency, responsiveness to the plan submitter, and evaluation of system performance and maintainability) requires: 1) the reviewer obtaining appropriate and on-going technical training; 2) development of common/consistent tools, protocols and data requirements such that pertinent design information is quantified and presented in an understandable fash-

ion; and 3) pre-design and periodic meetings among the reviewer(s) and developer, engineer and site planners.

Removal of Barriers to Implementation

A number of issues impede the implementation of low impact stormwater systems:

- ▶ regulations focused on peak discharge control instead of runoff volume;
- ▶ zoning and subdivision requirements, e.g., required connection of downspouts to storm drains, that impede low impact designs;
- ▶ lack of urban drainage know-how;
- ▶ lack of understanding of alternative designs by plan reviewers;
- ▶ lack of common tools for quantifying performance of alternative systems;
- ▶ an aesthetic attachment to the “clean” look of curb and gutter streets;
- ▶ expectations by land owners that rain water will go away immediately; and
- ▶ a pipe-and-pond culture amongst designers and reviewers.

All these issues limit the implementation of alternative stormwater systems, either blocking designs completely or, at least, slowing down the design and review process to the point that alternatives become too costly. Removal of these “disincentives” will facilitate more interest, innovation and implementation of alternative systems.

Incentives for Implementation

Incentives typically can be classified as “the carrot” or “the stick.” The best examples of “the stick” approach are regulations that require incorporation of low impact practices. All enacted within the last 10 years, examples from the states of Minnesota, Wisconsin, Maryland, and Washington, and local or regional requirements, e.g., the Darby Watershed NPDES Construction Stormwater Permit show the trend toward groundwater recharge and runoff volume controls. Maryland’s new Environmental Site Design criteria (MDE, 2008) are probably the best example of these requirements. Because of the limitations of detention-based stormwater controls noted earlier (McCuen, 1974, 1979; Duru, 1981; Urbonas and Glidden, 1983; Traver and Chadderton, 1983), it is likely that Ohio will adopt some form of statewide runoff volume control standard in the near future, and it is possible that U.S. EPA may develop some nationwide standard for runoff volume control.

Carrot-type incentives for LID primarily are either removal of the disincentives mentioned in the last section or economic incentives. Economic incentives include:

- ▶ proper regulatory crediting of LID practices that result in reduced stormwater BMP costs - e.g., giving credit for peak flow reduction that results in a smaller detention basin storage requirement;
- ▶ reduction in stormwater infrastructure costs - e.g., smaller storm sewer pipes and catch basins;
- ▶ any action that would reduce the time, and thus money, to gain plan approval;

- ▶ cost shares and grants for alternative or innovative designs;
- ▶ marketing boost from “green” advertising.

Because monitoring and modeling LID-based systems is still a relatively new endeavor, there is still much work to be done in appropriately quantifying and crediting this approach. Minnesota (MPCA, 2005) and Pennsylvania (PaDEP, 2006) have made attempts for incentivizing LID.

Evaluation of WinSLAMM as a Modeling/Planning Tool

WinSLAMM was selected for this exercise because it was the best tool available for the job. As with any model, there is a learning curve, and the user doesn’t develop a full sense of how the model functions, and what does or doesn’t work, until several models have been developed and run. Based on over 50 scenarios modeled or attempted, a brief evaluation of WinSLAMM is offered here to help potential evaluate its suitability for their needs.

WinSLAMM Strengths

- ▶ Ease of use – WinSLAMM uses a Windows-based interface with drop down menus, and a mixture of spreadsheet-like and fill-in-the-blank data entry sheets. Many of the selection options are self-explanatory, and the accompanying documentation and help tool are adequate to address most questions. Anyone with a basic understanding of stormwater runoff processes, stormwater BMPs and spreadsheets should be able to get up to speed in a few hours, and become proficient within development of 5 or 10 sites or models. Full-day and multiple-day training on the use of WinSLAMM has been offered.
- ▶ Small storm hydrology approach - WinSLAMM’s strength is estimating runoff volume, a measure that has become increasingly important as our understanding of watershed hydrology has developed. WinSLAMM hydrology is based on simple volumetric runoff coefficient relationships for each source area. This approach allows WinSLAMM to predict runoff volume much more accurately than NRCS curve number method over the 99% of runoff-generating events smaller than 2 inches. This should also allow improved accuracy in estimating stormwater runoff quality because pollutant loading is integrally linked to accurate prediction of runoff volume.
- ▶ Source area specific input and analysis - The model contains source area specific pollutant build-up and wash-off algorithms, and estimates run-off and pollutant yield by source area. This allows targeting source control or treatment to areas that generate the highest concentration of a pollutant of concern (i.e., “hot spots”).
- ▶ Input data requirements - The volumetric runoff coefficients and pollutant algorithms were developed empirically and are representative of, but not based on, physical processes. This means a simple description (type, size, condition) of source areas is all that is needed to populate the land use model. This information

can be based on a pre-development layout/design or a quick delineation of an existing site with GIS. The field data sheets included with WinSLAMM documentation allow rapid field characterization of sites to add further specificity. Obtaining or developing an appropriate rainfall data set may be the biggest data input challenge.

- ▶ BMP and treatment train options - The model has the capability to model water quantity and water quality impacts of wet detention basins, swale drainage, impervious area disconnections, bioretention and pervious pavement. This capability allows comparison of a range of approaches from the traditional hard-engineering, pipe-and-pond approach to extreme low-impact development scenarios.
- ▶ Ability to quickly run or explore alternative “what if” scenarios - WinSLAMM is set up such that the user can start with a baseline model, make and save minor or major changes quickly, and run multiple scenarios through a batch editor to compare the differences among many “what if” scenarios. This attribute allows the stormwater professional - whether designer, reviewer or planner - to rapidly assess alternative site layouts or BMPs, to assess the impact of changes to regulations, or to conduct sensitivity analyses.
- ▶ Excellent planning tool - The conceptual simplicity of WinSLAMM allows rapid consideration of a range of alternatives, allows targeting of resources to the most effective strategies, and facilitates communication amongst interested parties
- ▶ Wisconsin experience - The State of Wisconsin, through their Department of Natural Resources, has extensive experience using WinSLAMM as a stormwater planning and assessment tool, and has been intimately involved in the development of data sets and model options. In addition, WinSLAMM is one of the modeling options available to site designers and Phase II communities to show compliance with Wisconsin stormwater regulations. This experience adds a measure of legitimacy to the model.

WinSLAMM Weaknesses

- ▶ Pervious area hydrology - Under the best of circumstances (e.g., tightly controlled laboratory conditions), soil hydrology is a challenge to model. As with other hydrologic models, the higher the percentage of pervious area at the modeled site, the more likely WinSLAMM will have significant errors in runoff prediction. Comparison of scenarios with low impervious area should acknowledge this caveat.
- ▶ Site specificity - WinSLAMM is designed as a planning tool, showing relative comparisons of different development scenarios and management practices. Though more specific characterization of some parameters is available (e.g., surface texture of pavement), other site variables such as slope and vegetation cannot be specified. Much additional input data, including matched rainfall and discharge data would be necessary to calibrate WinSLAMM to individual site conditions. As mentioned above, there is much hydrologic variability within a soil classification. With the movement toward low impact development, it would be beneficial to have a more

explicit way in WinSLAMM to account or credit for practices used to improve soil quality and infiltration within the same soil classification.

- ▶ BMP limitations - Several realistic model scenarios, such as bioretention treating the runoff from streets, cannot be modeled. WinSLAMM BMP modeling capabilities seem to improve with each model update. Concerns encountered with results from scenarios that included bioretention and pervious pavement in earlier versions appear to be corrected or improved in the latest version (v9.4).
- ▶ Hydrograph generation - Though not the primary use for WinSLAMM, the model does have the ability to generate an output hydrograph that could be used as input to another model such as HEC-RAS. WinSLAMM uses a unit hydrograph, and allows the user to set the “peakiness” of the unit hydrograph. WinSLAMM performs hydrologic routing on flows directed through BMPs, but does not account for hydraulic routing through the drainage network that determines travel time and hydrograph characteristics. Hydrograph generation was the aspect of WinSLAMM that produced the most glitches during model runs for this study. It appears that those glitches have been corrected in the most recent release (v9.4).
- ▶ WinSLAMM flow duration analysis - WinSLAMM now includes a flow duration analysis application (Pitt, 2007). The flow duration from a single development site seems to be of dubious value as a measure of channel stability since flow duration depends on the in-stream hydrograph resulting from summation of the cumulative hydrographs from all contributing parcels.
- ▶ Translatability - Though likely to change with the shift toward managing runoff volume, stormwater professionals typically think in terms of the curve number or rational methods. Therefore, there may be a translatability concern with WinSLAMM results.
- ▶ Not supported by an extensive research literature base - There are hundreds of research studies for the commonly used stormwater management models - e.g., the rational method, the curve number method, SWMM. This allows multiple users to share their experiences and identify strengths and weaknesses with the model. For an empirical model such as WinSLAMM, this also would allow validation and verification of the model assumptions at sites other than those where the original data was collected. A literature search and canvassing of the model developers and known users resulted in very few WinSLAMM publications (Bachhuber and Sipple, No Date; Bannerman, 2003, 2005; Bannerman et al., 1993; Bochis-Micu and Pitt, 2005; Hurley, 2008; Narayanan et al., 2007; Pitt, 2005).
- ▶ User interface - For model users used to a fancy graphical user interface, plan view with spatial placement of system components, or model output with multiple bells and whistles, WinSLAMM may be a disappointment.

WinSLAMM Calibration

Model calibration is worth another mention. From Pitt (2008):

“The recommended strategy for using WinSLAMM is to start with the supplied parameter file set and rain files. The most important element will be to prepare an accurate site file based on a correct site description. It is also easy to prepare a site specific rain file using local data. Collection of local or regional outfall monitoring data is also strongly recommended in order to modify the parameter files, as needed.”

Also from Pitt (2008):

“Without regional calibration, one will have to accept larger calculation errors than if local calibration was conducted. Even so, the model will still be useful for comparative purposes, especially if accurate rain and site files are used. In most cases, the runoff file needs very little change in order to accurately predict runoff volumes, for example.”

The modelers in this study took care to develop accurate site files and used gage rainfall data collected at Burton, Ohio. However, resources were not available to collect outfall data (flow or water quality) to calibrate the model for the Chagrin Watershed. WinSLAMM’s value as a planning tool for stormwater professionals in Ohio would only be helped by studies that collected paired rainfall-runoff and water quality data that would allow validation or calibration of input parameter files.

Conclusions and Recommendations

The Source Loading and Management Model (WinSLAMM) was used to evaluate the effectiveness, in reducing runoff volume and controlling annual sediment loads, of alternative stormwater management practices compared to the more traditional approaches favored by local and state regulations. The practices evaluated included impervious area disconnection, open swale drainage, bioretention and pervious pavement, practices that are typically classified as low impact development (LID) strategies.

For the modeled residential subdivisions, swales reduced runoff volume 7-8% over the curb & gutter and sewer pipe drainage specified by local regulations. For the same residential subdivisions, disconnecting impervious areas resulted in annual runoff volume reductions of 32 to 53%. Whereas wet detention basins created no significant reduction in runoff volume, bioretention practices reduced annual runoff volume by 30-50% when sized for the WQv and reduced runoff volume 62-76% when sized as 0.2 x site impervious area. Using pervious pavement for the parking lot reduced annual runoff volume for the commercial site by 41%. These practices, especially when used together, effectively manage runoff volumes with several combinations approaching pre-development runoff volumes. These LID stormwater management strategies also provide benefits to the developer and community in meeting local peak discharge re-

quirements and water quality targets.

Historic (and many current) stormwater management practices in the Chagrin River Watershed do not adequately address the stormwater impacts that result from the increase in runoff volume. Many local zoning, subdivision and post-construction stormwater management regulations encourage a pipe-and-pond approach that:

- ▶ treats stormwater as a nuisance that should be disposed of as quickly as possible;
- ▶ treats stormwater management as an afterthought rather than an integral part of site layout and design;
- ▶ ignores or removes valuable landscape services offered by the soil, vegetation and surface flow paths;
- ▶ moves the consequences and costs of not managing stormwater runoff volume onto downstream property owners and taxpayers.

The science of stormwater management has progressed to the point that developers, designers and local decision-makers should be encouraging stormwater systems that make economic and ecological sense at both the site and community scales.

The following recommendations are based on the best current science and the results of this study.

Recommendations - Low Density Residential (lots > 0.5 acre)

- ▶ Disconnection of all impervious areas should be required.
- ▶ The use of swale drainage instead of curb & gutter and storm sewers (swales should be required for lots 1 ac and larger) should be strongly encouraged, the default rather than the exception.
- ▶ Open space protection, grading and soil renovation requirements are needed to protect the landscape functions and infiltration capacity.
- ▶ Subdivision and stormwater regulations need to be updated to reflect the above recommendations.
- ▶ For these low impervious area developments, a low impact approach – selective grading, soil renovation, swale drainage and use of rain gardens - should eliminate the need for “end of pipe” BMPs (i.e., detention ponds) for peak discharge control.

Medium Density Residential (2-8 lots/acre)

- ▶ Disconnection of impervious areas should be the design standard, e.g., all catch basins should be located in vegetated areas with 15 ft minimum/> 25 ft average flow path.
- ▶ The use of swale drainage instead of curb & gutter should be encouraged.
- ▶ Soil quality maintenance or renovation requirements are needed. Open space protection and selective grading should be encouraged to protect the landscape functions and infiltration capacity.

- ▶ For these medium density developments, a low impact approach – focus on soil quality (selective grading, soil renovation), impervious area disconnection, distributed bioretention/rain gardens, pervious pavement parking lanes, and engineered swales - would address both water quality and water quantity. Some less costly and intrusive form of detention can be incorporated to meet peak discharge control requirements.
- ▶ Subdivision and stormwater regulations must be updated to allow/encourage LID approach.

Recommendations - Commercial, Institutional, and Multi-Family Residential

- ▶ Incorporate minimum green space or landscape requirements (recommend 10-20%; 15% a good compromise).
- ▶ Disconnection of impervious areas should be the design standard. All catch basins should be located in vegetated/landscaped areas with 15 ft minimum/> 25 ft average flow path. Parking lot islands should be designed to receive and treat runoff from impervious pavement.
- ▶ For C&D soils, landscaped areas should use engineered soils and bioretention design.
- ▶ Pervious pavement should be encouraged or required except for “hot spots” (sites with high pollution potential) or sites with physical limitations.
- ▶ Stormwater regulations should be updated to incorporate minimum landscaping requirements and parking “maximums”, and require/encourage bioretention and pervious pavement where appropriate.

Needs/Next Steps

Currently, there is little impetus for developers or their engineers to include LID stormwater practices in the design of new developments. Widespread implementation of these alternatives will require:

- ▶ OEPA and local government comfort with LID;
- ▶ CRWP work with local jurisdictions to review all aspects of development regulations (zoning, subdivision, stormwater) that affect implementation of stormwater systems and remove barriers to implementation.
- ▶ CRWP work with local governments and ODNR to develop guidance that appropriately credits LID practices for peak discharge requirements;
- ▶ Identification or development of other financial incentives for LID;
- ▶ Update of state and local regulations to reflect latest technical understanding;
- ▶ Development of clear design guidance and maintenance requirements for LID practices;
- ▶ More and better design guidance on overall site design, site drainage, construction and construction oversight, and management of soil quality;
- ▶ Facilitation of learning curve for LID practices such as bioretention and pervious

pavement with better design tools and models, materials specifications and sources, cost information, demonstration projects, training, and monitoring;

- ▶ Monitoring of individual BMPs and alternative designs to document Ohio-based stormwater BMP/system performance (hydrologic, water quality, aesthetics, maintenance, cost);
- ▶ Quantification through monitoring and modeling of impacts on surface and groundwater;
- ▶ Improved quantification of internal and external costs – flooding, infrastructure, etc.;
- ▶ Work with interested member communities to use WinSLAMM for stormwater planning and plan evaluation;
- ▶ Identification of opportunities to collect rainfall-runoff-water quality data to calibrate WinSLAMM for Ohio conditions.

References

Aquafor Beech Limited. 2006. Stormwater Management and Watercourse Impacts: The Need for a Water Balance Approach. Toronto Region Conservation Authority.

ASCE. 1992. Design and Construction of Urban Stormwater Management Systems. Manual of Practice No. 77. American Society of Civil Engineers, New York.

ASCE. 1998. Urban Runoff Quality Management. ASCE Manual of Practice No. 87. American Society of Civil Engineers, Reston, VA.

Bachhuber, J.A. and D. Sipple. Draft. Stormwater Pollution Management at a Foundry Site - Monitoring, Modeling and Design.

Bannerman, R., D. Owens, R. Dobbs and N. Hornewer. 1993. Sources of Pollutants in Wisconsin Stormwater. *Wat. Sci. Tech* 28(3): 241-259.

Bannerman, R. 2003. A Procedure for Selection of Stormwater Treatment Practices in Established Areas. Proc. 3rd South Pacific Stormwater Conference, Auckland, New Zealand, New Zealand Water & Wastes Association.

Bannerman, R. 2005. Verification of a Method for Sizing All Proprietary Single Chamber Treatment Devices with Settling as a Unit Process. Wisconsin Department of Natural Resources, Madison.

Barr Engineering. 2006. Burnsville Stormwater Retrofit Study. Prepared for City of Burnsville, MN.

Belan, G., and B. Otto. 2004. Catching the Rain: A Great Lakes Resource Guide for Natural Stormwater Management. American Rivers, Washington, DC.

Bitting, J. and C. Kloss. 2008. Green Infrastructure Retrofit Policies. EPA-833-F-08-008. U.S. EPA, Washington, DC.

Bledsoe, B. 2002. *J. Water Resources Planning & Mgmt.*, 128(6): 451-455.

Bochis-Micu, C., and R. Pitt. 2005. Impervious Surfaces in Urban Watersheds. Presented at 78th Water Env. Federation Tech. Expo and Conf., Washington, DC, Oct. 29-Nov. 2, 2005.

Booth, D.B. 1990. Stream-Channel Incision Following Drainage-Basin Urbanization. *Water Resources Bulletin* 26(3): 407-417.

- Booth, D.B., and C.R. Jackson. 1997. Urbanization of aquatic systems: Degradation thresholds, stormwater detection, and the limits of mitigation. *J. American Water Resources Assn.* Vol. 33(5): 1077 - 1090.
- Burton, G.A. Jr., and R. Pitt. 2001. *Stormwater Effects Handbook: A Tool Box for Watershed Managers, Scientists, and Engineers.* CRC Press, Inc., Boca Raton, FL.
- Clar, M. No Date. *Pembroke Woods: Lessons Learned in the Design and Construction of an LID Subdivision.* Ecosite, Columbia, MD.
- Claytor, R. And T. Schueler. 1996. *Design of Stormwater Filtering Systems.* Chesapeake Research Consortium, Solomons, MD.
- Coffman, L. No date. *Low-impact Development Design: A New Paradigm for Stormwater Management - Mimicking and Restoring the Natural Hydrologic Regime: An Alternative Stormwater Management Technology.*
- CRWP. 2006. *Improving Land Use in the Lake Erie Basin through Better Planning, Improved Regulations, and Stormwater Modeling.* Chagrin River Watershed Partnership grant proposal/application submitted (12/06) to Environmental Technology Development Program, The Cooperative Institute for Coastal and Estuarine Environmental Technology (CICEET).
- CWP. 1998. *Better Site Design: A Handbook for Changing Development Rules in Your Community.* Center for Watershed Protection, Ellicott City, MD.
- CWP. 2007. *National Pollutant Removal Performance Database, Version 3.* Center for Watershed Protection, Ellicott City, MD.
- Davis, J.P., C.A. Rohrer, and L.A. Roesner. No Date. *Effects of Catchment Modification on the Flow Frequency Curve Modeled Using the EPA-SWMM Model.* Dept. of Civil Engineering, Colorado State University, Ft. Collins, CO.
- DePhilip, M.M., W.M. Larson, T.M. Redder, J.V. DePinto, and L.C. Hinz. 2006. *Developing methods to analyze, protect and restore flow regimes in Great Lakes tributaries.* The Nature Conservancy, Great Lakes Program. Chicago, IL.
- Doyle, M., J. Harbor, C. Rich, and A. Spacie. 2000. *Examining the Effects of Urbanization on Streams Using Indicators of Geomorphic Stability.* *Physical Geography* (21)2: 155-181.
- Duru, J.O. 1981. *On-site Detention: A Stormwater Management or Mismanagement Technique?* In *Proc. 1981 Intl Symp Urban Hydrology, Hydraulics and Sediment Con-*

trol, Lexington, KY.

Elliott, A.H., and S.A. Trowsdale. 2006. A review of models for low impact urban stormwater drainage. *Env. Modeling & Software* 22: 394-405.

Emerson, C., R. Traver, and C. Welty. 2003. Changing from Peak Flow to Volume Requirements, a Watershed-Wide Perspective. Urban Stormwater Partnership Conference, Villanova University, PA, Oct. 16-17, 2003.

Ferguson, B. 1984. Infiltration and Recharge of Stormwater: A Resource Conserving Alternative for the Urban Infrastructure. P1563, Vance Bibliographies, Monticello, IL.

Ferguson, B. 1994. Stormwater Infiltration. Lewis Publishers, Boca Raton, FL.

Ferguson, B. 2005. Porous Pavements. Taylor & Francis, Boca Raton, FL.

Freeze, R.A., and J.A. Cherry. 1979. Groundwater. Prentice-Hall, Englewood Cliffs, NJ.

Goff, K.M. and R.W. Gentry. 2006. The Influence of Watershed and Development Characteristics on the Cumulative Impacts of Stormwater Detention Ponds. *Water Resources Mgmt* 20: 829-860.

Graham, P., L. Maclean, D. Medina, A. Patwardhan, and G. Vasarhelyi. 2004. The Role of Water Balance Modelling in the Transition to Low Impact Development. *Water Qual. Res. J. Canada* 39(4): 331-342.

Hershfield, D.M. 1961. Rainfall Frequency Atlas of the United States, Technical Paper No. 40, U.S. Weather Bureau, Washington, DC.

Hinman, C. 2005. Low Impact Development Technical Guidance Manual for Puget Sound. Puget Sound Action Team, Olympia, WA.

Hirschman, D., K. Collins and T. Schueler. 2008. The Runoff Reduction Method. Technical Memorandum, Center for Watershed Protection, Ellicott City, MD.

Huber, W.C., L. Cannon and M. Stouder. 2006. BMP Modeling Concepts and Simulation. EPA/600/R-06/033. U.S. EPA, Washington, DC.

Huff, F.A. and J.R. Angel. 1992. Rainfall Frequency Atlas of the Midwest. Illinois State Water Survey, Bulletin 71, Champaign.

Hurley, S. 2008. Design Scenarios for Low Impact Development in Ultra-Urban Watershed-Scale Redevelopment Projects: Case Studies from Boston's Charles River. Ameri-

can Water Resources Assn, Annual Water Resources Conference, November 17-20, 2008, New Orleans, LA.

Jarrett, A.R., M. Nassry, and W.F. Hunt. 2003. Stormwater Infiltration, Treat and Use It: Its Time to Stop Giving It Away. Proc. 2003 Pennsylvania Stormwater Mgmt Symp., Oct. 16-17, Villanova University, Philadelphia.

Kaufman, M., and M. Wurtz. 1997. Hydraulic and Economic Benefits of Downspout Diversion. J. American Water Resources Assn, Vol 33(2): 491-497.

Konrad, C. Effects of Urban Development on Floods. Fact Sheet 076-03, USGS, Tacoma, Washington.

Konrad, C., and D. Booth. 2005. Hydrologic Changes in Urban Streams and Their Ecological Significance. American Fisheries Society Symposium 47:157-177, 2005.

Lee, J.G., and J.P. Heaney. 2003. Estimation of Urban Imperviousness and Its Impacts on Storm Water Systems. J. Water Resources Planning & Mgmt, 129(5): 419-426.

LIDC. 2007. Low Impact Development Techniques Applied to the Village at Watt's Creek Traditional Neighborhood Development (TND), Denton, Maryland. Prepared by the Low Impact Development Center for The Chesapeake Bay Trust Pioneer Grant Program.

Livingston, Eric H. 2000. Lessons Learned About Successfully Using Infiltration Practices. In Proc Natl Conf on Tools for Urban Water Management & Protection, Chicago, Illinois, United States Environmental Protection Agency, February 7-10, 2000.

Lloyd, O., and W. Lyke. 1995. Ground Water Atlas of the United States - Illinois, Indiana, Kentucky, Ohio, Tennessee. U.S. Geological Survey, HA730-K.

Locklear, H. 2009. Washington State Decision Makes LID Mandatory. Stormwater 10 (5): 14-19.

MacRae, C.R. 1997. Experience from Morphological Research on Canadian Streams: Is Control of the Two-year Frequency Runoff Event the Best Basis for Stream Channel Protection? In, L.A. Roesner (Ed.), Proc. Effects of Watershed Development and Management on Aquatic Ecosystems conference, Snowbird, Utah, August 1996. American Society of Civil Engineers, New York.

McCuen, R. 1974. A Regional Approach to Urban Storm Water Detention. Geophysical Research Letters 1(7): 321-322.

McCuen, R. 1979. Downstream Effects of Stormwater Management Basins. J. Hydraulic Div. ASCE 105(11): 1343-1356.

McCuen, R. 1998. Hydrologic Analysis and Design, 2nd Edition. Prentice Hall, Upper Saddle River, NJ.

MDE. 2000. Unified Stormwater Sizing Criteria. Chapter 2 in Maryland Stormwater Design Manual. Maryland Department of the Environment.

MDE. 2008. Environmental Site Design. Chapter 5 in Revised Maryland Stormwater Design Manual. Maryland Department of the Environment. http://www.mde.state.md.us/assets/document/sedimentStormwater/Chapter_5_10-03-2008.pdf

Mecklenburg, D., and A. Ward. 2002. Quantifying and Managing the Impacts of Urbanization on the Effective Discharge and Stream Stability. In Proc. Environmental Flows for River Systems, Cape Town, South Africa, March 3-8, 2002.

MMSD. 2005. LID Quicksheet 1.2, A Spreadsheet for Determining the Capacity of LID Features to Meet MMSD Chapter 13 Requirements - User Manual. The Milwaukee Metropolitan Sewerage District, Milwaukee, WI.

Montgomery, R.J. and J.G. Voorhees. 1991. SLAMM Model Calibration and Example Application Project. Prepared for Wisconsin Department of Natural Resources, Madison, WI.

MPCA. 2005. Minnesota Stormwater Manual, Version 2. Minnesota Pollution Control Agency, St. Paul, MN.

Muthukrishnan, S., R. Field, and D. Sullivan. 2004. Structural BMP Design Practices. Chapter 3 in Muthukrishnan, S., B. Madge, A. Selvakumar, R. Field, and D. Sullivan, The Use of Best Management Practices in Urban Watersheds. Publication EPA/600/R-04/184, U.S. Environmental Protection Agency, NRMRL-ORD, Cincinnati, OH.

Narayanan, A., C. Bochis, and R. Pitt. 2007. Modeled Flow Duration Variations and Costs for Pollutant Removal Associated with Different Stormwater Control Practices. Proc. of the 2007 Georgia Water Resources Conference, March 27-29, 2007, University of Georgia.

NCHRP. 2006. Evaluation of Best Management Practices for Highway Runoff Control. NCHRP Report 565. National Cooperative Highway Research Program, Transportation Research Board of the National Academies, Washington, DC.

NRC. 2008. Urban Stormwater Management in the United States. Committee on Re-

ducing Stormwater Discharge Contributions to Water Pollution, Water Science and Technology Board, Div. of Earth and Life Studies, National Research Council. National Academies Press, Washington, DC.

NRCS. 1965. Computer Program for Project Formulation. Technical Release 20 (TR-20), U.S. Dept. of Agriculture, Natural Resources Conservation Service, Washington, DC.

NRCS. 1986. Urban Hydrology for Small Watersheds. Technical Release 55 (TR-55), U.S. Dept. of Agriculture, Natural Resources Conservation Service, Washington, DC.

NWS-NOAA. 2004. Precipitation-Frequency Atlas of the United States, NOAA Atlas 14, Vol 2, Version 3, NOAA, National Weather Service, Silver Spring, MD. [This data can be accessed through the internet Precipitation Frequency Data Server (PFDS): <http://hdsc.nws.noaa.gov/hdsc/pfds/>]

ODNR. 1980. Ohio Stormwater Control Guidebook. Ohio DNR, Division of Soil & Water Conservation, Columbus.

<http://www.dnr.state.oh.us/soilandwater/water/urbanstormwater/default/tabid/9190/Default.aspx>

ODNR. 2004. Improving Stream Protection and Assistance to Phase II Communities through Advanced Storm Water Standards. ODNR-DSWC Grant Proposal/ Application to the Research and Development Program, Ohio Water Development Authority, Columbus, OH.

ODNR. 2006. Rainwater and Land Development Manual, 2006 Edition. Ohio DNR, Division of Soil & Water Conservation, Columbus.

<http://www.dnr.state.oh.us/water/rainwater/default/tabid/9186/Default.aspx>

Ohio EPA. 2003. NPDES Construction General Permit, April 2003.

Ohio EPA. 2007. Post-Construction Q & A Document, March 2007.

Ohio EPA. 2008. NPDES Construction General Permit, April 2008.

PaDEP. 2006. 363-0300-002. Pennsylvania Stormwater Best Management Practices Manual. Pennsylvania Department of Environmental Protection.

Pitt, R. 1987. Small Storm Urban Flow and Particulate Washoff Contributions to Outfall Discharges. Ph.D. Thesis, University of Wisconsin-Madison.

Pitt, R., S. Clark, K. Parmer, and R. Field (Eds.). 1996. Groundwater Contamination from Stormwater Infiltration. Ann Arbor Press, Ann Arbor, MI.

- Pitt, R. 1999. Small Storm Hydrology and Why It Is Important for the Design of Stormwater Control Practices. In W. James (ed.), *Advances in Modeling the Management of Stormwater Impacts*, Volume 7. Computational Hydraulics International, Guelph, Ontario and Lewis Publishers/CRC Press. 1999.
- Pitt, R., J. Lantrip, R. Harrison, C. Henry, and D. Xue. 1999. Infiltration Through Disturbed Urban Soils and Compost-Amended Soil Effects on Runoff Quality and Quantity. EPA/600/R-00/016, U.S. EPA, Office of Research and Development, Washington, DC.
- Pitt, R. 2002. Receiving Water Impacts Associated with Urban Runoff. In D. Hoffman, B. Rattner, G.A. Burton, Jr., and J. Cairns, Jr. (Eds.), *Handbook of Ecotoxicology*, 2nd Edition. CRC-Lewis. Boca Raton, FL.
- Pitt, R., Shen-En Chen, and Shirley Clark. 2002. Compacted Urban Soils Effects on Infiltration and Bioretention Stormwater Control Designs. Presented at the 9th International Conference on Urban Drainage. IAHR, IWA, EWRI, and ASCE. Portland, Oregon, September 8-13, 2002.
- Pitt, R. and J. Voorhees. 2002. SLAMM, the Source Loading and Management Model. In R. Field and D. Sullivan (eds.), *Wet-Weather Flow in the Urban Watershed: Technology and Management*. CRC Press. Boca Raton, FL. 2002.
- Pitt, R. and J. Voorhees. 2004. The use of WinSLAMM to evaluate the benefits of low impact development. Low Impact Development Conference: Putting the LID on SWM. College Park, MD. Sept. 21-23, 2004.
- Pitt, R. 2005. Clay County, NC/Towns County, GA Industrial Park Stormwater Quality Evaluation. Pilot study, Tennessee Valley Authority, Economic Development (TVAED).
- Pitt, R. 2008. Calibration of WinSLAMM. Provided by PV and Associates, Madison, WI.
- Prince George's County. 1999a. Low-Impact Development Design Strategies: An Integrated Design Approach. Prince George's County, Dept. of Env. Resources.
- Prince George's County. 1999b. Low-Impact Development Hydrologic Analysis. Prince George's County, Dept. of Env. Resources.
- Quigley, M., and T. Lawrence. 2000. Multi-functional Landscaping: Putting Your Parking Lot Design Requirements to Work for Water Quality. Fact Sheet CL-1000-01, Ohio State University Extension, Columbus, OH.

Reese, A. 2007. Stormwater Paradigms. Stormwater Magazine, Forester Communications.

Rodman, D., D. Hart, and B Lemke. 2003. The Use of GIS to Support Operation of the Source Loading and Management Model (SLAMM) for Analysis of Urban Non-Point Source Pollution. University of Wisconsin-Madison.

Roesner, L.A. and C.A. Rohrer. No date. Protocols for Evaluating the Effects of Land-use Patterns and Runoff Management on Urban Streams. Dept. of Civil Engineering, Colorado State University, Fort Collins, CO.

Rohrer, C.A. and L.A. Roesner. 2005. Matching the Critical Portion of the Flow Duration Curve to Minimize Changes in Modeled Excess Shear. 10th International Conference on Urban Drainage, Copenhagen/Denmark, 21-26 August 2005.

Rohrer, C.A., N.A. Postel, P.A. O'Neill and L.A. Roesner. No Date. Development of Design Criteria for Regional Stormwater Management Facilities to Maintain Geomorphic Stability in Cedar Creek. Dept. of Civil Engineering, Colorado State University, Ft. Collins, CO.

Roseen, R. M., Ballesteros, T. P., Houle, J. J., Avelleneda, P., Wildey, R., and Briggs, J. F. 2006 . Performance Evaluations for a Range of Stormwater LID, Conventional, Structural, and Manufactured Treatment Strategies for Parking Lot Runoff under Varied Mass Loading Conditions. Transportation Research Record, 1984: 135-147.

Rossman, L. 2008. Storm Water Management Model, Version 5.0. EPA/600/R-05/040. U.S. EPA National Risk Management Research Laboratory, Cincinnati, OH.

Sabourin, J-F., and H. Wilson. 2008. 20 Year Performance Evaluation of Grass Sswale and Perforated Pipe Drainage Systems. J.F. Sabourin and Assoc., Inc. For Infrastructure and Management Division, City of Ottawa, Canada.

Schueler, T. 1987. Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban BMPs. Metro Washington Council of Governments, Washington, DC.

Schueler, T., J. Galli, L. Herson, P. Kumble and D. Shepp. 1992. Developing Effective BMP Systems for Urban Watersheds. In Anacostia Restoration Team, Watershed Restoration Source Book, Proc. Restoring Our Home River: Water Quality and Habitat in the Anacostia, November 6-7, 1991, College Park, MD. Dept. Environmental Programs, Metropolitan Washington Council of Governments, Washington, DC.

Selbig, W.R. and R.T. Bannerman. 2008. A Comparison of Runoff Quantity and Quality from Two Small Basins Undergoing Implementation of Conventional- and Low-

Impact-Development (LID) Strategies: Cross Plains, Wisconsin, Water Years 1999-2005. USGS-SIR 2008-5008, U.S. Geological Survey, Reston, VA.

Stephens, K., and J. Dumont. 2008. Establish Watershed-specific Runoff Capture Performance Targets.

Traver, R.G., and R.A. Chadderton. 1983. The Downstream Effects of Storm Water Detention Basins. In Proc. 1983 Intl Symp Urban Hydrology, Hydraulics and Sediment Control, Lexington, KY.

Turney, D.C. 2008. Modeling Annual Groundwater Recharge Using Recharge Wells to Meet Ohio EPA Requirements for the Darby Watershed. 16th National Nonpoint Source Monitoring Workshop, September 14-18, 2008, Columbus, Ohio.

UNHSC. 2007a. UNHSC Design Specifications for Porous Asphalt Pavement and Infiltration Beds. University of New Hampshire Stormwater Center, Durham, NH.

UNHSC. 2007b. 2007 Annual Report. University of New Hampshire Stormwater Center, Durham, NH.

Urbonas, B., and M. Glidden. 1983. Potential Effectiveness of Detention Policies. Presented at the Southwest Storm Drainage Symposium; Texas A & M, November, 1983

USEPA. 1982 Results of the Nationwide Urban Runoff Program. U.S. EPA, Washington, DC.

USEPA. 2004. Stormwater Best Management Practice Design Guide. EPA/600/R-04/121. U.S. EPA, Washington, DC.

USEPA. 2005a. Using Smart Growth Techniques as Stormwater Best Management Practices. EPA 231-B-05-002. U.S. EPA, Washington, DC.

USEPA. 2005b. National Management Measures to Control Nonpoint Source Pollution from Urban Areas. EPA 841-B-05-004. U.S. EPA, Washington, DC.

USEPA. 2007a. Reducing Stormwater Costs through Low Impact Development (LID) Strategies and Practices. EPA 841-F-07-006. U.S. EPA, Washington, DC.

USEPA. 2007b. National Management Measures to Control Nonpoint Source Pollution from Hydromodification. EPA 841-F-07-002. U.S. EPA, Washington, DC.

USGS. 2008. SLAMM Source Loading and Management Model Parameter and Standard Land Use Files for Wisconsin - An Urban Area Nonpoint Source Water Quality

Model. Wisconsin Water Science Center, U.S. Geological Survey. <http://wi.water.usgs.gov/slamm/>

Walesh, S. 1989. Urban Surface Water Management. John Wiley & Sons, New York.

Wanielista, M., and Y. Yousef. 1993. Stormwater Management. John Wiley & Sons, New York.

Weiss, P.T., G. LeFevre and J.S. Gulliver. 2008. Contamination of Soil and Groundwater Due to Stormwater Infiltration Practices: A Literature Review. Univ. Minnesota Stormwater Assessment Project, St. Anthony Falls Laboratory, Minneapolis, MN.

WiDNR. 2008. Runoff Management Models - SLAMM and P8. Runoff Management, Wisconsin Dept. of Natural Resources. <http://dnr.wi.gov/runoff/models/slamm.htm>

Wulliman, J., and P. Thomas. 2005. Learning from Nature: Reducing Urban Stormwater Impacts. Lake Line magazine, Urban Drainage and Flood Control District, Denver, CO.

Wulliman, J., and B. Urbonas. 2005. Peak Flow Control for Full Spectrum of Design Storms. Concept Paper - Urban Drainage and Flood Control District, Denver, CO.

Zhen, J., L. Shoemaker, J. Riverson, K. Alvi and M-S. Cheng. 2006. BMP Analysis System for Watershed-Based Stormwater Management. J. Env. Science & Health, 41: 1391-1403.

===

Other WinSLAMM related papers available at: <http://www.unix.eng.ua.edu/~rpitt/Publications/Publications.shtml>

Bochis, C. and R. Pitt. 2005. Site Development Characteristics for Stormwater Modeling.

Pitt, R. 2003a. The Integration of Water Quality and Drainage Design Objectives.

Pitt, R. 2003b. Using WinSLAMM.

Pitt, R. 2005b. Module 0: Introduction - Historical Review of Wet Weather Flow Management and Designs for the Future.

Pitt, R. 2007. Flow-Duration Analyses and Stream Stability for Habitat Evaluations and the Design of Stormwater Controls.

Appendix 1

Table A-1. Local Regulations that Affect Stormwater System Design.

Restriction/ Requirement	Solon	Mentor	Aurora
Lot Size	R1A 16,000 sf (0.37Ac) R1C 24,000 sf (0.55Ac) R1D 1 Ac R1E 5 Ac D/W < 5/1	R-1 16,000 sf (0.28Ac) R-2 15,000 sf (0.34Ac) R-3 18,000 sf (0.41Ac) R-4 22,000 sf (0.5Ac) R-5 1 Acre	R1 1.5Acre R2 3-Acre R3 29,000 sf (0.67Ac) R4 17,420 sf (0.4Ac) R5 11,200 sf (0.26)
Lot Width/ Setbacks	R1A W=80 ft Front setback <60 ft Side setback = 5 ft/20 ft Rear setback >.2D		See Table 1155.01 R1 W = 150 ft R2 W = 250 ft R3 W = 115 ft R4 W = 95 ft R5 W = 75 ft
Minimum House Size	1600 sf		
Street Width	Minor Sts - 26 ft (for lots > 2Ac, 16 ft) Major Sts - ?	Cul-de-sac – 20 ft Local Sts – 22 ft Minor Collector – 30 ft Major Collector – 36 ft Arterial – 48 ft + 2 ft per vert curb	Cul-de-sac – 22 ft Local Rd – 24 ft Secondary Rd – 24 ft Major Collector – 26 ft Private Rd – 22 ft
Cul-de-sacs di- ameter	126 ft	120 ft (see 1115.03 for specifics)	100 ft
Sidewalks	Required, W = ??		Required except R-1, R-2, W=5 ft
Roof drainage (connected vs dis- connected)	All directly connected to storm sewer	Downspouts outletted on splashblocks (allowed to connect directly to curb/ gutter or storm sewer?)	All directly connected to storm sewer (note: typically not enforced; some down- spout disconnection has been encouraged on certain projects) Rear yard drains
Subdivision drain- age (curb & gutter vs open swale/ ditch; storm sew- ers)	1250.20 Drainage Etc. "In any of the foregoing circumstances, the con- struction of open drainage ditches as a substitute for such storm drains or storm sewers shall not be permitted"	Curb & Gutter	Both options (C&G, open channels) available. Curb and gutter is required on all roads except R-1 & R2 zon- ing. C & G can be exempted by planning commission & council.
SW Design Meth- odology	"Design Standards for Stormwater Control" Sewers/channels/culverts – rational, TR55 Culverts/open channels – ODOT Cir- cular 5 Provided: P, I, Tt(sheet), C, n Detention – TR55 Peak discharge - release 100-yr, 24- hr post (4.6") at 5-yr, 24-hr pre (3.0")	Subdiv Regs – 1115.07 Drainage Storm sewers - Ra- tional/2-yr design storm Peak Discharge – CSM Storm gradient – sur- charge @ 10-yr	Open Channels – 10-yr de- sign storm Storm sewers – 5-yr storm residential/10-yr storm comm. Peak Discharge - CSM

Appendix 2

Source Area Identification and Delineation for Medium Density Residential

Review zoning and subdivision regulations for requirements that will affect source area size and dimensions (lot size, house size, setbacks, street width, cul-de-sac diameter, open space requirements, etc.).

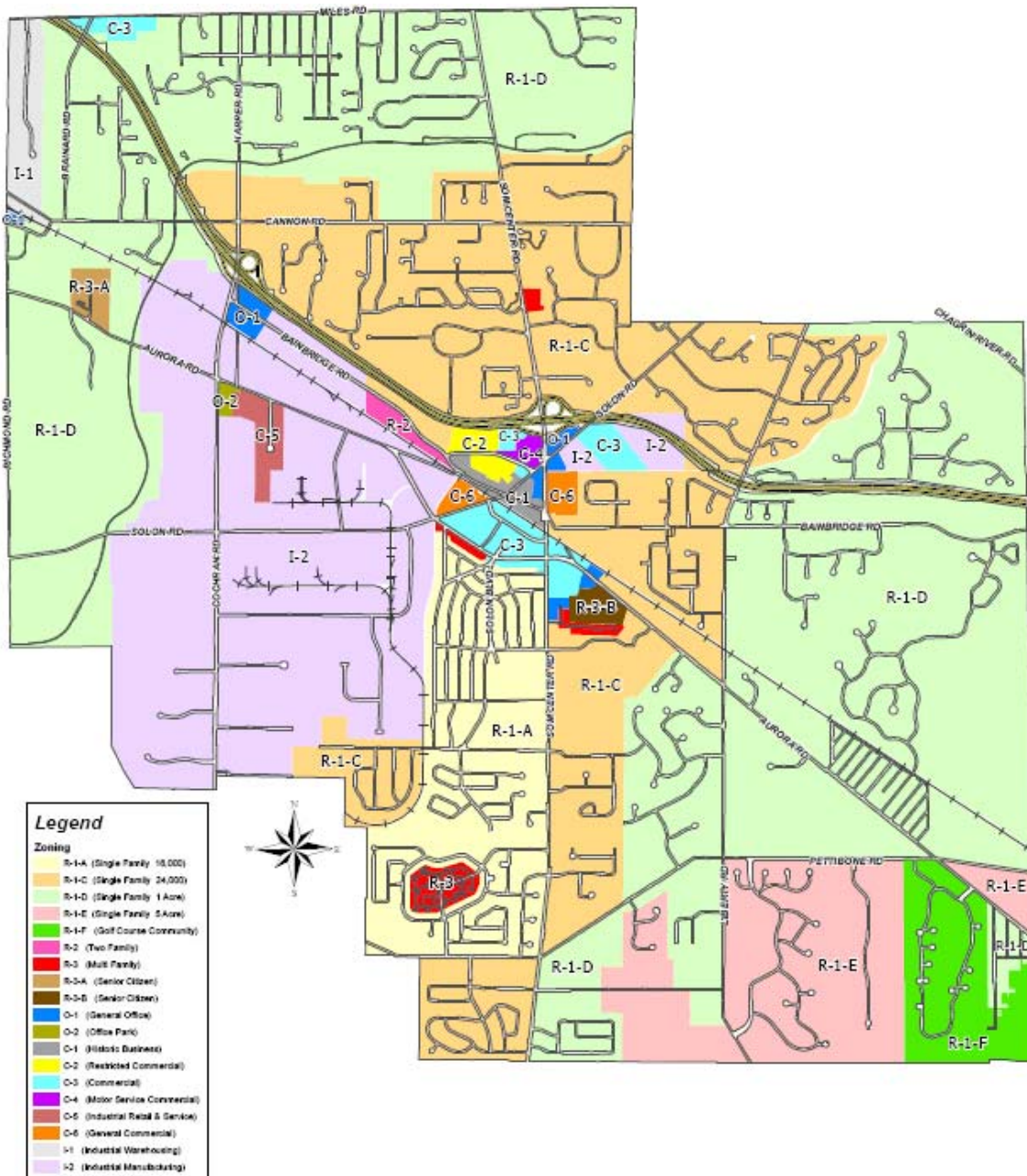


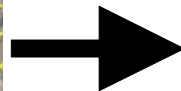
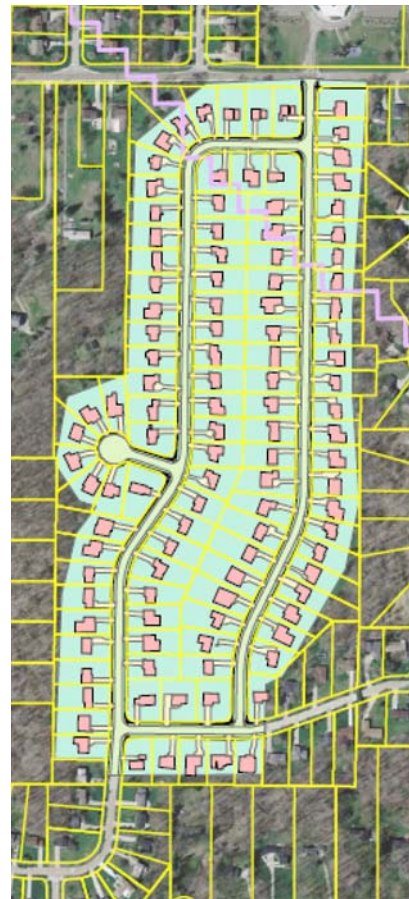
Figure A-1. Solon Zoning Map.

Use aerial photos in GIS to delineate representative developments.

Solon GIS



Source-area Delineation



Cannon Estates Subdivision

Density = 110 lots/49.4 Ac
= 2.2 lots/acre

Figure A-2. Source-area Delineation.

Source Area	Area (Ac)	Area (%)
Driveways	3.70	7.5
Sidewalks	1.55	3.1
Roofs	6.33	12.8
Streets	3.83	7.8
Total Impervious	15.4	31.2
Total Pervious	34.0	68.8
Total	49.4	100

Visit sites and complete WinSLAMM field data form.



Rapid Field Assessment

Cannon Estates Subdivision

SOLON 2-8-08 (13)

Table 2. Study Area Description Field Sheet
Cannon Estates

Location: _____ Site number: _____
 Date: 2-8-08 Time: _____
 Photo numbers: _____ Roll number: _____

Land-use and industrial activity:
 Residential: low medium high density single family
 multiple family
 trailer parks
 high rise apartments
 Income level: low medium high
 Age of development: <1930 '30-'50 '51-'70 '71-'80 new
 Institutional: school hospital other (type): _____
 Commercial: strip shop center downtown hotel offices
 Industrial: light medium heavy (manufacturing) describe:
 Open space: undeveloped park golf cemetery
 Other: freeway utility ROW railroad ROW other: _____

Maintenance of building: excellent moderate poor
 Heights of buildings: 1 2 3 4+ stories
 Roof drains: underground gutter impervious pervious
 Roof types: flat comp shingle wood shingle other:
 Sediment source nearby? No Yes (describe):
 Treated wood near street? No Yes (describe):
 Landscaping near road:
 quantity: None some much
 type: deciduous evergreen lawn *few trees*
 maintenance: excessive adequate poor
 leaves on street: none some much

Topography:
 street slope: flat (<1%) medium (2-5%) steep (>5%)
 land slope: flat (<1%) medium (2-5%) steep (>5%)
 Traffic speed: <25 mph 25-40 mph >40 mph
 Traffic density: light moderate heavy
 Parking density: none light moderate heavy
 Width of street: number of parking lanes: 1
 number of driving lanes: 2

Condition of street: good fair poor
 Texture of street: smooth intermediate rough
 Pavement material: asphalt concrete unpaved
 Driveways: paved unpaved
 condition: good fair poor
 texture: smooth intermediate rough

Gutter material: grass swale lined ditch concrete asphalt
 condition: good fair poor
 street/gutter interface: smooth fair uneven
 Litter loadings near street: clean fair dirty

Parking/storage areas (describe):
 condition of pavement: good fair poor
 texture of pavement: smooth intermediate rough
 unpaved

Other paved areas (such as alleys and playgrounds), describe:
 condition: good fair poor
 texture: smooth intermediate rough

Notes:

3 photos

3 total

Figure A-3. Field Assessment.

Compare findings to other communities through regulations, discussion, and research results. Create “generic” development scenario.

Table A-2. Source Area Percentages for Representative Low Density Residential (LDR), Medium Density Residential (MDR) and Commercial Sites.

Source Area	Cannon Estates Area (%)	WinSLAMM MDR Area (%)	WinSLAMM LDR Area (%)	Model MDR (0.4 ac lot) Area (%)
Roofs	12.8	15.0	8.0	12.5
Driveways	7.5	7.7	4.6	7.0
Sidewalks	3.1	2.2	0.7	2.0
Streets	7.8	12.8	7.0	8.5
Total Impervious	31.2	37.7	20.3	30.0
Lawns/landscaping	68.8	62.3	79.7	70.0
Total	100	100	100	100