THE ROLE OF THE RESIDENTIAL SHORELAND LAWN AS A HYDROLOGIC CONNECTION BETWEEN DOWNSPOUT AND LAKE

By

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ABSTRACT

The degree to which residential shoreland lawns function as a hydrologic disconnection between impervious surfaces and the adjacent lake was explored at Shawano Lake in Shawano County, Wisconsin. Ten lawns were studied for their capacity to infiltrate runon discharged from downspouts. Soil and surface variables incorporated in the study included slope, soil bulk density, textural class and initial water content, and grass thickness. Water discharged through a mock downspout and into a constructed grassed runoff channel simulated runon; variable discharge rates represented different roof sizes draining to the downspout. Runoff velocity and volume was measured at the terminal end of the channel. The standard method of measuring infiltration—a double-ring infiltrometer—was used for comparison.

Results indicated that runoff velocity increased as runon application rates increased, and that infiltration rates obtained from double-ring infiltrometers were generally lower than those observed in runoff channels. The most important factors influencing runoff delivery were storm size, source area size, and saturated hydraulic conductivity (K_{sat}). Grass thickness also appeared influential, although to a lesser degree. Any influence by other surface and soil variables was masked by source area size and the high I_{ss} rates associated with the coarse-textured soils of Shawano shorelands. Field observations were used to calibrate the Vegetative Filter Strip Model (VFSMOD) and evaluate its usefulness in a residential setting. Although intended to model runoff and sediment reduction from an agricultural field draining to a buffer strip, VFSMOD functioned well as a tool for residential runoff predictions. However, its applications are limited due to its single-event, field scale design. A linear regression was developed from VFSMOD output that predicted the volume of runoff delivered from various roof sizes, setback distances, infiltration rates, and storm sizes. The regression was applied to the entire Shawano shoreland region to obtain an annual estimate of runoff volume and evaluate the importance of different storms over the course of the average year and recent years (2005-2007). The most notable finding was the influence of storm size distribution. Typically, two or three large storms contributed most of the runoff in the years examined. 2007 was the year with the highest annual precipitation, but a high frequency of small storms resulted in less runoff delivery than years with lower annual rainfall.

ACKNOWLEDGMENTS

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INTRODUCTION

Riparian shorelands represent the interface between aquatic and terrestrial systems. Undisturbed shorelands play an important role in infiltrating rainfall, intercepting runoff and filtering contaminants, and contributing to the overall water quality of the receiving water body. Shorelands provide a degree of hydrologic disconnection between the nutrient cycling on land and the nutrients in the lake by slowing the movement of phosphorus and other plant-essential elements from land to water. When shorelands are developed, their hydrologic functions are altered and frequently compromised (Markham, L., 2003). Infiltration rates may be limited by impervious surfaces and soil compaction, resulting in greater annual runoff delivery and increased contaminant and nutrient loading to streams and lakes.

The impact of shoreland development on water quality has become a management concern nationwide (Graczyk, D. J. *et al.*, 2003). The current trend of rapid development of the nation's shorelands is reflected along the shores of Wisconsin's lakes, where residential development has increased approximately 216% on shorelands of northern Wisconsin lakes (Wisconsin Department of Natural Resources, 1996). Residential development is of particular concern to watershed managers because of the high phosphorus concentrations in runoff. Phosphorus is the limiting nutrient in the productivity of most Wisconsin lakes. Consequently, increased phosphorus loads lead to increased productivity and accelerated eutrophication rates.

Runoff from residential lawns often yields higher phosphorus concentrations than any other source area in an urban, or developed, environment. Included in the definition of development are commercial, industrial, and transportation zones (Legg, A. D. *et al.*, 1996). Garn (2002) observed that runoff from residential developments on shorelands contributed 51% of the annual phosphorus budget of Wisconsin's Lauderdale Lakes, although the shoreland area comprised only 4% of the watershed. These figures are alarming in light of the heavy development pressure on Wisconsin's shorelands. Based on current rates in Wisconsin, predictions of developed lakeshore area range from 90% of all privately owned shoreland by 2025 (Hunt *et al.* 2006), up to 100% as early 2020 (Wisconsin Department of Natural Resources, 1996).

Phosphorus loading from shoreland properties to adjacent water bodies is a function of storm runoff. In the most basic sense, phosphorus loading can be reduced by decreasing runoff. The difficulty in managing runoff arises from the relatively un-studied interactions between impervious surfaces and pervious surfaces. In addition to direct precipitation on a lawn, runon (water draining from an impervious to a pervious surface) must also be considered when attempting to control runoff. The nature of the runon further complicates runoff management. In particular, runon that originates and remains as sheet flow is likely to deliver considerably less runoff to a receiving water body than runon concentrated through a downspout and conveyed to a receiving water body via grassed drainage swales.

An important concern is whether the factors that are commonly used to estimate runoff reduction at the watershed scale are also relevant for describing reduction of *runon* at the scale of individual parcels. A variety of surface and soil characteristics are known to affect the velocity and volume of runoff. Some of the most important characteristics are embodied in the empirical values utilized by runoff prediction tools, such as the rational method and the NRCS curve number method. The rational method (which predicts peak runoff rates) uses empirical coefficients based on hydrologic soil group, slope and landuse. The NRCS method, which estimates total event runoff, uses curve numbers that relate to landuse, hydrologic condition of vegetation, and hydrologic soil group. Manning's equation, which calculates velocity or discharge of overland flow, relies on channel dimensions and slope, in addition to an empirical Manning's roughness coefficient that reflects the degree of friction associated with different types of vegetation(McCuen, R. H., 2004). It can be deduced from these methods that some of the most important parameters for calculating runoff at the watershed scale are soil characteristics, slope, and vegetation.

Another important parameter that must be considered when generalizing about runon disconnection and runoff reduction at the parcel scale is the size of the contributing area drained by the downspout, and the distance of lawn between the downspout and the lake shore. Combining roof area and flow path distance with other parameters that are influential at the parcel level provides a general standard by which shoreland property owners can assess whether the possibility of connection justifies management practices beyond relying on a lawn to intercept runon. Further, an analytical method of predicting runon may be an important tool for managers, who are more likely to extend their focus beyond the individual parcel to the entire developed shoreline.

Objectives

The objective of the research was to understand when a connection will occur between shoreland downspouts and a lake during precipitation events, and to describe the interactions, both qualitatively and analytically. The project was comprised of three segments: a field study, a model calibration, and a model application. The objectives of the three segments were:

1. Field study: determine how soil, vegetation, and topography influence runon movement and infiltration, and to obtain a data set by which to calibrate the Vegetative Filter Strip Model (VFSMOD)

2. Model calibration: determine whether a model that uses Manning's Equation (for overland flow) and the Green Ampt Equation (for infiltration) is an appropriate tool for describing runon/runoff interactions on residential shorelands

3. Model application: use a model to predict the annual runoff volume for runon from the near-shore area

Site Description

Studies were conducted on the shorelands of Shawano Lake, located in Shawano County in east central Wisconsin (Figure 1). The experimental lawns were distributed along the 19-mile perimeter of Shawano Lake (Figure 2). Outlined below are general physical descriptions of the soil and surface characteristics of the lawns. Detailed descriptions of individual study sites are available in APPENDIX A.

Slopes

- Range: 2%- 11%
- Median: 6%

Grass Thickness

- Sparse grass with significant bare patches: 22% of sites
- Medium grass with some thin patches and few bare patches: 39% of sites
- Thick grass with no thin or bare patches: 39% of sites

Soil Texture

- Sandy loam (58% of sites)
  - Range, percent sand: 75-85
  - Range, percent clay: 2.5-4.6
- Loamy sand (42% of sites)
  - Range, percent sand: 41-70
  - Range, percent clay: 1.2-5.0

Soil bulk density

- Sandy loam range: 1.01 g/cm^3-1.71 g/cm^3 sites

- Loamy sand range: 1.27 g/cm^3-1.33 g/cm^3

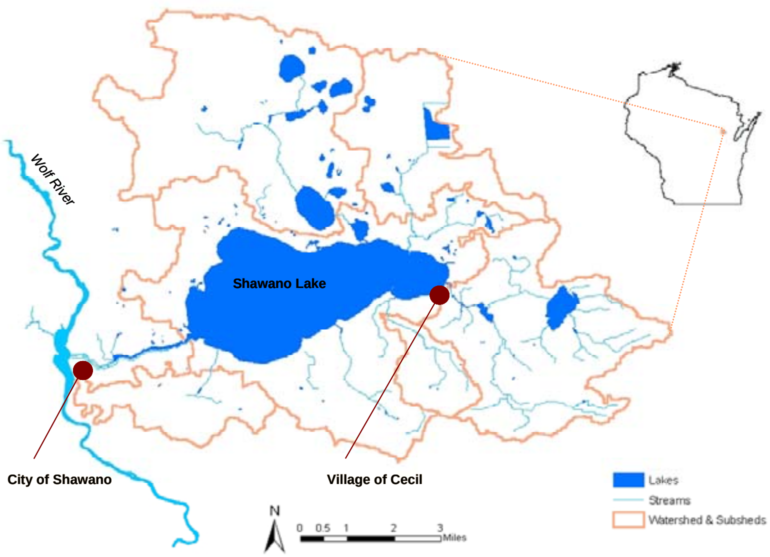


Figure 1. Location of Shawano Lake and watershed

Figure 2. Location of study sites

LITERATURE REVIEW

Management actions to reduce phosphorus loading from shoreland residential developments are effective to the extent that shoreland hydrology is understood and incorporated. The relationship between development and increased runoff has been extensively documented (Carpenter, S. *et al.*, 1998); however, the hydrologic interactions between impervious and pervious areas are relatively unstudied. Residential impervious surfaces (roofs, paved surfaces) generate high quantities of storm runoff; shoreline topography dictates that some portion of the runoff is channeled from the impervious surfaces across lawns, where it has substantial opportunity to encounter phosphorus, and directly into the lake. The rapid development of Wisconsin's shorelands requires an increased understanding of the degree to which shoreland residential lots facilitate runoff rather than infiltration. Knowledge of the hydrologic function of shoreland lawns in the presence of impervious surfaces will permit an evaluation of the effectiveness of current shoreland zoning regulations.

Shoreland Regulations

In the US, the regulation of shoreland management is the responsibility of the states. In Wisconsin, it is the responsibility of the Wisconsin Department of Natural Resources (DNR) to ensure that counties adhere to the state's shoreland protection and navigable waters protection statutes. The statutes are addressed in NR 115, Wisconsin's Shoreland Management Program (Wisconsin Administrative Code). NR 115 establishes minimum requirements for county regulation of shoreland development in unincorporated areas (NR 115 does not apply to incorporated areas). Included are restrictions on minimum lot widths and sizes, minimum building setbacks, and the cutting of trees and shrubs.

The provisions of NR 115 are intended to protect aquatic resources, but deficiencies in the document may limit the effectiveness of the regulations. Zoning regulations in NR 115 for minimum lot sizes and setbacks were developed in the mid-1960's, were based on the limited hydrological studies available, and were influenced by politics. Minimum building setbacks are 75 feet from the ordinary high water mark. Whether these zoning restrictions function in accordance with their purpose of "avoiding water pollution" (Wisconsin Administrative Code) is unknown; however, approximately one third of Wisconsin counties have upgraded shoreland ordinances since 1995 to address the potential inadequacies of NR 115 and incorporate the results of studies since NR 115 was developed (Markham 2007 personal communication).

Turfgrass Emphasis

To date, most research on runoff from pervious surfaces in a developed setting has focused on turfgrass. Turf became an object of intense study in the 1990's in response to increased regulatory actions and the presumption that large areas of highly-maintained turf, specifically golf courses, were important sources of nutrient export. Research has focused largely on practices that minimize phosphorus export, such as timing of fertilization (Linde, D. & Watschke, T., 1997; Shuman, L., 2002), type and amount of fertilizer, and choice of turf (Linde, D. *et al.*, 1995). A recurring theme amongst the turfgrass studies is diminutive runoff and phosphorus export. Dense, established turfgrass has been shown to generate very low runoff volumes and phosphorus concentrations (Watschke, T. & Mumma, R., 1989; Gross, C. M. *et al.*, 1991; King, K. *et al.*, 2001). This information may not be applicable to residential lawns. Most experiments were conducted on artificially constructed turfgrass plots or golf courses, where the soils were undisturbed and the turf was well-managed and thick. In residential areas, lawns may be established on compacted soils that neither promote rainfall infiltration nor easy root penetration (Schueler, T. & Holland, H., 2000). As a result, lawns are typically not as thick as experimental turf plots and may not intercept runoff as effectively. It cannot be assumed that a residential lawn and a turfgrass plot will infiltrate runoff similarly.

Difficulties in Evaluating Residential Runoff

Runoff from residential (and other developed) areas, can be evaluated with hydrologic models. In Wisconsin, the Source Loading and Management Model, or SLAMM, is used to ensure compliance with the states Stormwater Management Program (Wisconsin Administrative Code). A key variable in SLAMM is the percent impervious cover within a source area, as well as a breakdown of the amount of impervious cover that is directly connected to storm sewers. The importance of this variable lies in the increased runoff, sediment, and pollutants associated with increased connectivity (Waschbusch, R. *et al.*, 1999).

The “disconnected” category refers to impervious surfaces that drain to pervious surfaces, such as roofs that drain to lawns. This category raises the fundamental question of the degree to which residential lawns attenuate runon (the water that is shed from adjacent impervious surfaces). SLAMM calculates runoff from disconnected impervious surfaces by simply assigning the runoff coefficient of the surrounding pervious surface (Pitt, R. & Voorhees, J., 2005). This reduces a large flux of water, both from runon and precipitation, to a much lower volume of runoff delivered from the lawn. The runoff coefficients for lawns are specific to direct precipitation observations (Shoemaker, L. *et al.*, 2005). Reducing the impervious runon to a volume dictated by lawn runoff coefficients may not fully describe runoff delivery from a residential lawn. The model, which is not process-driven, is an obvious simplification of interactions between impervious and pervious surfaces. Further, the model assumes any impervious surface draining to a pervious surface is disconnected; the potential for connection when runon is concentrated via downspout and conveyed to an outfall via grassed drainage swales is not considered. Because actual lawn runoff is poorly understood, Legg *et al.* (1996) advise developing a basin-scale lawn runoff database to increase the model's predictive accuracy.

At the field scale, widely-used methods of obtaining runoff estimates also involve calculations with runoff coefficients or curve numbers. Supplemental parameters including slope, vegetation density, hydrologic soil type, antecedent soil moisture, and rainfall intensity and duration can be specified to estimate runoff from various land uses. The transferability of all of these parameters to residential lawns is questionable due to interactions which typically do not occur in the non-urban setting (Pitt, R., 1999) and are poorly understood.

Soils in developed areas have an important influence on runoff delivery, or conversely, infiltration (Hamilton, G. & Waddington, D., 1999). Such soils are highly subject to compaction. Throughout the development process, grading, excavation, and construction equipment and vehicles all contribute to compaction of exposed subsoil (Schueler, T. & Holland, H., 2000). On lawns, foot traffic continues to compact the soils long after the development stage (Kelling, K. & Peterson, A., 1975). Bulk densities of soils from residential lawns range from 1.5-1.9 g/cm^3. These values are consistently higher than undisturbed soils, and approach the bulk density of concrete at 2.2 g/cm^3 (Schueler, T. & Holland, H., 2000)). Implications of high bulk densities are observed in infiltration rates. Infiltration tests from Oconomowoc, WI revealed that nearly 1/3 of the observed infiltration rates remained at 0 in/hr after two hours of testing (Pitt, R., 1999). These rates occurred in areas of heavy foot traffic, such as playgrounds, public open spaces, and athletic fields. It must be stressed that lawn infiltration rates can range widely, as demonstrated by Pitt (1999), Hamilton and Wadding (1999) and Kelling and Peterson (1975). Legg *et al.* (1996) observed high runoff variability within and between lawns. Such variability suggests that the range of runoff coefficients or curve numbers for residential landuse may not accurately represent runoff from pervious surfaces in developed regions.

The runoff from residential lawns is further complicated by runon from adjacent impervious surfaces. Rooftops, driveways, roads, or sidewalks that drain directly to lawns contribute a potentially large flux of water in addition to the direct rainfall volume (USEPA, 2005). A focused examination of runon/runoff from shoreline lawns may reveal that runoff delivery is much greater than currently assumed. In the case of shoreland developments, lawns tend to extend to and slope toward the water's edge (Garn, H. S., 2002). The proximity of shoreland lots to the lake may also correlate with a shallow water table, which further inhibits infiltration. Little is known about how runoff from residential lawns is affected by the interactions of environmental and climatic variables, compacted soils, and impervious runon. The dearth of information on pervious runoff in zones of development has generated a call for "urgently needed" research on this topic (Schueler, T. & Holland, H., 2000). Modeling urban storm runoff using currently available data may misrepresent a more relevant topic: the export of phosphorus within the runoff.

Runoff and Phosphorus Export

Developed areas, categorized as urban landuse, are associated with the greatest runoff volumes of all land use categories (Table 7.9 in McCuen 2004). One of the implications of high runoff volume is that phosphorus that has accumulated on the ground is easily transported by runoff to a receiving water body. Several studies suggest that lawns may be of paramount importance in phosphorus export from developed areas. In addition to phosphorus that is stored in the soil and within the grass itself, residential lawns receive inputs from fertilizers, grass clippings, atmospheric deposition, animal wastes, and runon from impervious surfaces where phosphorus has accumulated (Schueler, T. & Holland, H., 2000). These combined inputs may render shoreland lawns a “direct source of [nutrient] loading” during runoff events (Garn, H. S., 2002).

In an effort to better understand the cumulative contribution of shoreland lawns to a lake’s nutrient budget, Garn collected storm runoff from lawns with various fertilizing regimes along Wisconsin’s Lauderdale Lakes. Results showed that phosphorus concentration in runoff was directly related to that of soils and fertilizing regimes. The study provided no information on the effects of impervious/pervious interactions on runoff and phosphorus transport; sites were chosen to specifically avoid runon, and runoff volume was not measured.

Legg *et al.* (1995) studied runoff from residential lawns in Madison, Wisconsin. A rainfall simulator was used to explore the rainfall/runoff relationship. The study indicated a high degree of runoff variability within single lawns and between different lawns, but offered little clarity in the ambiguous subject of residential lawn runoff.

Steuer *et al* (1997) collected runoff from a number of developed source areas in Marquette, MI, for pollutant analysis. Although low in most parameters, residential lawns had the highest total phosphorus concentrations and yielded the greatest individual phosphorus load when modeled with SLAMM. It should be noted that the lowest runoff volumes of all source areas were observed on lawns (the only pervious surface), yet they produced the greatest phosphorus load. In a similar study, Waschbusch *et al* (1999) examined phosphorus export in two developed basins in Madison, WI. Again, lawns were the greatest contributor of total and dissolved phosphorus.

These results are consistent with an earlier study, wherein Dennis (1986) described the role of residential areas in phosphorus loading relative to baseline conditions in two lake watersheds in Maine. Although the residential watershed consisted of very low density housing (one acre lots), few roads, and an equal amount of wooded and lawn area, phosphorus exported from the residential watershed ranged from 5-10 times that of the forested watershed. These results highlighted the potential for residential land use, even at very low densities, to contribute substantially to a lake's nutrient budget.

Runoff Disconnection

In an attempt to reduce runoff and pollutant transport to receiving waters, many states and municipalities encourage the integration of best management practices (BMPs) and low impact development (LID). Some municipalities offer stormwater credits to developers and property owners to encourage maximum disconnection, or runoff reduction, between impervious surfaces and receiving waters. Credits permit developers to reduce the required size of stormwater conveyance and treatment systems (Center for Watershed Protection, 2000) and reduce stormwater user fees for property owners (USEPA, 2007).

In residential areas a common BMP for which credits are allotted is disconnected impervious cover. The effectiveness of disconnection is debatable because nominal research exists on runoff delivery from residential lawns over a variety of storm conditions and percent impervious cover (Chapter 3 in McCuen 2004). The lack of research is reflected in the credit allotment specifications. Credits are awarded when impervious surfaces are "adequately disconnected" from the drainage system (Center for Watershed Protection, 2002). In management plans prepared by the Center for Watershed Protection, adequate disconnections are defined as those which "effectively spread runoff over an acceptable area." Such plans establish minimum standards of disconnection, including the allowable length of impervious surface, the total area of impervious surface, the length of disconnection, the total lot size, and the slope of the pervious area (Center for Watershed Protection, 2002; 2005). Other localities prioritize differently, as evident in the New Jersey stormwater management plan; emphasis is placed on the requirement that runoff originates and remains as sheet flow (Blick, S. A. *et al.*, 2004). The same concept is clear in both examples: runoff must be spread over a pervious area. Based strictly on these definitions, runoff from large impervious areas that is concentrated in a downspout and discharged to a grassed drainage swale is not disconnected from the outfall (or waterbody).

Summary

The need to describe disconnection of impervious surfaces is evident in modeling runoff and nutrient loading. Urban models intended for application at the catchment scale frequently require data that must be extracted from detailed maps (Burton, G. A. & Pitt, R. E., 2002). While percent disconnected impervious cover can be estimated with storm sewer maps, this parameter is not easily discerned in residential areas where some of the impervious cover can be expected to drain to lawns. In the case of shoreland development, it may appear that no connection exists because these areas typically do not have drainage systems (topography routes excess water to the lake). Assuming no connection implies that all impervious runon is infiltrated by the pervious area. Lawns, however, can only act as a disconnection to the extent that they can infiltrate precipitation and runon. When the flux of water exceeds a lawn's infiltration capacity or raises a shallow water table to surface elevation, runoff will occur. On shoreland lots, a lawn that generates runoff functions as a direct connection to the lake. Under these conditions, the lawn essentially becomes the storm sewer. To date, there is little understanding of *how* connected shoreline residential development is to the lake. Preliminary data by USGS suggest that impervious surfaces lacking an appropriate setback are connected to the lake by means of generating more runon than a lawn can infiltrate over its distance

(Graczyk, D. & Greb, S., 2006; Hunt, R. *et al.*, 2006). More research is needed to quantify the appropriate setback distance for varying degrees of impervious cover and rainfall intensity and duration on shoreland lots.

METHODS

Approach

Experiments were performed during the summer of 2007 to simulate runon and runoff on lakeshore lawns. The results were used to evaluate the importance of site-specific conditions on runon movement and to measure steady-state infiltration rate (I_{ss}). The overland flow infiltration measurements were then used to calibrate the Vegetative Filter Strip Model (VFSMOD). The model was used to describe the annual frequency with which runon connects to the lake as runoff, as well as the volume of runoff delivered to the lake.

Site Selection

Request letters to use lawns were sent to 80 property owners along Shawano Lake in the spring of 2007, and 10 lawns were chosen from the respondents based on an initial visual assessment for slopes greater than 2%. Three experimental transects were located in each lawn in areas with homogenous slopes. A microtopography survey was conducted along the transect at 0.30 m (1 ft) intervals with a laser level to determine where slope varied the least over a 2.44 m (8 ft) distance. The transect surveys were repeated at different locations on a single lawn until three appropriate transects were found.

Runoff Experiments

Runon/runoff simulations were performed in grassy-bottomed channels constructed on the surveyed experimental transects. Channels were 20.32 cm wide (8 in), and consisted of two parallel sidewalls perpendicular to the lawn gradient, an up-gradient water source, and a down-gradient capture plate and pump system where water was collected (Figure 3).

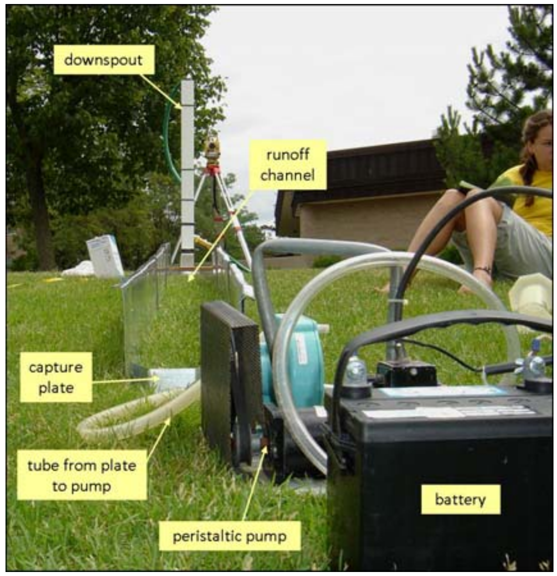


Figure 3. Assembled runoff plot and components

Equipment Specs

Channel sidewalls consisted of parallel, galvanized 18-gauge steel strips driven into the soil. Sidewalls were 2.44 m (8 ft) long by 20.32 cm (8 in) wide. Strip dimensions were 1.22 m (4 ft) long by 20.32 cm (8 in) wide. The strips were originally 2.44 meters long but were cut in half to aid transportation and channel construction. Two steel spikes were spot-welded at 0.30 m (1 ft) and .91 m (3 ft). Two strips laid end-to-end formed a complete channel sidewall. Strips were driven into the soil at depths of five to 10 cm, and the soil abutting the strips was tamped down with end of a hammer handle to ensure good connection between soil and steel.

A steel capture plate was placed at the bottom of the channel to capture runoff. The plate spanned the width of the channel, and had an edge that was bent downward at 90° which could be driven into the soil to prevent water from flowing under the plate. The soil was also tamped down at the interface where the plate edge was driven into the ground. To ensure that all runoff was captured, pieces of latex tubing were lodged at the junctions of the sidewalls and the plate. A brass barb fitting was soldered into a hole at the terminal end of the capture plate. A length a latex tube attached to the brass fitting connected the capture plate to a peristaltic pump (10 L/min capacity) which was powered by a 12-volt battery. The pump discharged water through a latex tube into graduated collection vessels (Figure 4).

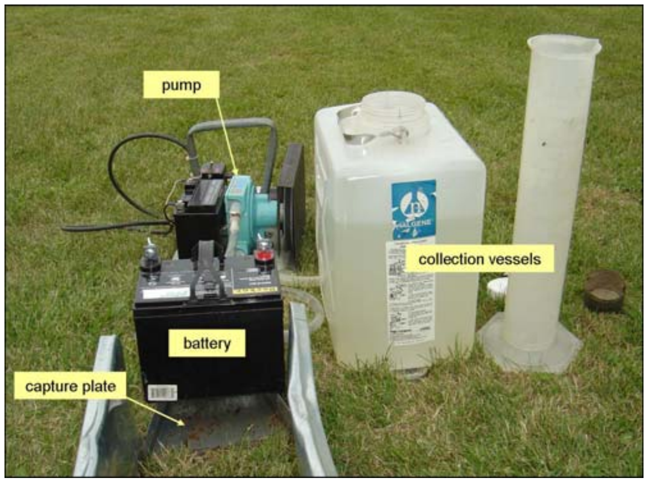


Figure 4. Collection apparatus for runoff channel

A mock downspout was positioned at the top of the channel. The downspout was mounted on a tripod base to ensure a level discharge point. An in-line flow meter was connected to the back of the downspout, with a length of garden hose that extended from the top of the flow meter to the top of the downspout. Discharge rate was controlled with a gate valve affixed to the bottom of the flow meter, which could be connected to any standard garden hose (Figure 5).

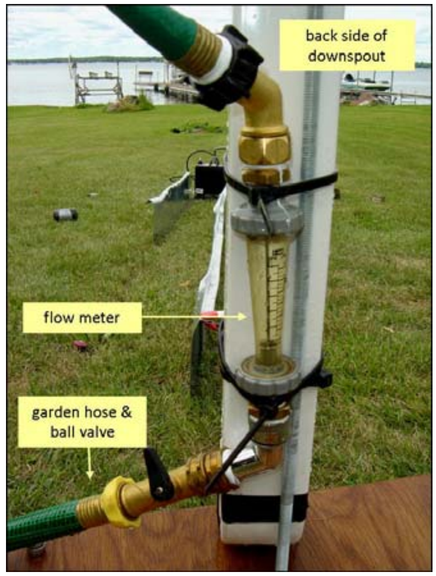


Figure 5. Water source and flow regulation components

Treatments

Three discharge rates (3 L/min, 5 L/min, and 7 L/min) were applied to each runoff site. These treatments can represent downspout discharge rates from many possible combinations of roof areas and storm intensities. For a storm intensity of 2.8 cm/hr (1.1 in/hr), which is the constant-intensity 1-year, 1-hour design storm for east central Wisconsin, the three discharge rates represent outflow from downspouts draining roofs with areas of 6.4 m^2, 10.7 m^2, and 15.0 m^2 (69 ft^2, 116 ft^2, and 162 ft^2). VDF curves, available in APPENDIX B, were derived from Hershfield's rainfall frequency map's (1961).

The experiment was conducted over the course of three five-day periods. Lawns were visited once per period. By the end of the study each site within lawns was administered every discharge rate one time, such that the three treatments were replicated three times per lawn.

Two responses to the treatments were measured: runoff velocity and runoff discharge. The leading edge of runoff was timed at 0.30 m (1.0 ft) intervals down the channel to provide a measure of runoff velocity. When runoff reached the capture plate at the end of the channel, the peristaltic pump was engaged. The first 2 L of runoff were collected in a 2000 mL graduated cylinder, and timed in 200-mL increments. The remaining runoff was collected in a 12 L carboy and timed in 1000 mL increments. Two collection vessels were used to obtain the desired data quality (provided by the fine scale of the graduated cylinder), and quantity (provided by large volume of the carboy). The trial was run until steady-state conditions were achieved. Similar to the runoff collection of Legg *et al.* (1996), three to four consistent runoff discharge rates were measured before the water was turned off. A minimum of 10 L were collected during each trial when steady-state conditions were reached in the early stages of a trial.

It was assumed prior to the study that some lawns could have rocky soils which would hamper equipment installation. Therefore, the first week of the field study was used to screen the lawns. A study was conducted on each site of every lawn, and those lawns (or individual sites within lawns) were eliminated from further study where equipment installation was consistently difficult, resulting in loss of runoff through leaking underneath the channel walls. The elimination of several lawns provided additional time for focused efforts on conducting runoff and infiltration studies on the remaining lawns. Three lawns were completely eliminated after the first week, and several sites on two additional lawns were eliminated because one or more treatments were not successfully administered. The lawns selected for runoff reduction analysis were Lawns 2, 3, 4, 5, 7 (one site), 8 (one site) and 9. A total of 53 trials were used for analysis.

Measured Effects

Data were collected on surface and soil characteristics that could influence the volume and velocity of runoff. Surface data included channel slope, grass height, and a qualitative measure of grass thickness. Grass thickness was described on an integer scale of 1-3, where 1=sparse cover with significant bare patches, 2=medium cover with some thin patches and few bare patches, and 3=thick grass with no thin or bare patches.

Soil data included volumetric water content (θ) immediately before each trial, bulk density, texture, and I_{ss} rates. θ was measured using the direct method, where a soil sample was weighed, dried at 105°C for 24 hr, then re-weighed. The same samples were also used for bulk density calculations and particle size analysis using the hydrometer method (Black, C. A., 1965).

Infiltration and Hydraulic Conductivity

I_{ss} was measured with a double-ring infiltrometer and Mariotte tubes, according to the methods described by the American Society of Testing and Materials standard D3385-94 (American Society for Testing and Materials, 2002). A single infiltration test was performed on each lawn. An area with no gradient was required for the test. Such areas often had different soil properties than the sloped sites where the runoff experiments were conducted, so the transferability of the I_{ss} rates to the runoff sites was questionable. A more accurate representation of I_{ss} was achieved by calculating the difference between inflow rates from the downspout and final outflow rates from the buffer strip (Abu-Zreig, M. *et al.*, 2001).

I_{ss} rates observed for all methods were assumed to represent K_{sat} rates in order to solve the Green Ampt equation. This was necessary for comparing infiltration capacity curves for the different methods used to measure infiltration. Comparisons using direct field measurements were difficult because infiltration measurements were performed using objective time scales that varied between treatments, and infiltration rates fluctuated. Infiltration capacity curves created with the Green Ampt equation standardized the time scales and smoothed fluctuations between subsequent measures.

Vegetative Filter Strip Model (VFSMOD)

Field data were used to calibrate the Vegetative Filter Strip Model (VFSMOD) with the intention of applying the model at a shoreland-scale. VFSMOD was designed to model runoff and sediment trapping in a filter strip from an up-slope disturbed source area. The program has two separate sections: the first generates runoff from the source area (i.e. the unit hydrograph, or UH, portion of the program) and the second simulates runoff and sediment movement in a vegetated filter strip (i.e., the vegetated filter strip or VFS portion of the program). Both portions utilize a graphic user interface where inputs are specified. The UH is generated by user inputs that include storm hyetograph, source area curve number, and source area dimensions. Sediment load in the runoff is generated by user-specified soil characteristics of the source area. The UH can then be used as in input into the filter strip. The volume of outflow from the filter strip is calculated by combining Manning's overland flow equation with infiltration using the Green-Ampt method (Munoz-Carpena, R., 1997). Inputs in the filter strip portion of VFSMOD include filter strip dimensions, soil properties, vegetation properties, storm hyetograph, and the UH from the source area.

For application to this research, only the filter strip portion of the program was needed. The program allows the user to create an incoming hydrograph by specifying discharge rates at arbitrary time intervals, rather than using the hydrograph generated by the UH portion of the program. A user-created hydrograph was used during model calibration in order to represent the constant discharge rate from the downspout.

Modification of Model Inputs

Each valid experimental trial was simulated in VFSMOD as a separate project. Only the filter strip portion of the program was used during this stage. The project window for the filter strip allows the user to specify the inputs listed above. The following is a step-by-step outline describing how a project was created and how the model was calibrated.

First, a buffer strip file was created using specified dimensions, which included the length, width, and slope the strip. The dimensions of the runoff plots were specified, where length was typically 2.44 m (8 ft) and width was 20.32 cm (8 in). The buffer characteristics of slope and Manning's *n* were provided in 0.30 m (1 ft) increments (the scale at which slope was measured in the field).

A soil properties file was created which included the K_{sat} rate (cm/hr), suction at the wetting front (m), and initial and saturated water content. All values except suction at the wetting front had been measured in the field; suction was chosen from recommended values based on soil textural class listed in the appendices of the VFSMOD user manual (Munoz-Carpena, R. & Parsons, J. E., 2005). Two soils files were created for each site using two measures of K_{sat}. The first used the recommended K_{sat} rate based on soil textural class, and the second used the observed I_{ss} rate calculated as the difference between inflow and outflow in the runoff channels. I_{ss} rates were assumed to accurately represent K_{sat}.

Buffer strip vegetation file was created with properties including grass height, stem spacing, Manning's *n* for surface roughness, and a modified roughness coefficient specific to vegetation type. Grass height was measured in the field. Stem spacing and roughness coefficients were chosen based on vegetation type (Munoz-Carpena, R. & Parsons, J. E., 2005). The roughness coefficients for sod range from 0.39 to 0.63. The average value, 0.45, is recommended. The three qualitative descriptions of grass thickness observed in the field were associated with roughness coefficients of 0.39 (sparse grass), 0.45 (medium grass), and 0.63 (thick grass).

All values for incoming sediment characteristics were set to “0” to disable this function of the program because the focus of the field study was purely hydrologic. The same file was used for all projects.

A storm hyetograph file was created where all time steps were associated with a rain depth of “0”. By doing so, the model reflected the field experiment, where no rain fell on the runoff plot.

The final file created in a project was the source area input file which described the incoming hydrograph. Typically, the output from the UH section of the program would be used at this step. For calibration purposes, an incoming hydrograph with a steady flow rate was created to mimic the discharge rate from the downspout. For the three discharge rates of 3 L/min, 5 L/min, and 7 L/min, the respective hydrograph flow rates were 0.00005 m^3/s, 0.00008 m^3/s, and 0.0001 m^3/s. A separate file was created for each trial to reflect the differences in trial durations.

Once a project was created, the filter strip model was run and the cumulative outflow volume was compared to the outflow volume collected in the field study. Calibration was achieved by adjusting the infiltration rate (or, in VFSMOD terms, K_{sat}) to produce the outflow observed in the field. Infiltration was adjusted, rather than any of the recommended values, because it is the only variable that has a strong effect on outflow (Abu-Zreig, M. *et al.*, 2001; Munoz-Carpena, R. & Parsons, J. E., 2005). The adjustment was made using VFSMOD’s sensitivity analysis feature, in which the model runs a range of infiltration rates at intervals specified by the user. The I_{ss} rate that produced the same cumulative outflow volume that was observed in the field was selected for each project.

Assessing Model Predictive Ability

The observed times when runoff connected with the end of the channel and the observed runoff delivery ratios were the standards by which model outputs were assessed. The field observations of total runoff volume and time of connection with the end of the channel were compared to outputs from three model runs (recommended, observed, and calibrated infiltration rates). The predictive ability was examined to determine:

1. if the model could be calibrated (i.e. whether VFSMOD was appropriate for a residential setting);
2. if a K_{sat} range could be found that approximated the soils on Shawano Lake shoreland parcels

Ultimately, the assessment of model predictive ability provided the necessary information to achieve the final objective of the study, which was to apply VFSMOD to the entire shoreland. The preceding analysis (Runoff Experiments) indicated which site properties were the most influential regarding runoff; this section of the analysis explored the values to be assigned to the influential variables that characterized Shawano shoreland parcels.

Annual Runoff Estimates

Data Reduction

VFSMOD is an event-based tool intended to model runoff and sediment delivery from a single source area cross a single filter strip. On the Shawano shoreland parcels, there are approximately 1400 structures at variable distances from the shoreland. This translates to a wide range of source area dimensions (rooftops) and filter strip lengths (flow path distance to lake). Legg *et al.* (1996) pointed out that, rather than attempting to gather data from individual lawns to predict runoff, a more realistic approach could be achieved through "a basin-scale analysis of runoff from pervious landscapes." In the case of the Shawano Lake watershed, the basin was approximated as the shoreland regions that drained directly to the lake. The initial step was to summarize the shoreland dataset to reduce it to manageable size. A GIS point-in-polygon analysis was performed (ArcMap 9.2) in which buffers were created around the lake up to a distance of 65 m, in 5 m intervals. The density of structures was very low beyond 65 m. From these buffer intervals, the average roof size was extracted and the shoreland setback was assigned as the upper limit of the corresponding interval (e.g. 10 m in the 5-10 m buffer interval).

Expanding the Utility of VFSMOD

Although the data were substantially reduced, it was still impractical to model more than a single precipitation event. To overcome the limits imposed by a single event-based model, a linear regression model was created from VFSMOD outputs (specifically runoff volume and flowpath distance) using only a few roof sizes and storm sizes. The linear model made it possible to efficiently predict the volume of runoff over a much wider range of roof sizes, K_{sat} rates, shoreland setbacks, and storm sizes. Twelve VFSMOD projects were created using source area files with combinations of three roof sizes and four soil infiltration rates. Source area files had roof sizes were 46.45 m^2, 92.90 m^2, and 185.81 m^2 (500 ft^2, 1000 ft^2, and 2000 ft^2). The four soils files used infiltration rates that characterized the soils of Shawano shorelands, as determined by the preceding analysis (Assessing Model Predictive Ability). An initial soil moisture content of 0.20 (approximately 50% of pore space filled with water) was assumed for all soils files. This assumption eliminated the need to estimate a θ value when the model was applied, which was particularly helpful when predicting runoff from multiple events. All remaining files required by the model--buffer strip physical properties, vegetation, sediment, and hyetograph and incoming hydrograph (both generated by the UH feature)--were identical for the nine projects. To represent sheet flow in a grassed drainage swale between the downspout and the lake, the buffer strips were constrained to a width of 5 ft. This width was a conservative estimate based on the research of Abu-Zreig *et al.* (2001), where flow through a vegetative filter was distributed across the entire width of the 4-foot channel in 25% of runoff trials.

Once the twelve projects were created, they were analyzed using the design function of VFSMOD. The design function allows the user to examine runoff and infiltration volumes over a range of storm sizes, durations, and filter lengths (Munoz-Carpena, R. & Parsons, J. E., 2005). Design storms ranging from 10 mm to 60 mm in 10 mm increments, with durations of 2, 6, and 18 hours, were chosen for the design analysis, and the type II rainfall pattern was specified for its regional appropriateness. The resulting output included the distance runoff traveled across the filter (in 5 m increments) and the runoff volume delivered at each distance. These outputs provided the necessary data to create a multiple-regression model in the form of Equation 1.

$$\textit{Runoff Volume} = \beta_1 \times (\textit{roof area}) + \beta_2 \times (K_{sat}) + \beta_3 \times (\textit{storm size}) + \beta_3 \times (\textit{storm duration}) + \beta_4 \times (\textit{setback distance})$$

Equation 1. Framework of regression model derived from VFSMOD output

General Model Application

The first approach examined the application of VFSMOD in a general sense. The objective was to determine the volume of runoff delivered to Shawano Lake from the average shoreland structure and setback. Information from the data reduction process discussed previously was used for average size and setback. The regression was applied using several representative K_{sat}

values to explore how effective the average set back was at reducing runon from the average shoreland structure during 6-hour design storms with depths of 10 mm through 60 mm in 10-mm increments. The 6-hour duration was used to maintain consistency with the duration used to create the regression from VFSMOD output. The range of storm depths were chosen because they represent the range observed in the average year. The regression was used to further explore the setback distance required to *completely* disconnect the average shoreland structure over a range of storms between 40 mm and 85 mm. This range was chosen because it encompassed storms with recurrence intervals between 1 year and 25 years.

This method of calculation assumed that all aspects of a roof drained to the same discharge point. The results were insightful for exploring the influence of reduced K_{sat} on runoff volume, but such routing scenarios are unlikely to exist on peaked roofs. To gain a closer representation of reality, the calculations were performed to imitate a peaked roof with two aspects that drained to two discharge points and flowpaths. Runoff was calculated as before, with the only change being that the average roof area was reduced by half and the resulting runoff was multiplied by two to represent two grassed runoff channels. Ultimately, this method of calculating annual runoff used the same runon volumes as the original, full-roof calculations, but the assumed infiltration area was twice as large.

Annual Model Application

Runoff delivery prediction for the average Shawano structure is useful; however, it is also useful to have a prediction of the annual runoff volume and a description of the most problematic shoreland areas in terms of runoff generation. Such values were achieved using the linear regression models developed in the previous section. The following steps outline the procedure used to predict annual runoff to Shawano Lake from shoreland structures:

1. Runoff volume delivered from the average structure in each buffer interval was predicted with the regression model created from VFSMOD output;
2. The volume was multiplied by number of structures within the corresponding buffer interval;
3. The operation was performed at all intervals (up to 65 m from shore), and summed for total event runoff volume; and
4. The operation was repeated for each precipitation event and summed for annual runoff volume.

As with the general application of VFSMOD, annual runoff volume was calculated a second time assuming two discharge points per roof.

The 1982 precipitation record from Green Bay, WI was used because it represents precipitation events for the average year based “on long-term average conditions that represent the average annual rainfall” (USGS, 2007). Green Bay was chosen for its proximity to Shawano. Additionally, runoff from events during 2005-2007 was calculated to gain a better understanding of recent runoff.

RESULTS & DISCUSSION

Velocity of the Leading Edge of Runoff

Velocity of the leading edge of runoff varied at the different sites and with different runon application rates. These differences and any unusual behaviors in leading edge velocity were further explored to determine the soil and surface characteristics potentially responsible. Exploring trends on individual lawns provided insight on the most important factors that may influence the velocity of runoff at the shoreland scale. The results from each lawn are presented and discussed separately.

Lawn 2

The velocity of runoff on Lawn 2 is shown in Figure 6. On this lawn, the time for runoff to traverse a given distance generally increased as runon application rate decreased. The lower velocity with smaller runon application rates was observed at many sites.

The Lawn 2 sites had very thick grass established on well-structured loamy sand. Site 2C was unique only in that it had less of a gradient (3%) than sites 2A and 2B, both of which had a 6% slope (Figure 7).

The decrease in slope on site 2C may explain why the velocities of the 5 L/min and 7 L/min trials were lower than the velocities of the same treatments at sites 2A and 2B. Such logic suggests that velocity for the 3 L/min treatment at site 2B should be similar to that of 2A because of similar slopes; however the velocity at site 2B for 3 L/min was remarkably lower. This result is difficult to explain. Even the micro-topography perspective in Figure 7 indicates that, for ¾ of the channel length, site 2B was *steeper* than site 2A. Further, the soils at both sites had nearly identical volumetric water content (θ,Table 1) when the 3 L/min trials were performed; however, site 2B did have higher θ values when the 5 L/min and 7 L/min trials were performed. The subtle increases in velocity observed when site 2B was contrasted with 2A are likely a reflection of higher θ.

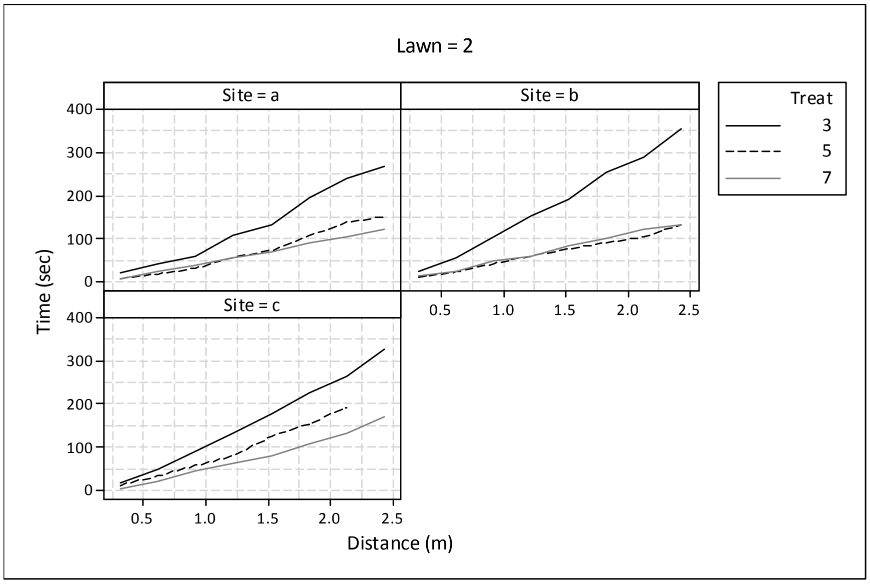


Figure 6. Travel time over flow path on Lawn 2

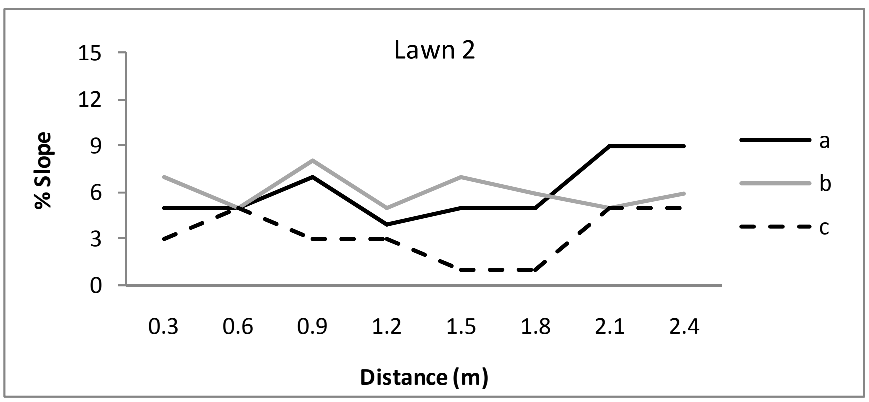


Figure 7. Slope at runoff sites on Lawn 2

Table 1. Soil volumetric water content (θ) at Lawn 2

[redacted]

Lawn 3

Runoff velocity results from Lawn 3 are shown in Figure 8. Similar to most lawns, the highest flow rate had the greatest velocity. Lawn 3 was the most unique lawn in the study, and produced results that were the most difficult to interpret at the 3 L/min and 5 L/min treatments. In this lawn, medium-density grass was maintained at a height of about 1.5 inches and regularly irrigated, surface soils were unusually silty for this area, and a steep grade was established that shed water to a drainage swale. Figure 9 shows that slope usually ranged from 6% to 12% on the Lawn 3 sites. These surface and soil characteristics facilitated rapid conveyance of storm water.

Sites 3A and 3B had unexpected reversals of runoff velocity between the 3 L/min and 5 L/min treatments, where 3 L/min runoff traveled *faster* than 5 L/min along most of the channel length. A possible cause for such a reversal would be a low θ during the 5 L/min trial and a high θ during the 3 L/min, but the opposite was true on 3A. In fact, the soils were saturated at the start of the 5 L/min trial (Table 2). Higher runoff velocities for the 3 L/min trial versus 5 L/min were also observed at site 3B. Again, soils during the 5 L/min run were initially saturated while soils during the 3 L/min trial had lower θ values. The fact that this unexpected trend occurred twice reduces the likelihood of experimental error as an explanation. A more likely explanation is that the saturated conditions correspond with low matric potential (that is, the soil does not hold water very tightly), resulting in hydraulic conductivities that can be “thousands of times greater than at potentials that characterize typical unsaturated flow” (Brady, N. C. & Weil, R. R., 2002). The influence of θ on matric potential becomes more pronounced as clay and silt content increase.

Lawn 3 had higher clay and silt contents than other lawns, which may explain why high θ corresponded with lower runoff velocities on this lawn.

Different results were obtained at site 3C, where runoff velocities varied with flow runon rate as expected. Site 3C probably had a reduced ability to convey runoff as rapidly as sites 3A and 3B. The first meter of the 3C runoff channel had an overall lower gradient than the other sites, especially between the 0.3 m and 0.6 m intervals (Figure 9). Runoff velocity was probably slowed down initially due to a flattening of the gradient, which then influenced the velocity for the remainder of the channel.

Although the effect of θ was difficult to evaluate due to the regular irrigation on Lawn 3, an unintentional replication of the 7 L/min trial at site 3B indicated that θ was more influential than these data suggest (Figure 8). The initial trial had θ=0.48 and an overall runoff velocity of 0.04 m/s, whereas the replicate had θ=0.33 and an overall runoff velocity of 0.03 m/s (that is, it took an additional 13 seconds to connect with the end of the channel when soil moisture content was lower).

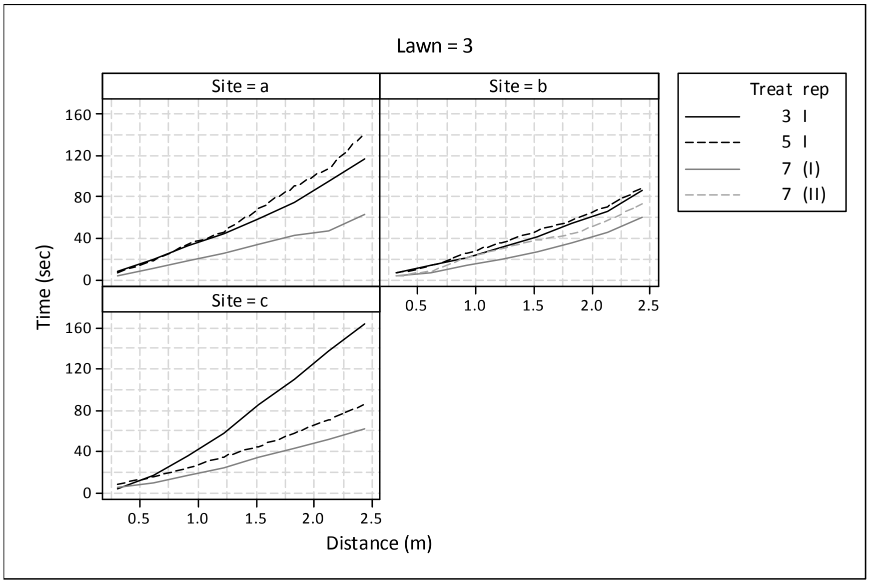


Figure 8. Travel time over flow path on Lawn 3

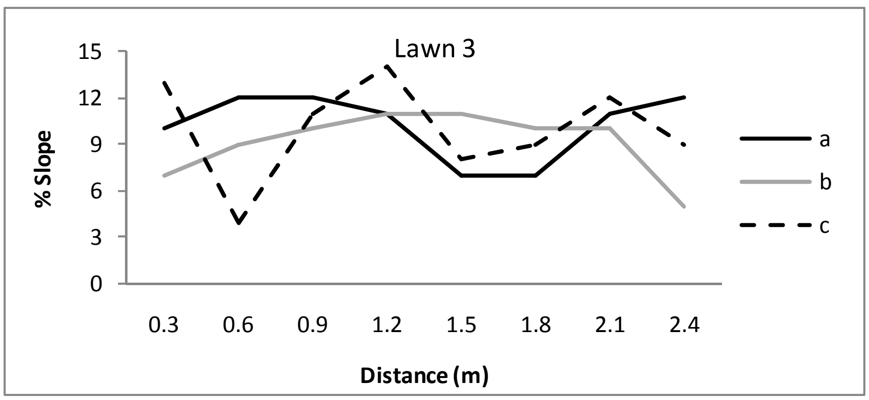


Figure 9. Slope at runoff sites on Lawn 3

Table 2. Soil volumetric water content (θ) at Lawn 3

lawn	Q (l/min)	θ at site:		
		a	b	c
3	3	0.43	0.36	0.52
	5	0.57	0.57	0.47
	7 (I)	0.36	0.48	0.52
	7 (II)		0.33	

Lawn 4

The results from Lawn 4 are shown in Figure 10. The three sites had markedly different runoff velocity patterns, and rarely adhered to the expectation of increasing velocity with increasing flow rates.

Lawn 4 exhibited two drastically different categories of surface and soil characteristics. Site 4A was close to the shoreline and had a sandy to gravelly soil and a gentle slope. Sites 4B and 4C were near the house where silty fill soil had been used, and were located where the lawn was graded to shed water away from the house and toward Shawano Lake. Such soil and grade characteristics were similar to those of Lawn 3, discussed previously. Also similar to Lawn 3, Lawn 4 was a highly manicured lawn with medium density grass that was maintained to resemble a putting-green. It must be noted that the particle-size analysis for this lawn (APPENDIX G) appeared to have been influenced by a laboratory error, as the hydrometer results indicated that sites 4B and 4C were very sandy and site 4A was very silty.

Site 4A immediately stands out in Figure 10 due to the low velocities at the 3 L/min and 5 L/min trials. The non-linear travel time at the 3 L/min trial is particularly interesting. Several interacting factors may have contributed to the reduced velocity (or deceleration) at the end of the channel. As the runoff traveled down the channel, the leading edge experienced high initial infiltration rates, so a certain degree of deceleration was expected. Because 3 L/min was the lowest flow rate, the influence of high initial infiltration rates at the leading edge may have had a more pronounced effect on deceleration relative to the higher flow rates. Additionally, θ at the start of the 3 L/min trial on site 4A was lower than the initial θ for the 5 L/min and 7 L/min trials (Table 3). Finally, the exaggerated deceleration may have been influenced by the slope of

4A. The site had a gentle gradient that averaged only 4%, and flattened out considerably at the end of the channel (Figure 11). The high initial velocity of runon leaving the downspout during the two higher runon applications, as well as the higher θ values (Table 3), may have functioned to suppress the non-linear travel time observed during the 3 L/min application.

The similar velocities and patterns observed at sites 4B and 4C reflected their spatial similarities. The nearly identical velocities between the treatments at site 4B probably resulted from saturated soil conditions. The 5 L/min trial actually had a greater velocity than the 7/min trial, perhaps a result of the *slightly* higher initial θ during the 5 L/min trial (0.54 vs. 0.52). The influence of initial θ is more clearly demonstrated on site 4C. The soils were saturated at the 3 L/min and 5 L/min trials, and both had similar velocity patterns. The 5 L/min trial is unusual because the runoff velocity decreases such that, after 1.75 m, the 5 L/min trial has a lower velocity than the 3 L/min trial. Unlike the other two application rates, the initial θ for 5 L/min was not saturated (0.44 vs. 0.52). While the initial runoff velocity of the 5 L/min trial was greater than the 3 L/min trial, the infiltration rate at the leading edge was, theoretically, higher during the 5 L/min trial due to increased available soil pore space for infiltration.

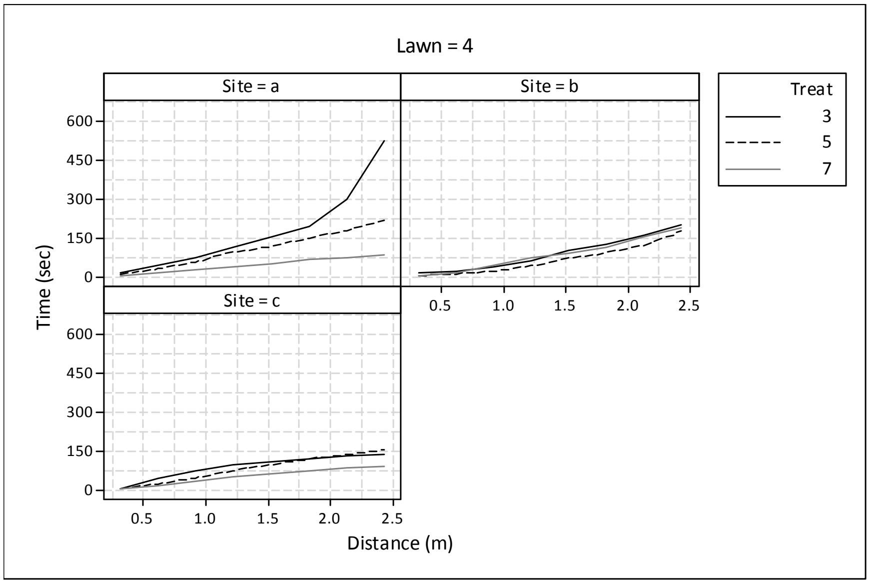


Figure 10. Travel time over flow path on Lawn 4

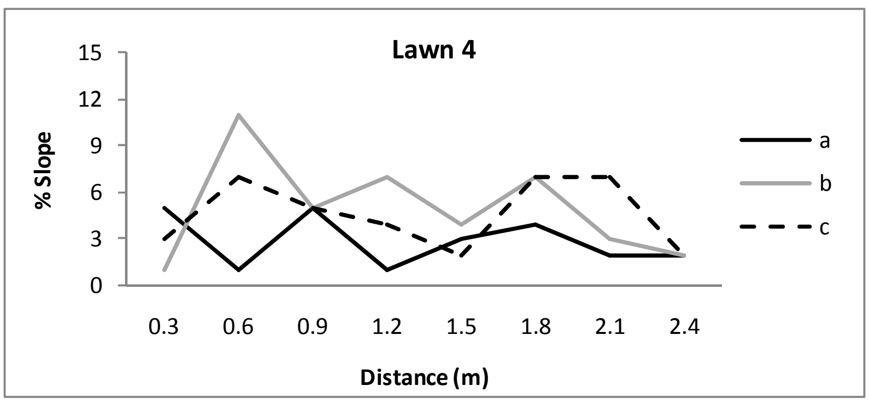


Figure 11. Slope at runoff sites on Lawn 4

Table 3. Soil volumetric water content (θ) at Lawn 4

[redacted]

Lawn 5

The results from Lawn 5 are shown in Figure 12. As with most trials on other lawns, the highest application rate had the greatest velocity, although some variability existed within treatments at the lower velocities.

Lawn 5 had some of the lowest-gradient slopes within the study. A seawall at the edge of the lawn had changed the gradient of the lawn (due to the pressure of ice during the winter), such that it drained back onto the property rather than the lake. The lawn had been re-graded to diverted water into a drainage swale to the lake. New loamy sand fill had been brought in the year before to re-grade to lawn. The sites were established on the gradient that drained to the swale. Although the lawn had been re-seeded only one year prior to the study, a lush turf was established.

Runoff velocities at site 5A for the 5 L/min and 7 L/min treatments were nearly identical (Figure 12). The similar velocities could not be attributed to initial θ, as the same value was observed during both trials (θ =0.43, Table 4). The combination of low gradient and thick grass probably sufficiently reduced the runoff velocity of both application rates so as to render any differences (at least at the two highest rates) negligible. This was not the case at 3 L/min on site 5A. The lowest initial θ of all nine replicates was observed at 5A during the 3 L/min trial. A remarkably lower velocity was not unexpected because the leading edge of the runoff was subject to a greater infiltration capacity as a result of low θ.

The 3 L/min velocity on site 5B, however, displayed a more unexpected trend. At every measured distance in the channel, runoff velocity was higher for the 3 L/min trial than the 5 L/min trial. This could not be explained as a function of initial θ, since the lower θ observed at the 3 L/min trial indicated that the leading edge of the runoff should have experienced a higher infiltration rate. The most likely explanation is unobserved experimental error. On low-gradient sites, runoff was occasionally observed leaking from the top of the channel because the slope was not great enough to route the water down the channel. It is possible that leaking occurred at the top of the 5 L/min trial on site 5B, but was never noticed due to the thick grass. The runoff velocities during the three trials at site 5C progressed as expected.

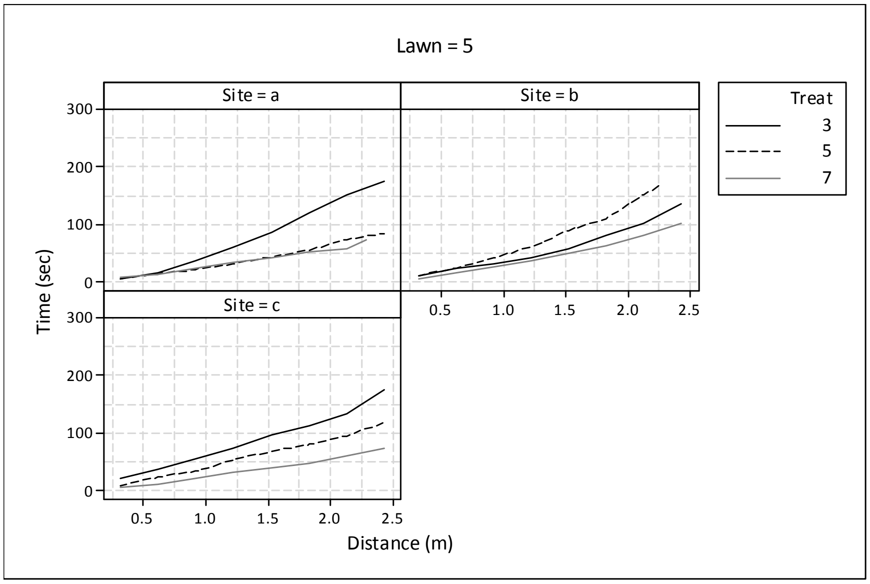


Figure 12. Travel time over flow path on Lawn 5

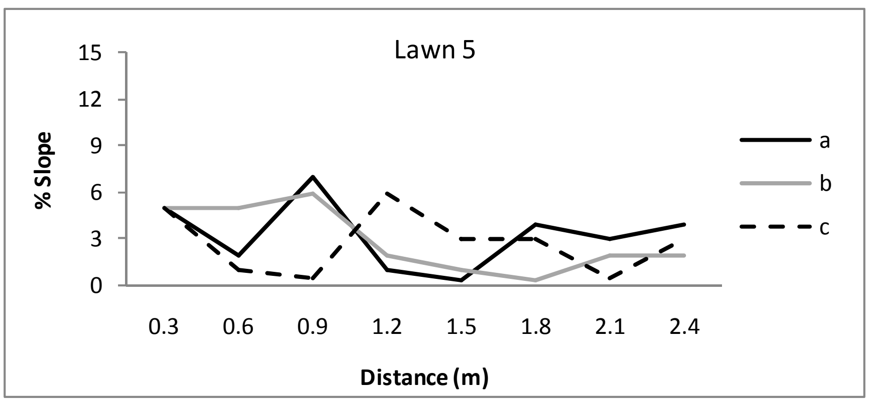


Figure 13. Slope at runoff sites on Lawn 5

Table 4. Soil volumetric water content (θ) at Lawn 5

[redacted]

Lawn 7

The results from Lawn 7 are shown in Figure 14. Runoff trials were successful at a single site on Lawn 7 (7B), because soils on the other sites were rocky prevented installation of channel sidewalls that did not leak. The lowest application rate had the lowest velocity, but velocity was not different for the higher application rates.

Site 7B was located on an exposed southern slope. It had extremely sparse, dry grass established on a sandy loam soil. Because the lawn was so sparse, a surface crust had developed on the bare soil from the impact of raindrops. The majority of the channel had a slope greater than 6% (Figure 15), which, when combined with the soil crust had a clear influence on runoff velocity.

Figure 14 shows nearly identical runoff velocities for the 5 L/min and 7 L/min trials, and a disproportionately lower velocity for the 3 L/min trial. The 5 L/min and 7 L/min trials are interesting because the 7 L/min trial had a slightly lower velocity than the 5 L/min trial. The presence of a surface crust, and a relatively steep gradient facilitated rapid conveyance of runoff in both the 7 L/min and 5 L/min trials. A plausible explanation for the similar velocity at both 5L/min and 7 L/min was that a brief downpour occurred shortly before the 7 L/min trial. The rain may have broken up the soil crust just enough to reduce the velocity of the 7 L/min trial. The trial occurred while the surface was still moist, before the soil crust was restored. This brief downpour did not appreciably change the soil profile moisture and the initial θ, collected immediately after the downpour, was only 0.07 (Table 6).

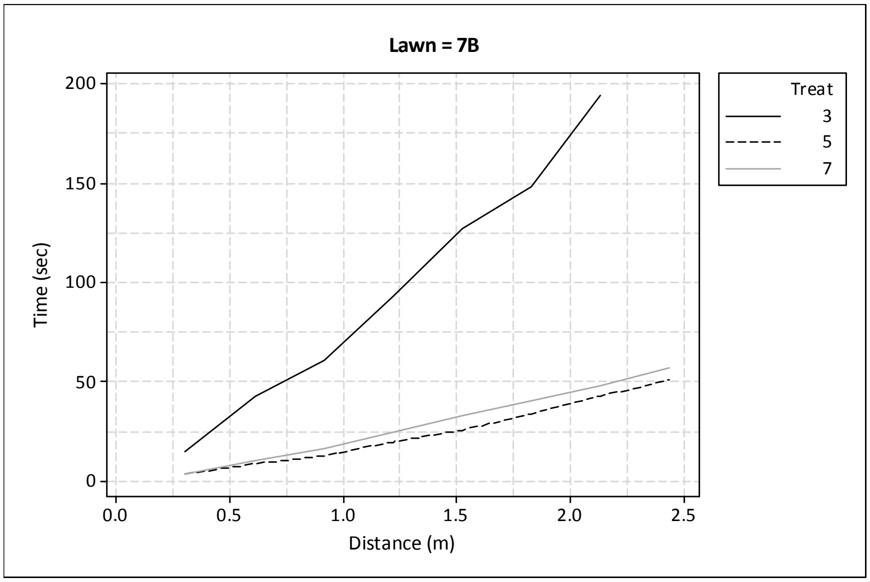


Figure 14. Travel time over flow path on Lawn 7

Figure 15. Slope at runoff sites on Lawn 7

Table 5. Soil volumetric water content (θ) at Lawn 7

[redacted]

Lawn 8

The results from Lawn 8 are shown in Figure 16. Runoff trials were successful at a single site on Lawn 8 (8A). On the unsuccessful sites, the gradient at the top of the channel was too low to route all of the runon down the channel, resulting in a significant amount of runon that ponded at the top of the channel or flowed around the outside of the channel. At site 8A, velocities varied with runon application rate as expected.

Lawn 8 was located on a former wetland that had been filled with sand from the lakebed. As a result, it had a low gradient, which is shown by the slope in Figure 17. The lawn had extremely thick grass, and well-structured sandy loam soils.

Runoff velocities for the 3 L/min and 5 L/min application rates were the lowest observed in the study, and the fourth lowest for 7 L/min trial. Little difference in velocity was observed between the 3 L/min and 5 L/min trials (Figure 16). The potential for error was high on this lawn; replicates on sites 8B and 8C failed because the gentle gradient and thick grass promoted ponding within the channel and leakage through the sidewalls. As with Lawn 5, it is possible that unobserved leaking occurred during the trials with lower flow rates. Further, the relatively high initial θ value for the 5 L/min trial compared to the lower initial θ at 3 L/min would suggest that there should have been a more pronounced difference between the velocities of these trials.

Although the runoff velocity during the 7 L/min trial appeared high compared to the other two trials, it is worth restating that this was one of the lowest 7 L/min velocities, and that it may appear unusually high in Figure 16 when compared to the potentially erroneous low velocities during the 5 L/min trial.

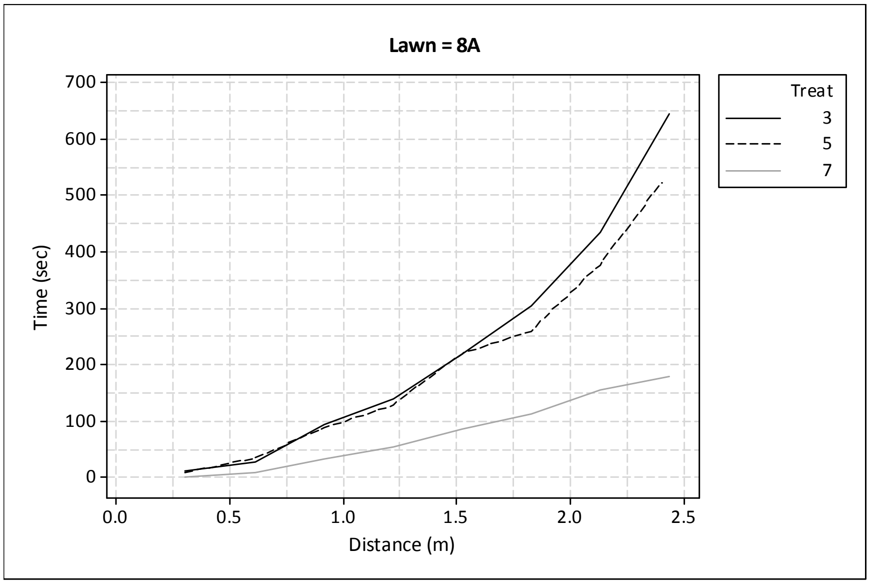


Figure 16. Travel time over flow path on Lawn 8

Figure 17. Slope at runoff sites on Lawn 8

Table 6. Soil volumetric water content (θ) at Lawn 8

[redacted]

Lawn 9

The results from Lawn 9 are shown in Figure 18. A large amount of variability was observed between sites and within treatments, and the velocity response to application rate rarely occurred as expected.

In many ways, Lawn 9 resembled Lawn 7. The lawn sloped steeply and continuously to the shoreline (Figure 19), had extremely sparse, dry grass, and periodically had a surface soil crust. Unlike Lawn 7, Lawn 9 had large ant colonies and, consequently, a matrix of large biopores that promoted rapid infiltration.

Runoff velocities at site 9B deserve comment due to the extremely low velocities at 7 L/min trial, and the very high velocities at the 3 L/min trial (Figure 18). Both velocities were a result of runoff interactions with a soil crust. At 3 L/min, the combination of steep gradient (Figure 19), sparse grass, and soil crust, efficiently routed runoff down the channel. Conditions were similar during the 7 L/min trial; however, the runoff advanced in a stepwise fashion. During the first 1.5 m of the trial, runoff advanced rapidly across the sealed soil surface. Between 1.25 and 1.5 m, the velocity slowed considerably (the leading edge of the runoff traversed this 0.25 m distance in 66 seconds, compared to a travel time of only 40 seconds during the first 1.25 m of the channel). This sudden decrease in velocity was the result of the runoff “breaking though” the up-stream soil crust and rapidly infiltrating into the high-porosity soil. The leading edge encountered a soil crust again between 1.5 m and 1.75 m, resulting in a temporary high runoff velocity, before the crust again disintegrated, promoting very rapid infiltration and greatly reducing runoff velocity. The influence of changes in slope also appeared to interact with the effects of soil crusting/break-up. Both points on the channel where velocity was considerably lower correspond to a reduction in slope (Figure 19). The potential effects of slope were not pronounced during the other trials on site 9B, so it is conceivable that high infiltration rates masked the effects of slope, but when a soil crust significantly reduced infiltration, slope exerted a more obvious influence on runoff velocity.

A surface crust was also present at site 9C during the 5 L/min trial which resulted in the highest runoff velocity observed at site 9C. The influence of the surface crust made it difficult to evaluate how much of an effect initial θ may have had on the velocity of the leading edge of the runoff. Soil moisture was generally low (Table 7), and was unlikely to have had much of an influence on runoff velocity due to the high soil porosity.

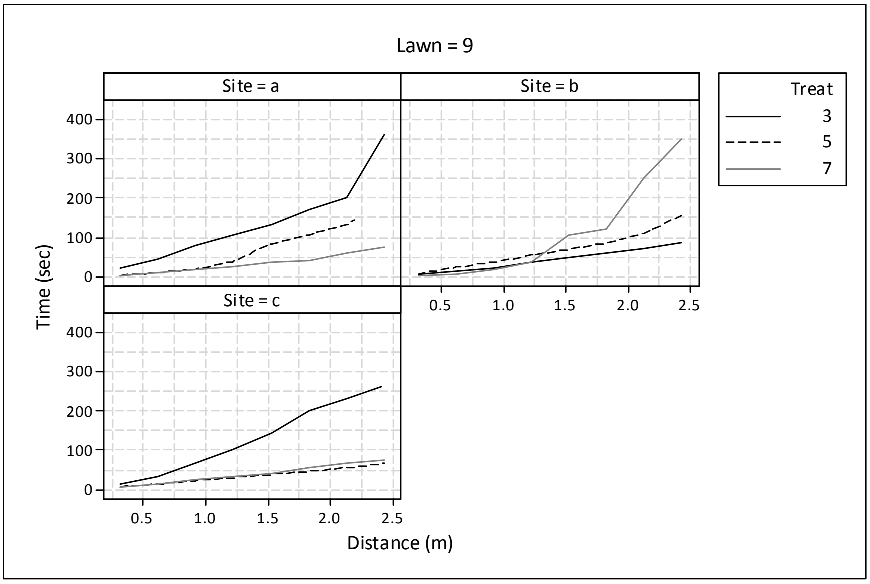


Figure 18. Travel time over flow path on Lawn 9

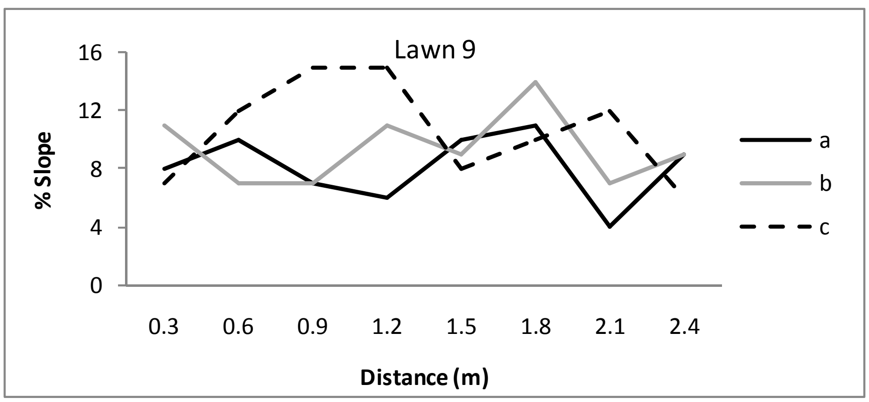


Figure 19. Slope at runoff sites on Lawn 9

Table 7. Soil volumetric water content (θ) at Lawn 9

[redacted]

Summary of Runoff Velocity

Considerable variability in soil characteristics, slopes, and vegetation condition was present on the lawns where experiments were conducted. While it is difficult to completely isolate some of the most influential parameters controlling runoff velocity, there appeared to be a general influence of slope and grass thickness. Figure 20, Figure 21, and Figure 22 indicate that thick grass at low slopes results in the greatest travel time (or lowest velocity), whereas medium and sparse grass typically have lower connection times (or greater velocities). There were only two replicates on sparse grass, so little can be deduced about velocity regarding the interaction with slope.

These figures reveal a large difference in overall travel time when slope is greater than about 8%. To reduce the trial-to-trial variability, overall travel time was plotted against runon rate only for sites with thick or medium grass on slopes less than 8% (Figure 23). Figure 23 shows that, in general, runoff velocity increases with runon application rate on small gradients.

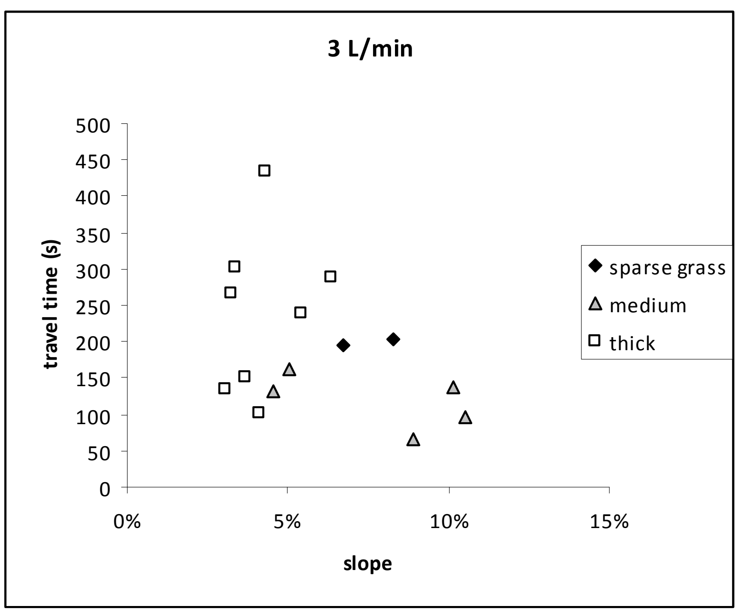


Figure 20. Scatter plot of slope versus travel time at 3 L/min

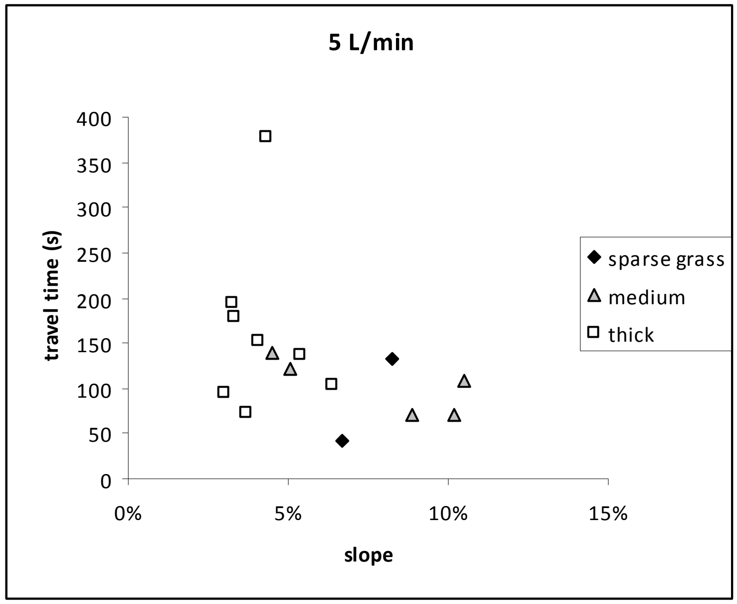


Figure 21. Scatter plot of slope versus travel time at 5 L/min

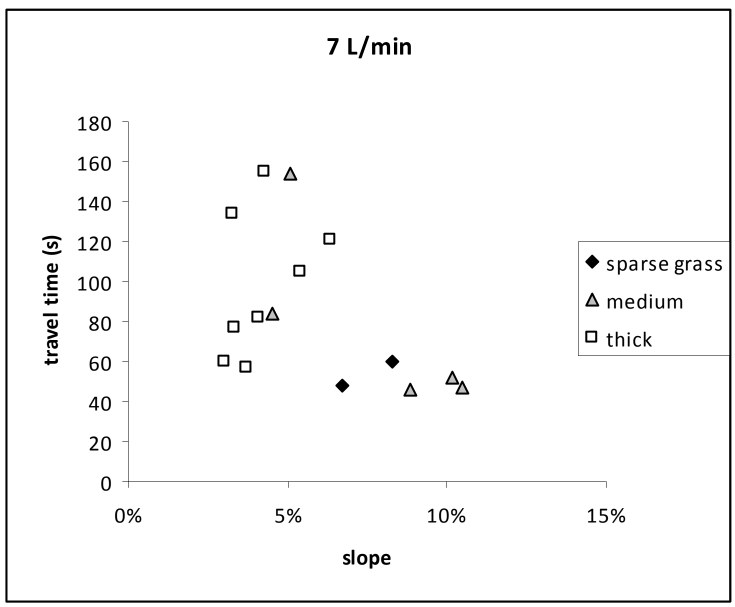


Figure 22. Scatter plot of slope versus travel time at 7 L/min

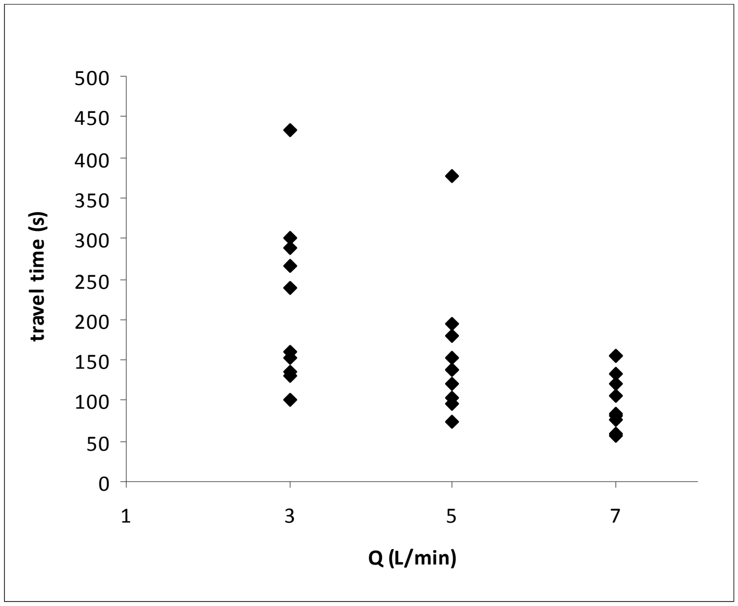


Figure 23. Plot of runon application rate versus travel time for medium and thick grass on slopes less than 8%

Infiltration

Infiltrometer Tests

The measured I_{ss} rates for double-ring infiltrometer tests are displayed in Table 8. Infiltration capacity curves were created for the Infiltrometer tests and are available in APPENDIX C.

Table 8. I_{ss} rates from double-ring infiltrometer

Lawn	Doubl-ring I_{ss} (cm/hr)
2	1.90
3	10.54
4	3.68
5	1.88
7	2.48
8	18.24
9	3.36

Because a single infiltrometer test was performed per lawn (compared to nine runoff tests), auxiliary falling-head tests were performed late in the study on Lawn 2 to gain a better understanding of the variability within a lawn. The tests established that infiltration rates can vary substantially within a lawn (Figure 24). It must be noted that the auxiliary tests were performed with a single cylinder that had a 6-in diameter, whereas the inner ring in the double ring-infiltrometer test had a 12-in diameter. The equipment differences may have contributed to the generally higher infiltration rates during the falling-head tests.

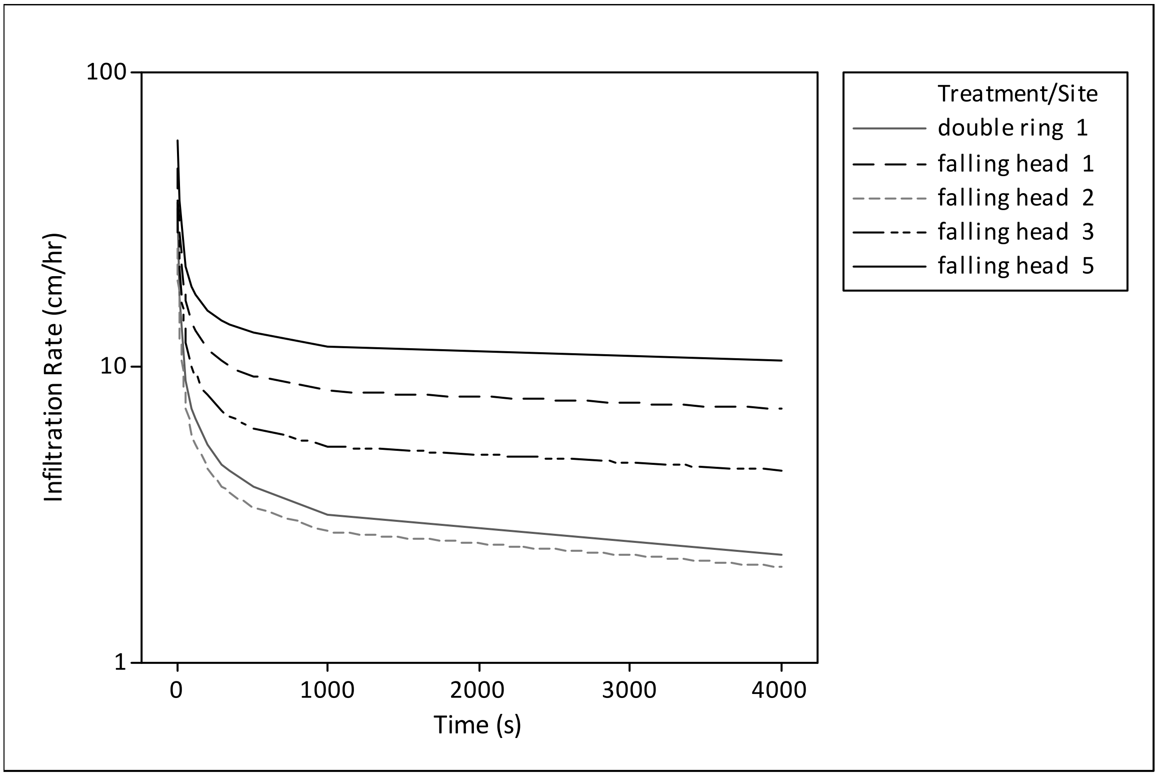


Figure 24. Lawn 2 Infiltration capacity curves created with Green Ampt equation using K_{sat} values obtained from falling- and constant-head infiltrometer tests

VFSMOD Predictive Ability

VFSMOD outputs were explored to evaluate how well the model works in a residential setting. The goal was to determine K_{sat} values that characterized shoreland lawns on Shawano Lake in order to proceed to the final objective of the study, which was to apply the model to actual shoreland. VFSMOD was calibrated to fit the observed cumulative outflow volume by adjusting the K_{sat} parameter. Cumulative outflow using observed apparent K_{sat} rates (inflow rate—outflow rate) were 1.1 times greater, on average, than observed outflow. When the model was run using recommended K_{sat} values from Rawls *et al.* (1983), predicted outflow was an average of 2.2 times greater than observed outflow. No further analysis was performed on recommended K_{sat} rates because they consistently overestimated runoff to a magnitude than the observed K_{sat} rates. Infiltration rates measured from double-ring infiltrometer tests were not modeled because they were even lower than the recommended rates; however, the differences between measured I_{ss} and calibrated K_{sat} rates are explored below.

Measured Apparent K_{sat} and Calibrated K_{sat}

The calibrated K_{sat} rates were compared to the observed apparent K_{sat} rates (inflow rate—outflow rate) to evaluate the degree of calibration required to make runoff predictions. An example from the calibration process, where the model was fitted to cumulative outflow volume, is shown in Figure 25. This figure shows that a relatively good prediction of the connection time was obtained when cumulative runoff volume was used as the standard to which the model is calibrated. When trials with surface crusts were ignored, there was a good correlation between observed and predicted connection times (R^2=0.87, Figure 26). Such a good correlation demonstrates the utility of the model for describing the data: runoff velocity was not the calibration standard, yet it was adequately predicted by VFSMOD.

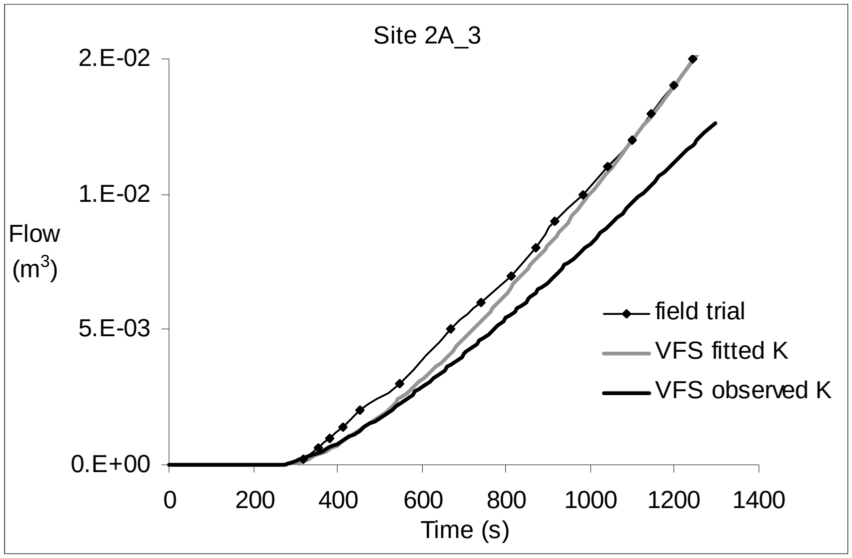


Figure 25. Cumulative runoff volume over time at site 2A, 3 L/min runon application rate from field observations and model predictions using the observed and calibrated infiltration rates

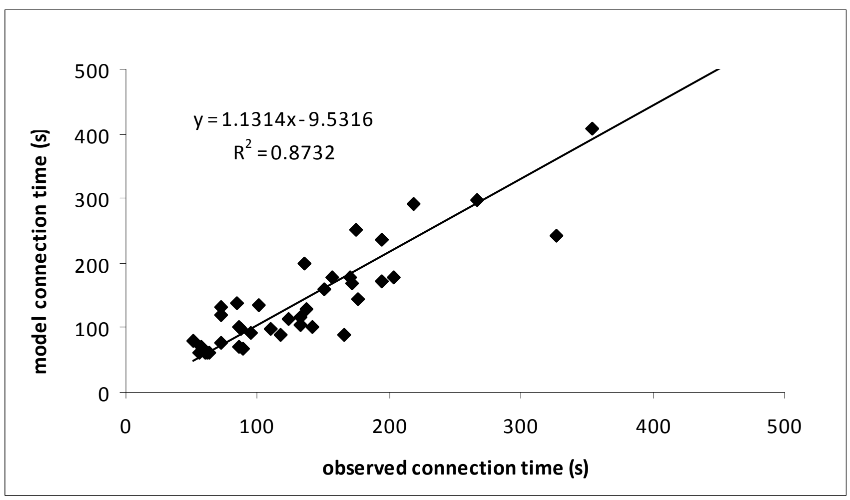


Figure 26. Observed versus predicted time at which runoff connected with the end of the channel

The observed K_{sat} value had to be decreased on most sites during calibration, which indicated that saturated conditions had not been reached during many of the experiments. The only deviations from this trend were Lawn 3, where five of nine replicates required increased K_{sat} rates to calibrate to the observed channel outflow, and Lawn 8, where one of three replicates required an increased K_{sat} rate. The observed and calibrated K_{sat} rates are displayed in Figure 27, as well as reference K_{sat} ranges typical of sandy loams and loamy sands (University of Colorado, 2002) and the K_{sat} rates recommended by (Rawls, W. J. *et al.*, 1983) in the VFSMOD user's manual.

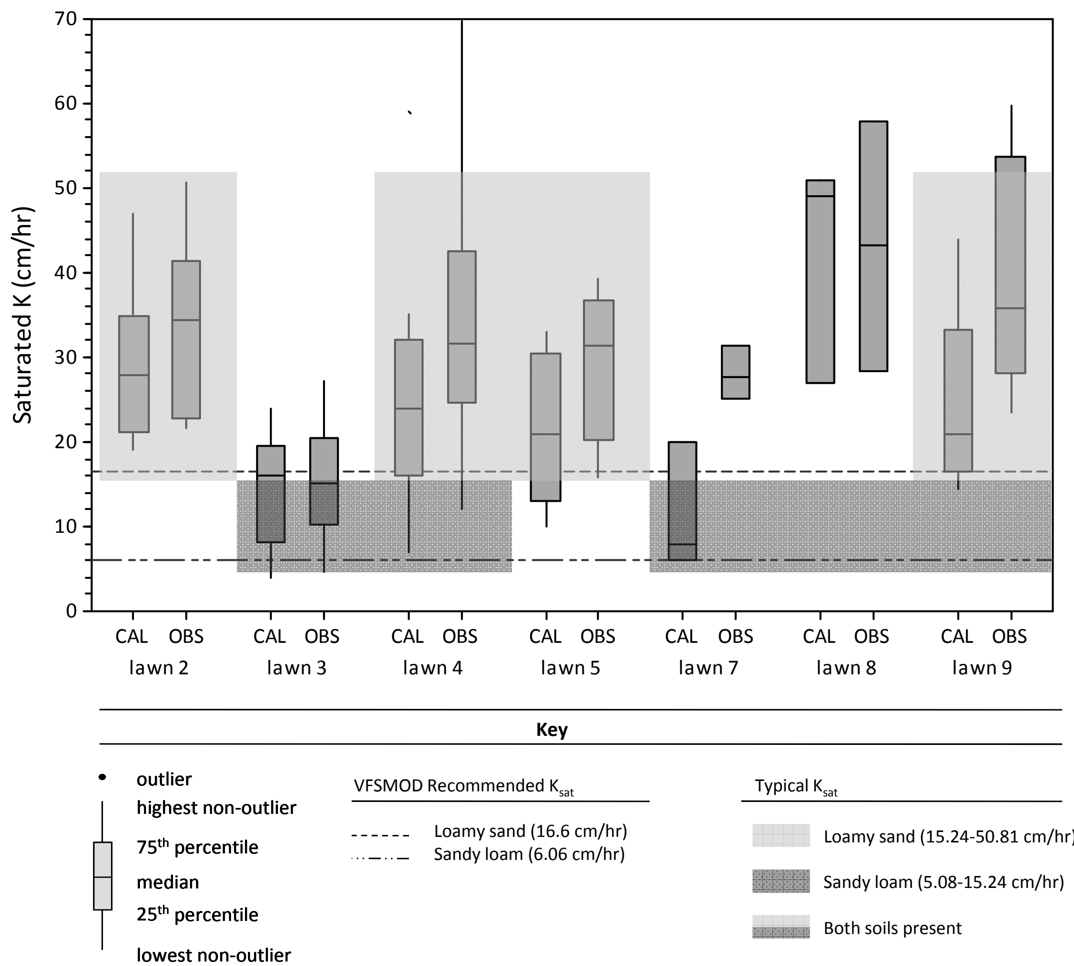


Figure 27. Observed and calibrated K_{sat} rates plotted with recommended rates (Munoz-Carpena, R. & Parsons, J. E., 2005) and typical rates (University of Colorado, 2002) expected for soil textural class

Figure 28 plots the observed runoff delivery ratios (the fraction of total runon collected as runoff at the end of the channel) against the predicted ratios. A nearly 1:1 relationship exists between the observed and calibrated runoff delivery ratios, and the 1.01 regression slope combined with an R^2 value of 0.9942 demonstrates how small the magnitude of difference is between observed and calibrated runoff delivery ratios. Together, Figure 27 and Figure 28 suggest little calibration is required to generate predictions that closely match observed results.

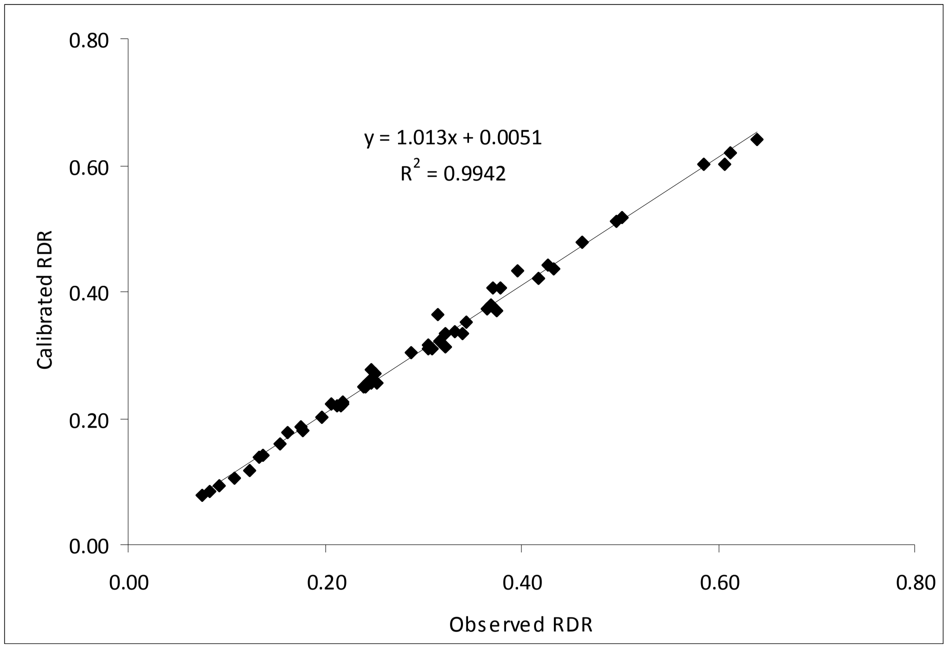


Figure 28. Relationship between observed and calibrated runoff delivery ratios (total runoff volume/total runon volume)

The ultimate goal of these comparisons was to determine if the gains in the predictive accuracy of the model justified the effort of calibration rather than using recommended K_{sat} or observed I_{ss} values. The K_{sat} rates suggested by VFSMOD were too low for soils on the Shawano Lake shorelands. The model recommended a rate of 6.06 cm/hr for sandy loam and 16.60 cm/hr for loamy sand. Figure 27 showed that observed K_{sat} rates were typically higher than those recommended by the model. It is not to be concluded that the observed rates were unusually high, or conversely, that the recommended rates were unusually low. In both cases, the K_{sat} generally fell within the range commonly reported for the soil textural classes (5.1 to 15.2 cm/hr for sandy loam and 15.2 to 50.8 cm/hr for loamy sand, (University of Colorado, 2002)). K_{sat} fell above the observed bounds on Lawns 7 and 8. Both lawns had a single experimental site rather than the standard three sites, resulting in three replicates rather than nine. It is likely that the number of replicates performed on Lawns 7 and 8 did not sufficiently describe K_{sat}. An alternative explanation is that the soil textural class was too constraining; the sand and silt proportions in soils on Lawn 8 were on the extreme edge of what constitutes sandy loam, and could conceivably be considered loamy sand. If re-classified, the calculated K_{sat} rates on Lawn 8 would fall within the range reported in the literature.

Another unusual observation was the magnitude of difference between calibrated and observed K_{sat} rates on Lawns 7 and 9. In the previous section (Velocity of the Leading Edge of Runoff), both lawns were the subject of discussion because of high runoff velocities resulting from surface soil crusting. The observed K_{sat} rates on Lawn 9 were some of the highest observed in the study, but it must be re-stated that these rates were calculated based on the outflow during the final stages of the trial (that is, the instantaneous discharge rate of the last three to four liters of collected runoff). The calibrated rates were lower because they accounted for the duration of the trial, which included the initial stages where the surface crust prevented infiltration. The Green-Ampt equation used to describe infiltration in VFSMOD does not have the ability to incorporate a soil crust.

These considerations were used as a process-of-elimination in determining an appropriate range of K_{sat} to represent Shawano shoreland parcels. Lawns 7 and 9 were excluded due the surface crusting. The geometric mean of calibrated K_{sat} at each site was calculated to ensure that lawns with more replicates did not influence the summary calculations. From these mean values, the median, 25th and 75th percentiles, and the extreme values were tabulated.

Table 9 shows the values representative of Shawano shoreland. These were used for VFSMOD input values in the final section of the research. The input values chosen for modeling were 5 cm/hr, 10 cm/hr, 20 cm/hr and 30 cm/hr. The outputs from model runs were used to create the regression used for the annual application of VFSMOD. The value of this range of K_{sat} rates is that it is applicable to silt loams, sandy loams, and loamy sands. These soil textural classes have overlapping ranges for total porosity, suction at the wetting front, and soil moisture status (i.e. field capacity or permanent wilting point), so a single value was chosen that adequately represented each parameter (Table 10). By doing so, the only variable differing across the three different soil textural classes was infiltration rate. This extended the functionality of the model beyond the Shawano shoreland parcels to a range of sandy soils. K_{sat} rates outside of the specified range were associated with soils that did not have ranges of total porosity, suction at the wetting front, and/or soil water retention capabilities that overlapped the three textural classes of interest.

Table 9. Summary, calibrated K_{sat} rates

Parameter	K_{sat} (cm/hr)
minimum	8.6
25th percentile	16.0
median	20.5
75th percentile	23.6
maximum	34.6

Table 10. Overlapping soil characteristics (derived from (Rawls, W. J. *et al.*, 1983))

Textural Class	Total porosity (cm3/cm3)	Suction at wetting front (m)	Field capacity (initial θ)
Loam	0.375-0.551	0.0133-0.5938	0.24-0.32
Sandy Loam	0.351-0.555	0.0267-0.4547	0.12-0.24
Loamy Sand	0.363-0.506	0.0135-0.2794	0.12-0.24

Measured I_{ss} and Calibrated K_{sat}

The previous section suggested that saturated conditions had not been achieved during most runoff experiments, but calibration of VFSMOD provided K_{sat} rates that accurately described the data. Saturated conditions *were* assumed to have been reached during the infiltrometer tests, and could therefore be compared to the calibrated rates. Because shallow saturated K_{sat} is a "useful predictor of steady ponded infiltration [I_{ss}]" (Soil Survey Division Staff, 1993), the corollary of this relationship indicates that I_{ss} rates can be assumed to accurately represent K_{sat}. The measured I_{ss} rates for double-ring infiltrometer tests are displayed in Table 8 along with the calibrated K_{sat} rates from the runoff channels. There was little similarity between the double-ring I_{ss} rates and the K_{sat} rates. K_{sat} rates from the runoff channels were consistently higher than I_{ss} rates from the double-ring infiltrometers.

Table 11. I_{ss} rates from double-ring infiltrometer and K_{sat} rates calibrated from runoff channels (geometric mean)

Lawn	Doubl-ring I_{ss} (cm/hr)	Calibrated K_{sat} (cm/hr)		
		3 L/min	5 L/min	7 L/min
2	1.90	20.57	28.25	36.68
3	10.54	10.62	18.22	10.77
4	3.68	12.70	30.52	29.96
5	1.88	11.89	26.05	26.22
7	2.48	20.00	6.00	8.00
8	18.24	27.00	49.00	51.00
9	3.36	18.17	22.47	30.43

As previously discussed, infiltrometers were installed on flat ground, whereas runoff channels were installed on gradients of at least 2%.The influence of slope may have contributed to the higher infiltration rates within the channel. Chen and Young (2006) extended the Green-Ampt equation to sloping surfaces and analytically demonstrated that infiltration is greater on sloping surfaces than on flat surfaces; however Chen and Young site numerous field studies that have shown negative, positive, or no relationships between slope and runoff. Another explanation for variable infiltration rates between the two methods may be equipment differences. The infiltration area in the runoff channels was nearly seven times greater than the area within a double-ring infiltrometer. The greater infiltration area may have increase the likelihood of water encountering macropores that facilitated rapid infiltration.

Annual Runoff Estimates

Expanding the Utility of VFSMOD

VFSMOD simulations were used to develop a predictive equation for runoff volume from impervious surface runon. Equation 2 displays the linear regression created from VFSMOD output using variable roof sizes, K_{sat} rates, a range of design storms, and flow path distances. When storm duration was excluded, the R^2 was 0.771 and the adjusted R^2 was 0.767. When storm duration was included, only a negligible increase in the R^2 values was observed (0.778 and 0.773 respectively). Duration did not improve the model sufficiently, so it was excluded in favor of the more streamlined model. This may be an artifact of infiltration rates that were consistently higher than rainfall intensity, such that the infiltration rate was not exceeded and runon volume was the most influential water source. On soils with lower infiltration rates, there may a greater likelihood of observing a compound influence of runon and direct precipitation at high rainfall intensities. Summary statistics (Table 12) and the ANOVA table (Table 13) are displayed below for the model without storm duration as a variable.

Equation 2. Regression model derived from VFSMOD output, where A=roof area (m^2), K_{sat}=saturated hydraulic conductivity (cm/hr), P=precipitation (mm), and D=setback distance (m)

$$\text{Runoff Volume} = -2.41 + 0.023\times(A) - 0.094\times(K_{sat}) + 0.082\times(P) - 0.043\times(D)$$

Table 12. Model summary, excluding storm duration as a variable

Coefficients a,b	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	-2.410	0.211		-11.430	0.000
roof area (m^2)	0.023	0.001	0.687	22.791	0.000
k_{sat} (cm/hr)	-0.094	0.007	-0.426	-13.982	0.000
rain (mm)	0.082	0.004	0.663	22.655	0.000
flowpath length (m)	-0.043	0.002	-0.862	-24.546	0.000

Table 13. ANOVA table for model, excluding storm duration as a variable

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	1059.02	4	262.20	210.23	0.00
Residual	431.87	399	1.25		
Total	1490.89	403			

The regressions documented above were applied to the "average" Shawano shoreland structure. The average roof size on a Shawano lake shoreland parcel is 140 m^2 (1507 ft^2). The average setback distance from the lake, measured at the edge of the structure that is closest to shore, is 31 m (102 ft). This distance was calculated as the surface-area weighted interval mean (that is, the fraction of the total rooftop surface area within 65 m of the lake that was found within each 5 m interval). The predicted runoff volumes from the average structure during the 6-hour (the VFSMOD default duration), 1-, 2-, 5-, 10-, and 25-year design storms are documented in Table 14 (VDF curves from which these storms were derived are available in APPENDIX B). A dramatic reduction in the volume of runoff was realized when only half of the roof (70 m^2) drained to an outfall in the smaller storms, but the difference between the two roof areas became less pronounced in the larger storms and the lower infiltration rates.

Table 14. Runoff volume delivered to Shawano Lake from 6-hour design storms using average shoreland roof size and setback (numbers in parentheses indicate the storm size)

Roof Size	K_{sat} (cm/hr)	Runoff Vol. (m^3) at Recurrence Interval:				
		1 year (44.45 mm)	2 year (50.8 mm)	5 year (63.5 mm)	10 year (76.2 mm)	25 year (82.55 mm)
full (140 m^2)	30	0.83	1.31	2.26	3.21	3.69
	20	1.49	1.97	2.92	3.87	4.35
	10	2.15	2.63	3.58	4.53	5.01
	5	2.48	2.96	3.91	4.86	5.34
half (70 m^2)	30	0	0	0.79	1.74	2.22
	20	0.02	0.50	1.45	2.40	2.88
	10	0.68	1.16	2.11	3.06	3.54
	5	1.01	1.49	2.44	3.39	3.87

The “average structure scenario” was taken one step further in order to explore the setback distance required to completely disconnect the average structure from the lake during the 6-hour design storm. Figure 29 and Figure 30 display the setback distance required to disconnect the average shoreland parcel over the four K_{sat} rates. To give this information some perspective, it is helpful to view the distances required for disconnection through the lens of the 75-ft shoreland setback maintained in Wisconsin’s Shoreland Management Program (chapter NR 115 of the Wisconsin Administrative Code. That setback is represented by the blue line labeled NR 115 in the figures below). When K_{sat}=30 cm/hr in the full roof scenario, runoff flowpath exceeded 75 ft when precipitation exceeded 50 mm (Figure 29). The predicted runoff flowpaths exceeded 75 ft when K_{sat} was decreased to 20 cm/hr and precipitation exceeded 40 mm; when K_{sat} was 10 cm/hr and precipitation exceeded 32 mm; and when K_{sat} was 5 cm/hr and precipitation exceeded 27 mm. These storms all have recurrence intervals of less than a one year.

The half-roof scenario required storms greater than 70 mm, 60 mm, 50 mm, and 47 mm to advance runoff beyond 75 ft when K_{sat} rates were 30 cm/hr, 20 cm/hr, 10 cm/hr, and 5 cm/hr, respectively (Figure 30). These events are expected to have recurrence intervals of less than 10, less than five, two, and less than two years.

Also noteworthy are the other two reference lines in Figure 29 and Figure 30, which represent the mean setback distance on Shawano Lake (31 m, or 102 ft) and the length of the primary buffer (that is, the distance from a roof at the minimum, 75-ft setback to the edge of the 35-ft shoreland buffer).

To maintain the "average" focus of this section, it should be understood that 20-25 cm/hr is probably the best approximate of K_{sat} rates for Shawano shorelands. From Figure 29, it can be deduced that runoff from the full roof draining to a single discharge point is expected to exceed the average setback about once every two years, and the 75-ft setback once per year. Runoff is expected to travel the distance of the primary buffer multiple times per year. The two-discharge points scenario in Figure 30 demonstrates that runoff is expected to exceed the average setback at least once every ten years, and the 75-ft setback at least once every five years. Runoff from half the roof is expected to travel the entire distance of the primary buffer at least once every two years.

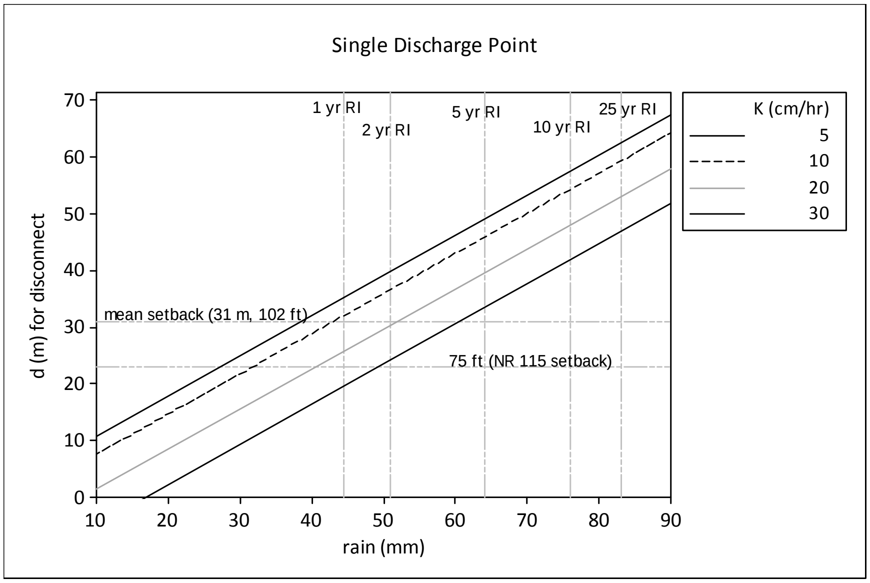


Figure 29. Distance required to disconnect runon from the average roof (140 m^2) roof over a range of storms

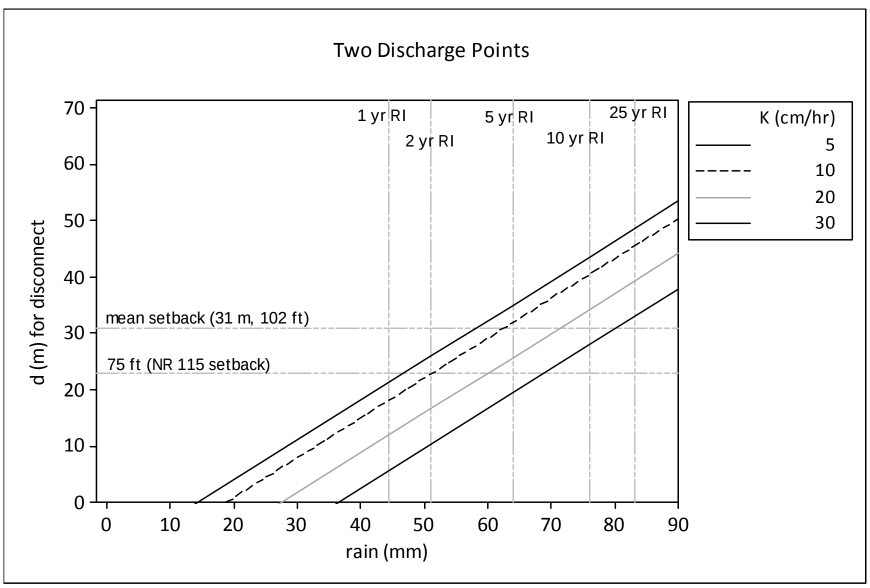


Figure 30. Distance required to disconnect runon from half of the average roof (70 m^2) over a range of storms

Finally, the 75-ft NR 115 setback was evaluated to determine the roof area draining to a single discharge point at which the setback no longer functioned to disconnect runon during the average year. The 1-year storm represents the largest storm expected to occur in the average year, so it was assumed that the maximum roof size at which runon was disconnected would, by default, disconnect all other storms during the year. Table 15 lists the maximum roof sizes draining to a single discharge point at which runon is disconnected during the one-year, six-hour storm (44.45 mm). In keeping with the average focus, where K_{sat} rates are 25 cm/hr, drainage areas no larger than 91 m^2 are expected to disconnect the 1-year storm at a 75-foot setback. On Shawano Lake, only 28% of houses within 75 ft have roofs less than or equal to 91 m^2. Even in the best-case scenario, where K_{sat} rates are 30 cm/hr, the majority of houses within 75 feet of the lake are larger than the maximum size at which disconnection will occur ("full roof" column in Table 15). If it is assumed that all roofs are peaked and have two aspects, such that the maximum roof size represents only half of the roof, there are a greater portion of houses that disconnect runon during the average year ("half roof" column in Table 15).

Table 15. Maximum roof size at which runon is disconnected at a 75-ft setback

K_{sat} (cm/hr)	max. roof size		% of houses where size represents:	
	m^2	ft^2	full roof	half roof
5	10	108	0	2
10	30	323	11	18
20	71	764	22	56
25	91	979	28	65
30	112	1205	39	78

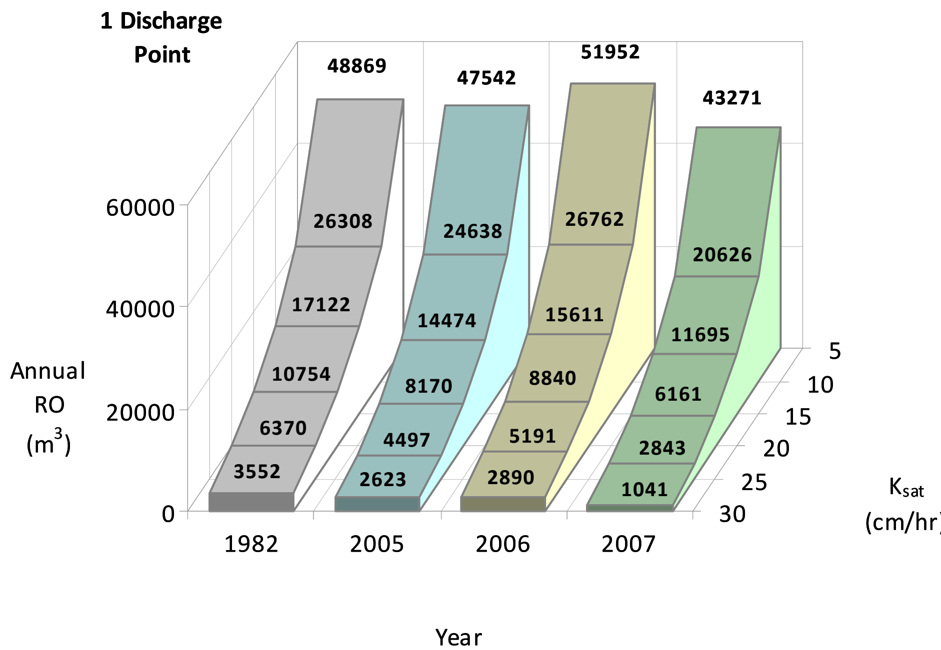
Annual Model Application

An estimate of the annual runoff for the Shawano shoreland lots can be made using the regression model. In calculating annual runoff, it was assumed that all runon was directed toward the lake (i.e. runon was not directed toward the property road frontage), and a direct runoff path existed between the roof and the lake. Temporal variance in initial soil moisture content was not considered in this model. All storms were modeled as separate events with the initial soil moisture content used when the regression was created (θ=0.20).

Influences of Storm Size Distribution on Annual Runoff for Various K_{sat}

Annual runoff volume was calculated as the sum of runoff from individual events throughout the year. Runoff predicted with the VFSMOD regressions for one- and two-discharge point scenarios shown in Figure 31. The y-axes for both scenarios in Figure 31 have the same scale to demonstrate the dramatic reduction in runoff volume when runon discharges from two points rather than one. Changing from one to two discharge points means that the same infiltration area received only half of the original runon volume, or that the same original runon volume discharged to an infiltration area that was twice as large. When infiltration area was increased by 100%, annual runoff was reduced by 73% to 100%, with an average reduction of 87% (over the four years and the six infiltration rates shown modeled in Figure 31). Such profound reductions demonstrate the importance of large infiltration areas.

Because 1982 is considered an average year according to the Wisconsin Administrative Code (ch. NR 151, Wisconsin's Storm Water Management Program), the runoff predicted from the 1982 precipitation record was considered representative of average annual runoff. In the single discharge point scenario, runoff predictions were very similar in 1982 and 2005, slightly greater in 2006, and slightly less in 2007. These predictions mirrored the differences in annual precipitation: both 1982 and 2005 saw 740 mm of rain, 2006 received 808 mm, and only 675 mm fell in 2007.



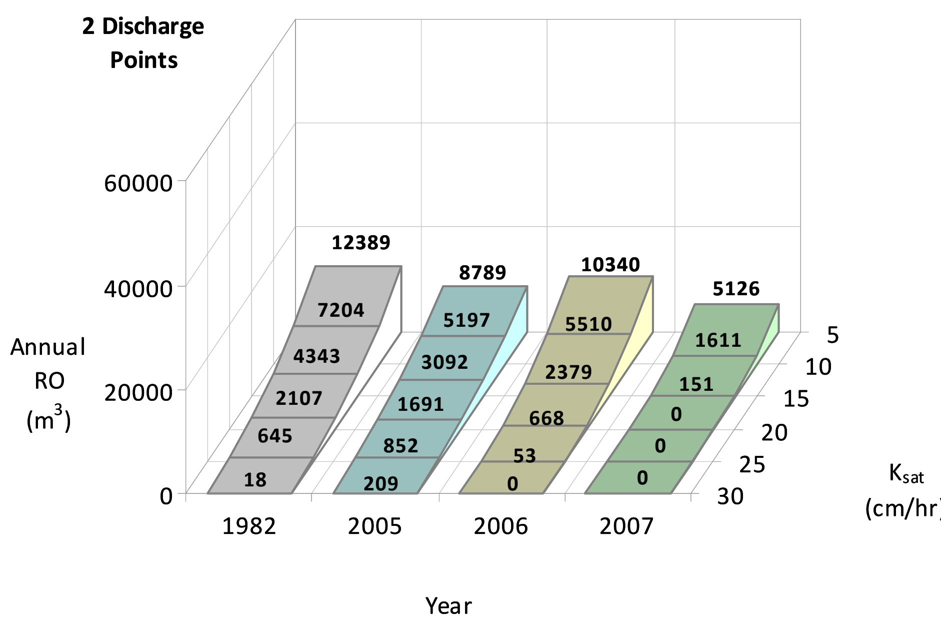


Figure 31. Total annual runoff volumes from all Shawano structures within 65 m of shore over a variety of K_{sat} rates

A larger difference between years was observed in the two-discharge points scenario, where the ratio of infiltration area to source area was twice as large as the single discharge point scenario. Under such circumstance, the influence of storm size distribution in generating runoff became increasingly pronounced. Figure 32 compares the storm distribution across the years of interest. Predicted runoff volumes from half-roofs were further examined by year at K_{sat} rates of 5, 10, 20, and 30 cm/hr to understand the relationship between storm distribution and runoff in Figure 33, Figure 34, Figure 35, and Figure 36. The following discussion focuses chiefly on the influence of storm size distribution at the *Ksat rate of 5 cm/hr*, as the influences of storm size are most distinct at the low infiltration rate. However, the same general concepts that are discussed below can be applied at the higher K_{sat} rates, and can be inferred from Figures 35-38.

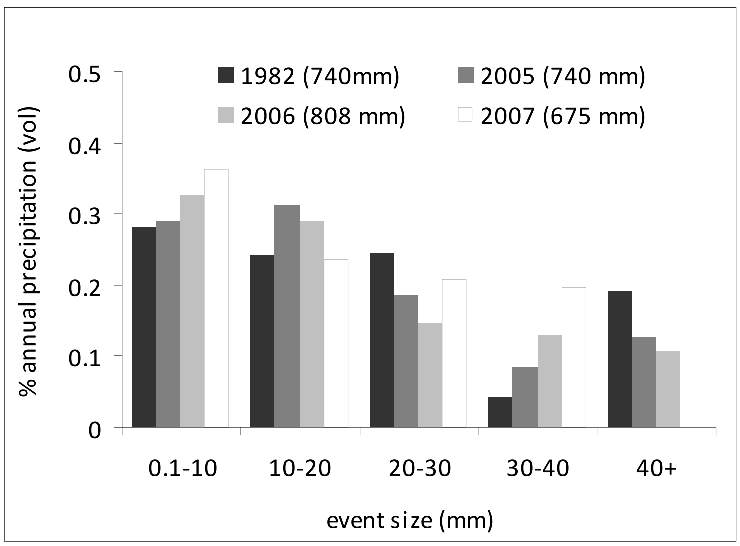


Figure 32. Storm size distribution during the average year and recent years

Runoff predictions in 2005 were lower than 1982 at K_{sat}=5 cm/hr, despite the same annual total rainfall. The differences between the two years reflect variability in storm size distribution. In all years, storms less than 20 mm did not contribute any runoff. Pitt (1999) refers to such events, where runoff is “totally captured…or infiltrated in upland areas,” as common rains. Fewer storms were completely infiltrated in 1982 than in 2005. In 1982, 91% of all events (115 events) produced no runoff and comprised 52% of the annual rainfall (Figure 33). In 2005, a similar proportion of events (90%, or 108 events) did not generate runoff, but contributed 60%

of the annual precipitation (Figure 34). The higher contribution in 2005 of completely infiltrated storms to the annual precipitation resulted in a lower total runoff for the year. Differences in annual runoff can be further explained through the distribution of the events that contributed the most annual runoff (referred to as “large events” in the following discussion). The large storms can be identified in Figure 32 as those in the highest rainfall category for a given year. In 1982 (47.5-52.5 mm), large events contributed 78% of the annual runoff, occurred during three events, and comprised 19% of the annual precipitation. Two large events in 2005 (52.5-57.5 mm) contributed 74% on the annual runoff, yet comprised only 13% of the annual precipitation. This contrast highlights the importance of large events in generating runoff.

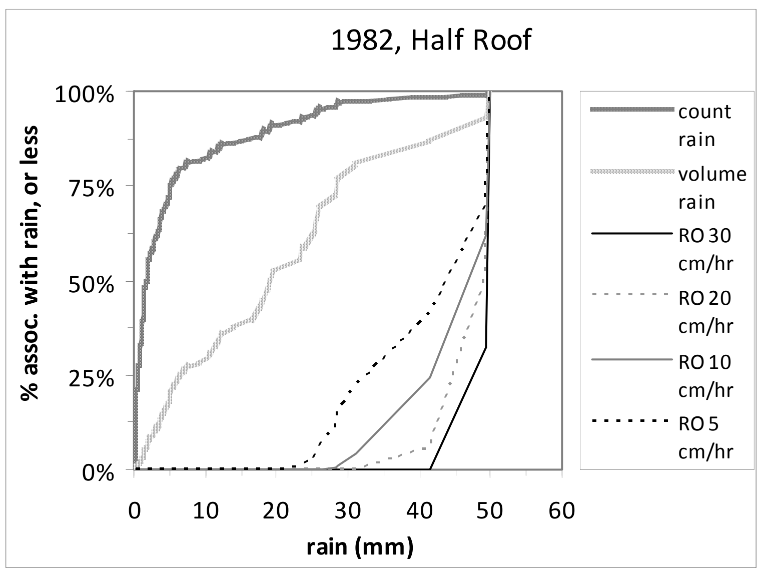


Figure 33. Accumulative rain and runoff in 1982, modeled with various K_{sat}

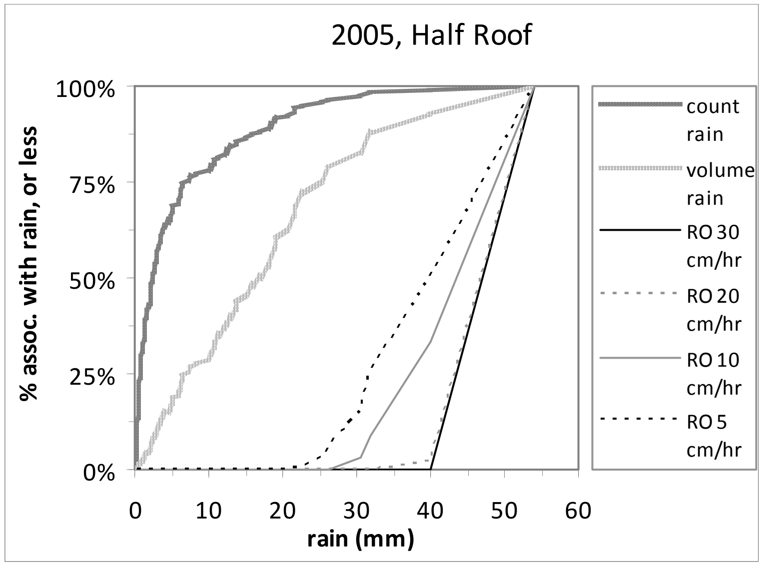


Figure 34. Accumulative rain and runoff in 2005, modeled with various K_{sat}

Although this exploratory analysis focused on the runoff predictions when K_{sat} was 5 cm/hr, it is noteworthy that, at the two highest K_{sat} rates (25 and 30 cm/hr), a *higher* runoff volume was predicted in 2005 than 1982. This reversal was caused by an interaction of storm size distribution and the influence of structure size and setback distance. At the high K_{sat} rates, all runoff was attributed to the one or two largest storms. The largest storms in 2005 were greater than the largest storms in 1983 and could therefore travel farther across a highly permeable flowpath. This concept is explored further in the following section.

The total runoff during 2006 may appear unusual because the runoff volume was consistently lower at all K_{sat} rates than in 1982, although the total precipitation was greater (808 mm). Small storms that did not generate runoff comprised 92% (119) of events in 2006 and 64% of the annual rainfall (Figure 35). The large storms had lower volumes in 2006 than 1982; storms greater than 40 mm contributed 51% of the annual runoff, occurred during two events and comprised 11% of the annual precipitation. The lower volume of large storms in 2006 than in 1982 was reflected in the lower annual runoff, despite the greater total precipitation.

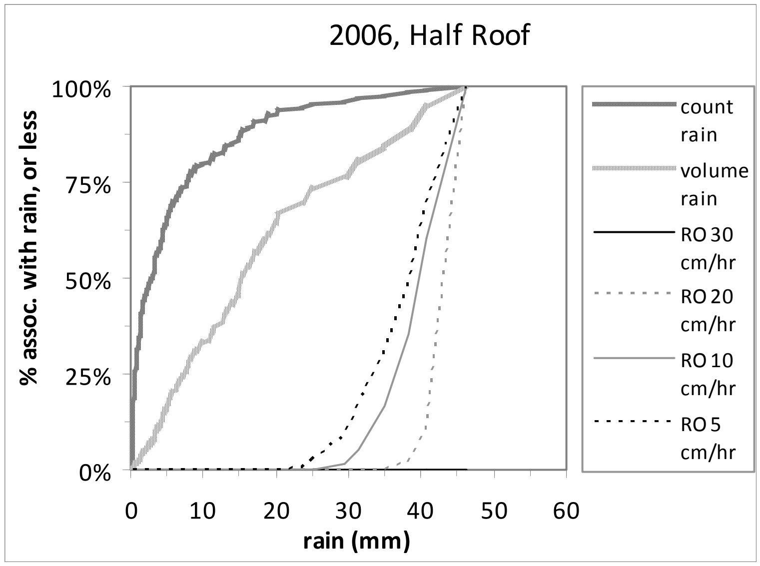


Figure 35. Accumulative rain and runoff in 2006, modeled with various K_{sat}

Substantially lower runoff volumes in 2007 mirrored the lower-than-normal annual precipitation (675 mm). 92% (109) of the events produced no runoff and contributed 60% of the annual rainfall (Figure 36). These statistics are not much different that those of previous years; the difference in runoff can be pinned on the size of the large storms in 2007. Although the large storms comprised 10.27% of the annual rainfall, they were relatively low-volume events (only 31-36 mm, compared to 41-50 mm in 1982).

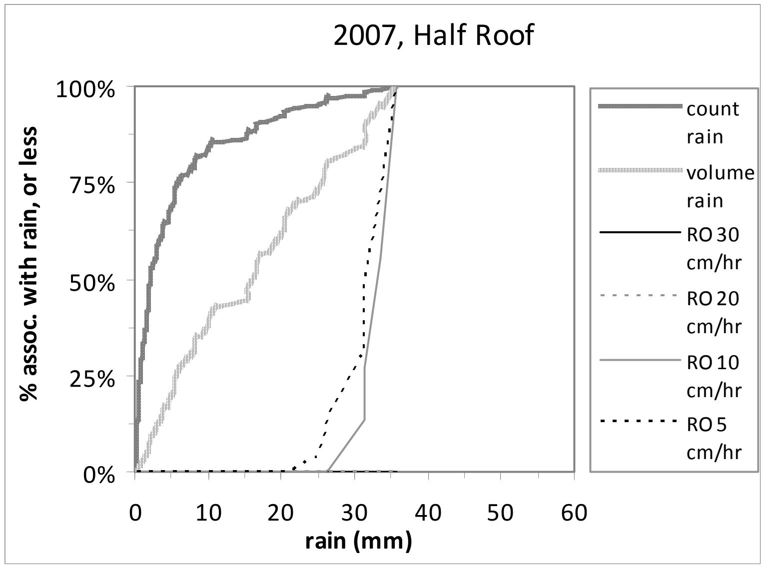


Figure 36. Accumulative rain and runoff in 2007, modeled with various K_{sat}

Relative Influences of Setbacks and Structure Sizes

Finally, runoff volume was explored at the setback (interval) scale in order to describe the total and relative contributions of shoreland regions and identify problem areas. The number, size, and setback of structures (Figure 37) are the driving variables for runoff contribution. The size and frequency distribution of structures help explain the predicted runoff volumes in 1982 documented in Table 16, but further insight is gained by graphically exploring the *percent* contribution of predicted annual runoff by setback distance.

Figure 38 displays the percent contribution assuming the one-discharge point scenario. Not surprisingly, the percent contributions from the setback intervals tend to mirror the normal-shaped distribution of structure size and frequency in Figure 37. Runon draining to one discharge point contributes the greatest proportion of annual runoff at the 25 m setback (Figure

38). The largest average structure size and greatest number of structures occurred in this interval. The contribution of structures to annual runoff volume was sharply reduced (figures have a log-scale y-axis) or completely eliminated beyond the 30-m setback, but it is difficult to discern whether greater setback distances (increased infiltration area) or decreases in structure size and number are responsible for the reversal.

An examination of annual runoff contribution from runon draining to two discharge points at various intervals serves to better highlight the interactions between structure size, frequency, and setback distance. The most conspicuous scenario displayed in Figure 39 is when K_{sat}=30 cm/hr. This scenario underscores the 15 m interval as in important runoff source area within the Shawano shorelands. Referring back to Figure 37 reveals that although there are only 75 structures within the 15 m setback interval, those present have an average roof area of 163 m^2 (1755 ft^2), whereas the average size of structures in the 5 m and 10 m intervals are 81 m^2 and 77 m^2. These values indicate that within approximately 10 m from shore, structures transition from small accessory buildings to full-sized home which contribute 13% to 100% of the annual runoff.

Table 16. 1983 total runoff volumes from various intervals, K_{sat} rates, and discharge points

Scenario	K_{sat} (cm/hr)	Runoff Volume (m^3) at Setback distance (m)										
		5	10	15	20	25	30	35	40	45	50	55
full roof (1 discharge point)	5	528	637	6636	10684	15246	10984	3301	853	546	236	70
	10	316	372	3160	5880	7587	6421	2087	484	356	124	9
	20	114	140	1325	2456	3213	2637	698	171	70		
	30	27	24	450	822	1085	895	249				
half roof (2 discharge points)	5	377	436	1613	2931	3161	2460	1039	371	223	39	
	10	238	284	908	1659	1828	1515	627	145	7		
	20	61	51	350	589	619	433	6				
	30			18								

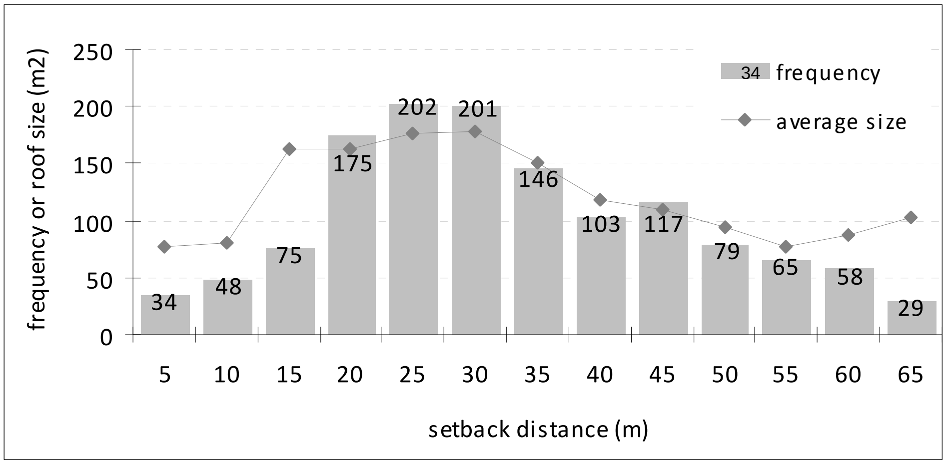


Figure 37. Plot of roof size and structure frequency at various setback distances from the Shawano Lake shoreline

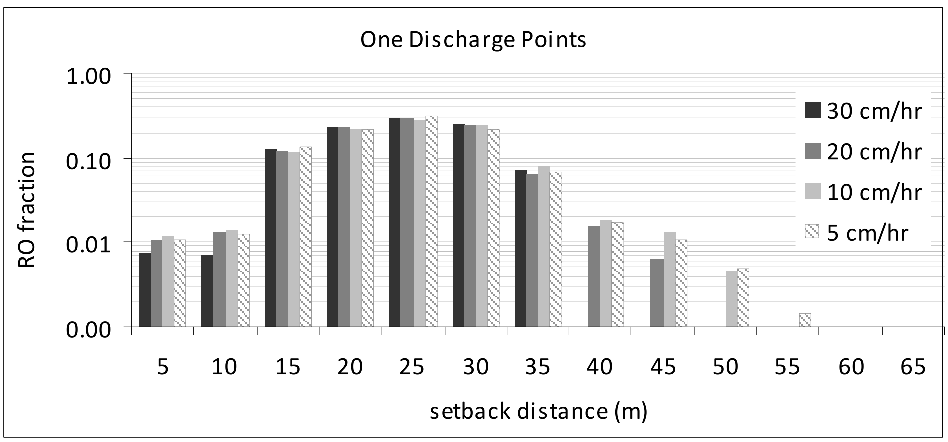


Figure 38. Proportion of 1982 annual runoff contributed by structures at increasing setback distances

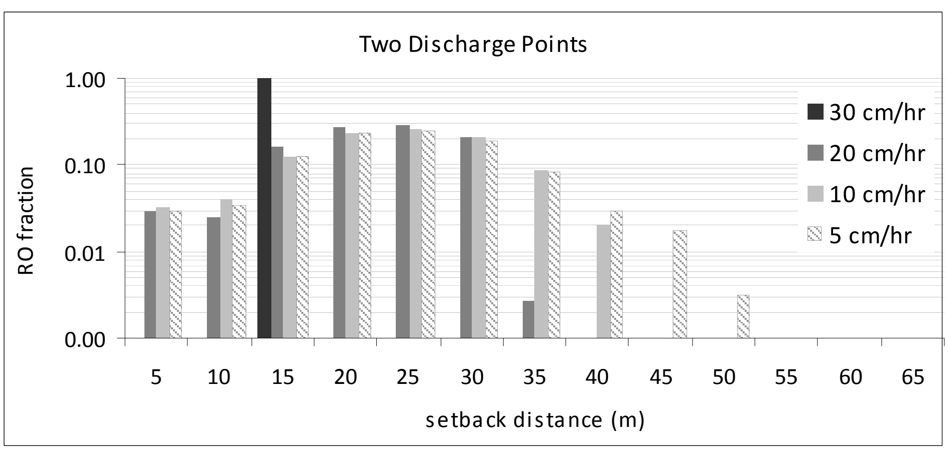


Figure 39. Proportion of 1982 annual runoff contributed by structures at increasing setback distances

The preceding interval analysis of runoff contributions disclosed information regarding the effect of structure size and frequency versus setback distance over several K_{sat} rates. Although not the *most* important runoff source, the 15 m interval stood out as clearly important for both the 1- and 2-discharge point scenarios. Even though only 75 structures were present in this interval, the large average size functioned to supersede the frequency. Also noteworthy from the interval analysis is the contributions from those intervals which are farther from shore than the 75 ft (22 m) setback mandated by NR-115. Especially interesting are large contributions from the 25 and 30 m intervals. Significant contributions are attributed to these intervals, suggesting that the NR-115 setback may not be an adequate management strategy when roof sizes are sufficiently large and runon is concentrated.

CONCLUSIONS

This research examined the movement of runon through pervious shoreland lawns. Parameters which are commonly used to predict runoff velocity and volume, such as slope, hydrologic (vegetative) condition, and soil condition, had a manifest influence on runoff when lawns were evaluated individually. Although many of these lawns appear to present a low connection risk, additional research involving finer-textured soil may show interactions that were masked by the high infiltration rates of the Shawano shoreland soils. The high runoff velocities and outflows from the single lawn with a silty soil (Lawn 3), suggested that lawns established on soils with finer textures present greater connection risk and that much can be learned by studying the interactions of soil and surface characteristics on runon/runoff behavior.

VFSMOD, although originally intended for agricultural settings, appears to be a reliable tool for the residential setting. Accuracy in predicting runoff is likely gained by using a process-based model over observation/empirical models such as SLAMM. This is especially useful in predicting runoff from general parameters that describe a residential parcel. Knowledge of local soil characteristics, approximations of slope, average setbacks and roof sizes are general characteristics that can be applied to the model to obtain a prediction of runoff per event.

The drawback of VFSMOD is its inability to model more than a single event. A regression approach helped extend the model's functionality to encompass variable roof sizes, setback distances, storm sizes, and, to a limited extent, soil properties. The limitations of developing a regression are that storm duration (and, by default, intensity) are not represented as important variables. While this may be the case on sandy soils with very high infiltration capacities, storm duration/intensity becomes increasingly important at low infiltration rates where infiltration capacity may be rapidly exceeded. Again, additional runoff research over a greater variety of soil textures is needed in the development of an analytical method for predicting runoff beyond the single-event scale, where impervious/pervious interactions exist.

Runoff generalizations based on qualitative parameters were made in the interest of property owners, who are unlikely to have the technical knowledge or resources for calculating or modeling runoff from their property. Shoreland residents along Shawano Lake have demonstrated an interest in actions they can take, as property owners, to contribute to lake management. Providing property owners with standards to determine the relative likelihood of a connection between their downspouts and the lake will assist in best management practice (BMP) choices.

Discharge rate was a very influential variable controlling runoff velocity. Although the scale at which the field study was conducted does not permit the results to be directly applicable to a shoreland parcel, the implications for property owners are clear: runon from a downspout that drains a large area of roof is more likely to connect to the lake than runon from a small area of roof. Regardless of the size of roof draining to a downspout, the distance of the roof from the shore is also very important in disconnecting runon

K_{sat} was a significant parameter in VFSMOD but is unlikely to be a useful standard for property owners. K_{sat} is a function of pore size distribution which is influenced by compaction and soil texture. Providing property owners with terms such as compacted soil, sandy soil, clayey soil, etc. is probably more appropriate. Grass thickness and slope are also parameters appropriate for property owner interpretation. Dense lawns on slopes less than approximately 8% resulted in lower runoff velocities, lower runoff volumes, and more infiltration than sparse lawns on steeper slopes. When combined with roof size and distance from shore, several noteworthy conclusions can be reached. Even where soil and surface characteristics are most conducive to infiltration, a large roof area draining to a downspout may exceed the lawn's infiltration capacity and the risk only increases for roofs that are closer to shore. Also, runon from smaller roofs may not be adequately reduced on steep slopes with sparse grass, especially if a crust is present at the soil surface.

Because of the apparent importance of setback distance and structure size in disconnecting rooftops from shorelines, the process-based calculations used by VFSMOD are probably more appropriate than coarse methods of runoff estimation that use empirical values, ignore spatial distribution of impervious areas, and consider only the total impervious area rather than the size distribution of impervious cover.

Finally, these results lend themselves for conclusions and implications regarding the effectiveness of the 75-ft setback in NR 115. In the absence of a shoreland buffer (as is frequently the case on Shawano Lake), the setback does not appear to sufficiently disconnect runon during the average year. Effectiveness of the 75 foot setback decreases as infiltration rate decreases, but even at the highest modeled infiltration rate (30 cm/hr), many houses on Shawano Lake are too large to ensure disconnection, as Table 15 demonstrated.

Options for Shoreland Property Owners

This research demonstrated a need for a sense of stewardship on Shawano Lake shoreland parcels. There are a range of actions homeowners can take to increase infiltration and reduce runoff from their properties. Appropriate lawn maintenance is a simple step towards increasing infiltration. On lawns with sparse grass, the lawn quality can be improved by overseeding, or spreading seed directly onto the existing lawn (Stier, J. C., 2000).

It is important that the grass species is appropriate for the area. On Shawano Lake, a turf type tall fescue is a good choice. Not only is tall fescue suited to sandy soils, it is also drought resistant, can tolerate minimal soil fertility, and can withstand foot traffic well (Stier, J. C., 2000). These characteristics imply that little or no irrigation is required, thereby preventing unnecessarily high soil moisture contents that decrease infiltration capacity. Further, the ability of tall fescue to thrive in low fertility conditions means that phosphorus fertilizer applications may not be necessary, which reduces the phosphorus concentration in runoff during large precipitation events. In fact, a study of soil-test phosphorus concentrations on Shawano Lake revealed that no shoreland lawns were phosphorus-deficient and additions were not necessary (Turyk, N. *et al.*, 2008). When lawn quality is adequate (i.e. no bare patches, minimum sparse patches), lawns can better function as a shoreline buffer if they are not mowed within 35 feet of shore (Wagner, C. *et al.*, 2003).

Although desirable, low phosphorus concentrations in runoff are unlikely to be achieved by withholding phosphorus fertilizers. There is a large amount of phosphorus that is naturally present in soils and vegetation, so a more pro-active approach is to capture runoff before it connects with the lake. Native plants filter runoff and pollutants, promote infiltration, provide erosion protection, and require minimal maintenance (Wilson, D. & Korb, G., 1999).

Rain gardens are another option for capturing runoff. Rain gardens are able to infiltrate significantly more runon than grassed drainage swales. The University of Wisconsin-Extension (2002) reports 30% more infiltration can occur in rain gardens than conventional lawns. Infiltration gains from rain gardens are probably even greater than 30% when compared to grassed drainage swales, where water is rapidly conveyed to the lake.

Simple mechanical changes can also promote infiltration. When gutters and downspouts are removed, runon is shed as sheet flow onto an area as wide as the roof rather than a narrow drainage swale. A significant amount of infiltration surface may be gained if the area receiving runon is completely pervious. Even placing runoff spreaders at the bottom of a downspout can encourage wider distribution of runon over a greater infiltration area.

Future Research

The study was performed on soils that were very sandy, had high infiltration rates, and were not particularly compacted. Such soils should be considered an ideal infiltration medium. Further research on finer-textured soils, both compacted and well-structured, is needed for a more complete understanding of hydrologic interactions between pervious and impervious surfaces. In the absence of high infiltration rates, surface properties such as slope and vegetative condition, and storm duration (or intensity) may have a greater influence on runoff from impervious/pervious interactions.

Inconsistencies between infiltration results from infiltrometers and runoff channels demonstrated a need for more infiltration research on sloping surfaces. Variable infiltration rates between the two methods may be a function of equipment differences, where the greater infiltration area in the runoff channels increased the likelihood of water encountering macropores that facilitated rapid infiltration. Another explanation for these differences is that infiltration rates may be greater on slopes than flat ground. Texture-based infiltration rates reported in the literature are specific to flat areas. This research highlights the importance of exploring and tabulating infiltration rates over variety of slopes and soil textures. The indications of differences between infiltration rates measured in infiltrometers and runoff channels suggests that more research is necessary on the spatial and temporal variations in infiltration rates in natural systems.

REFERENCES

ABU-ZREIG, M., RUDA, R.P. & WHITELEY, H.R. (2001) Validation of a Vegetated Filter Strip Model (Vfsmod). *Hydrological Processes*, **15,** 729-742.

AMERICAN SOCIETY FOR TESTING AND MATERIALS (2002) D 3385-94: Standard Test Method for Infiltration Rates of Soils in Field Using Double-Ring Infiltrometer. *Annual Book of ASTM Standards*. **04.08**.

BLACK, C.A. (1965) *Methods of Soil Analysis*. American Society of Agronomy, Inc., Madison, WI.

BLICK, S.A., KELLY, F. & SKUPIEN, J.J. (2004) Chapter 2: Low Impact Development Techniques. In: *New Jersey Stormwater Best Management Practices Manual* (Ed. by.

BRADY, N.C. & WEIL, R.R. (2002) *The Nature and Properties of Soils*, 13 edn. Prentice Hall, Upper Sadle River, NJ.

BURTON, G.A. & PITT, R.E. (2002) *Stormwater Effects Handbook: A Toolbox for Watershed Managers, Scientists, and Engineers*. Lewis Publishers, Washington, D.C.

CARPENTER, S., CARACO, N., CORRELL, D., HOWARTH, R., SHARPLEY, A. & SMITH, V. (1998) Nonpoint Pollution of Surface Waters with Phosphorus and Nitrogen. *Ecological Applications* **8,** 559-568.

CENTER FOR WATERSHED PROTECTION (2000) Stormwater Credits. *Stormwater Manager's Resource Center*. Retrieved February 18, 2007, from www.stormwatercenter.net.

CENTER FOR WATERSHED PROTECTION (2002) The Vermont Stormwater Management Manual, Volume I Stormwater Treatment Standards. V. A. o. N. Resources. Waterbury, VT.

CENTER FOR WATERSHED PROTECTION (2005) Issue Paper "F" Stormwater Credits. *Minnesota Stormwater Manual*. Minnesota Pollution Control Agency.

CHEN, L. & YOUNG, M.H. (2006) Green-Ampt Infiltration Model for Sloping Surfaces. *Water Resources Research*, **42**.

DE MASTER, D.W. (2002) Measuring Onsite Stormwater Infiltration of Runoff from Disconnected Impervious Surfaces. Unpublished Masters Dissertation, University of Wisconsin, Madison.

DENNIS, J. (1986) Phosphorus Export from a Low-Density Residential Watershed and an Adjacent Forested Watershed. *Lake and Reservoir Management* **2,** 401-407.

GARN, H.S. (2002) Effects of Lawn Fertilizer on Nutrient Concentration in Runoff from Lakeshore Lawns, Lauderdale Lakes, Wisconsin. *Water-Resources Investigations Report 02-4130*. U. S. G. Survey.

GRACZYK, D. & GREB, S. (2006) Data at Sites near Geneva Lake, Lake Geneva, Wisconsin, and Long Lake, near New Auburn, Wisconsin. Open-File Report 2006-1191. US Geological Survey. Reston, VA.

GRACZYK, D.J., HUNT, R.J., GREB, S.R., BUCHWALD, C.A. & KROHELSKI, J.T. (2003) Hydrology, Nutrient Concentrations and Nutrient Yields in Nearshore Areas of Four Lakes in Northern Wisconsin, 1999-2001 *Water-Resources Investigations Report 03-4144*. U.S. Geological Survey. Reston, VA.

GROSS, C.M., ANGLE, J.S. & WELTERLEN, M.S. (1991) Nutrient and Sediment Loss from Turfgrass. *Journal of Environmental Quality*, **53,** 564-568.

HAMILTON, G. & WADDINGTON, D. (1999) Infiltration Rates on Residential Lawns in Central Pennsylvania. *Journal of Soil and Water Conservation* **54,** 564-568.

HERSHFIELD, D.M. (1961) Rainfall Frequency Atlas of the United States for Durations from 30 Minutes to 24 Hours and Return Periods From1 to 100 Years, U.S. Department of Commerce. Washington, D.C.

HUNT, R., GREB, S. & GRACZYK, D. (2006) Evaluating the Effects of Nearshore Development on Wisconsin Lakes. Fact Sheet 2006-3033. US Geological Survey. Middleton, WI.

KELLING, K. & PETERSON, A. (1975) Urban Lawn Infiltration Rates and Fertilizer Runoff Losses under Simulated Rainfall. *Soil Science Society of America Proceedings*, **39,** 348-352.

KING, K., HARMEL, R., TORBER, H. & BALOGH, J. (2001) Impact of a Turfgrass System on Nutrient Loadings to Surface Water. *Journal of the American Water Resources Association*, **37,** 629-640.

LEGG, A.D., BANNERMAN, R.T. & PANUSKA, J. (1996) Variation in the Relation of Rainfall to Runoff from Residential Lawns in Madison, Wisconsin, July and August 1995. US Geological Survey. Madison, WI.

LINDE, D., WATSCHKE, T., JARRETT, A. & BORGER, J. (1995) Surface Runoff Assessment from Creeping Bentgrass and Perennial Ryegrass Turf. *Agronomy Journal*, **87,** 176-182.

LINDE, D. & WATSCHKE, T. (1997) Nutrients and Sediment in Runoff from Creeping Bentgrass and Perennial Ryegrass Turfs. *Journal of Environmental Quality*, **26**.

MARKHAM, L. (2003) Shoreland Development Density and Impervious Surfaces. Retrieved Jan 2, 2007, from http://www.uwsp.edu/CNR/landcenter/pdffiles/Imp_Surf_Shoreland_Dev_Density.pdf.

MCCUEN, R.H. (2004) *Hydrologic Analysis and Design, 3rd Edition*, 3 edn. Prentice-Hall, Inc., Upper Saddle River, NJ.

MUELLER, G. (2006) Hydrologic Response of Urban Lawns, Measuring and Monitoring the Ability of Lawns to Hydrologically Disconnect Rooftops, University of Wisconsin, Madison, WI.

MUNOZ-CARPENA, R. (1997) Abstract: Vegetative Filter Strip Modeling System. Retrieved 02/13, 2008, from http://carpena.if.as.ufl.edu/vfsmod/abstract.html.

MUNOZ-CARPENA, R. & PARSONS, J.E. (2005) VFSMOD-W. *Model Documentation and User's Manual, Version 2.x*. University of Florida.

PITT, R. (1999) Small Strom Hydrology and Why It Is Important for the Design of Stormwater Control Practices. In: *Advances in Modeling the Management of Stormwater Impacts* (Ed. by W. James), **7**. Computational Hydraulics International and Lewis Publishers/CRS Press, Guelph, Ontario.

PITT, R. & VOORHEES, J. (2005) Runoff Coefficient File Module, in SLAMM Help Menu. PV and Associates LLC. University of Alabama, Tuscaloosa, AL.

RAWLS, W.J., BRAKENSIEK, D.L. & MILLER, N. (1983) Green-Ampt Infiltration Parameters from Soils Data. *Journal of Hydraulic Engineering*, **109,** 62-70.

SCHUELER, T. & HOLLAND, H., eds. (2000) *The Practice of Watershed Protection*. Center for Watershed Protection, Ellicott City, MD.

SHOEMAKER, L., DAI, T. & KOENIG, J. (2005) TMDL Model Evaluation and Research Needs, EPA-8000-R-05-149. US Environmental Protection Agency, Office of Research and Development. Cincinnati, OH.

SHUMAN, L. (2002) Phosphorus and Nitrate Nitrogen in Runoff Following Fertilizer Application to Turfgrass. *Journal of Environmental Quality*, **31,** 1710-1715.

SOIL SURVEY DIVISION STAFF (1993) Soil Survey Manual, Us Department of Agriculture Handbook 18. US Soil Conservation Service.

STIER, J.C. (2000) UWEX Publication A3434: Lawn Establishment and Renovation,. Retrieved May 7, 2008, from http://www.uwex.edu/ces/pubs.

TURYK, N., FOSTER, K., HOVERSON, D. & MCGINLEY, P. (2008) Watershed Assessment of Shawano Lake, Shawano County, Wisconsin. , Center for Watershed Science and Education. University of Wisconsin-Stevens Point.

UNIVERISTY OF WISCONSIN-EXTENSION & WISCONSIN DEPARTMENT OF NATURAL RESOURCES (2002) UWEX Publication GWQ034: Rain Gardens, a Household Way to Improve Water Quality in Your Community. Retrieved May 7, 2008, from http://learningstore.uwex.edu/pdf/GWQ038.pdf.

UNIVERSITY OF COLORADO (2002) Saturated Hydraulic Conductivity. Retrieved March 14 2008, 2008, from http://instaar.colorado.edu/deltaforce/models/hydrotrend/ko_table.html.

USEPA (2005) National Management Measures to Control Nonpoint Source Pollution from Urban Areas, Epa-841-B-05-004. US Environmental Protection Agency, Office of Water. Washington, DC.

USEPA (2007) Using Tradable Credits to Control Excess Stormwater Runoff, Shepherd Creek, Cincinnati, Oh. US Environmental Protection Agency, Office of Research and Development. Washington, DC.

USGS (2007) March 2007. Source Loading and Management Model. *Rain Files*. Retrieved April 24, 2008, from http://wi.water.usgs.gov/slamm/slamm_web_doc_07.htm.

WAGNER, C., HAACK, J. & KORTH, R. (2003) UWEX Publication GWQ038: Protecting and Restoring Shorelands. *The Shoreland Stewardship Series*. Retrieved May 7, 2008, from http://learningstore.uwex.edu/pdf/GWQ038.pdf.

WASCHBUSCH, R., SELBIG, W. & BANNERMAN, R. (1999) Sources of Phosphorus in Stormwater and Street Dirt from Two Urban Residential Basins in Madison, Wisconsin, 1994-1995. Water Resources Investigations Report 99-4021. US Geological Survey. Middleton, WI.

WATSCHKE, T. & MUMMA, R. (1989) The Effect of Nutrients and Pesticides Applied to Turf on the Quality of Runoff and Percolation Water, Environmental Resources Research Institute, Pennsylvania State University. University Park, PA.

WILSON, D. & KORB, G. (1999) UWEX Publication GWQ014: Shoreline Plants and Landscaping. Retrieved May 7, 2008, from http://clean-water.uwex.edu/pubs/pdf/home.shorlpl.pdf.

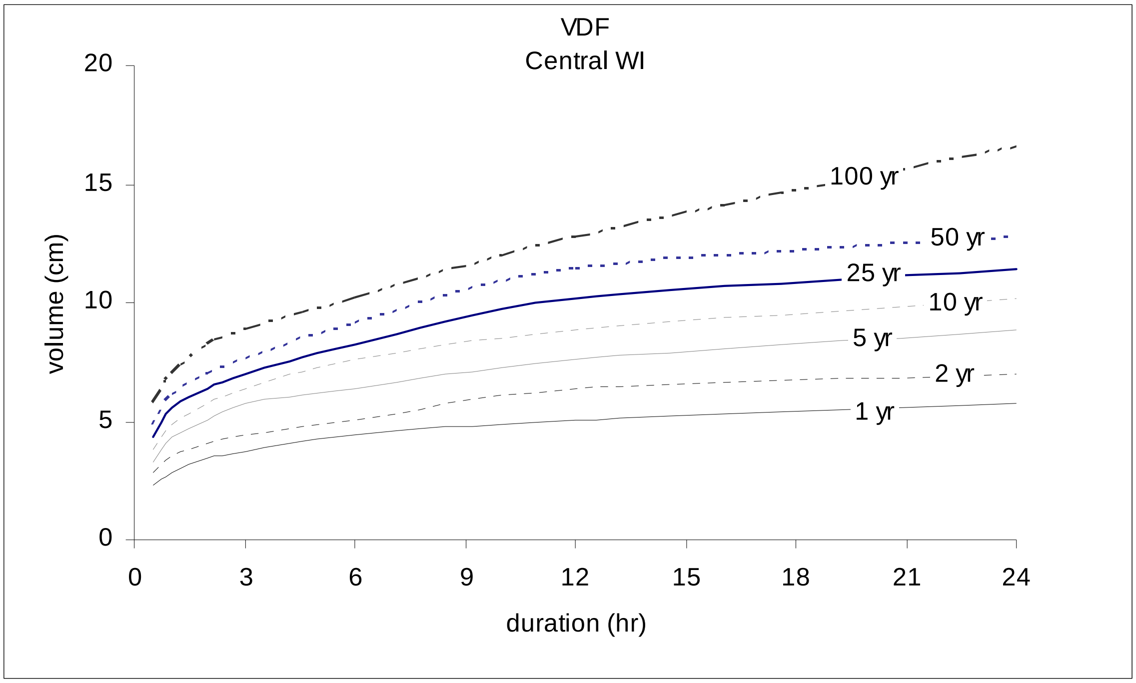
WISCONSIN ADMINISTRATIVE CODE Chapters NR 115 and 151.

WISCONSIN DEPARTMENT OF NATURAL RESOURCES (1996) The Northern Lakes and Shorelands Study.

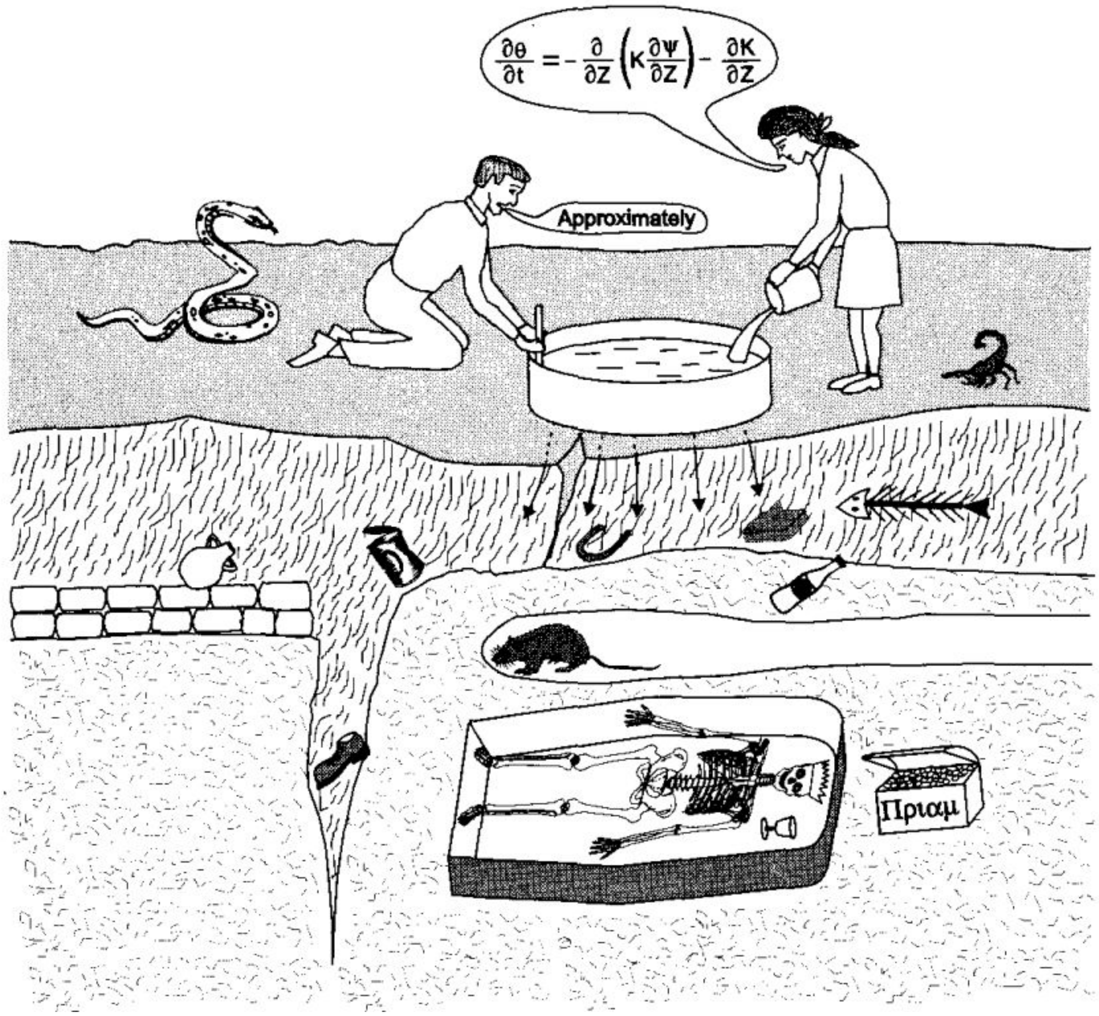
APPENDIX A Site Descriptions

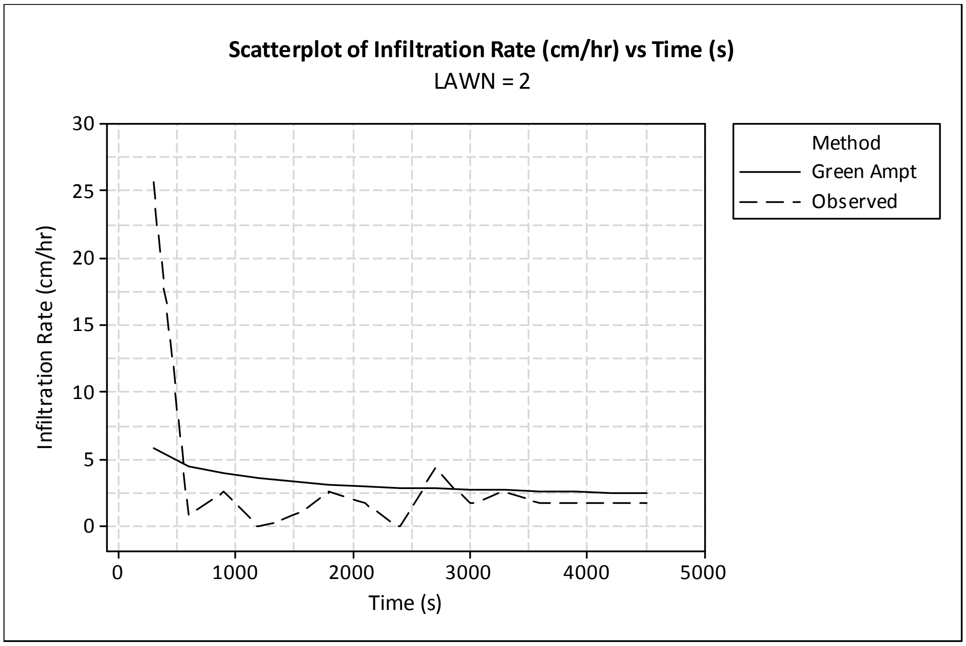
lawn	site	% Slope	Observed Soil Bulk Density (g/cm3)	Probable Soil Bulk Density (g/cm3)	Soil Textural Class	% Sand	% Clay	% Silt	Grass Density
	a	eliminated							
1	**b**	eliminated							
	c	eliminated							
	a	6.13	1.34	1.34	sandy loam	41.3	2.5	56.2	thick
2	b	7.25	1.34	1.34	loamy sand	78.5	0.3	21.2	thick
	c	3.17	1.34	1.34	loamy sand	85.0	2.8	12.2	thick
	a	10.25	0.76	1.29	sandy loam	48.0	4.6	47.4	medium
3	b	9.12	1.29	1.29	sandy loam	50.3	3.1	46.6	medium
	c	10.00	0.77	1.29	sandy loam	53.2	4.2	42.6	medium
	a	2.87	1.71	1.18	sandy loam	55.7	2.5	41.8	medium
4	b	5.00	0.98	1.18	loamy sand	74.6	1.2	24.1	medium
	c	4.63	0.97	1.18	loamy sand	74.6	1.2	24.1	medium
	a	3.25	1.49	1.16	loamy sand	77.5	3.7	18.7	thick
5	b	2.88	0.83	1.16	loamy sand	81.3	3.1	15.6	thick
	c	2.63	1.50	1.16	loamy sand	76.2	3.5	20.2	thick
	a	eliminated							
7	b	6.83	1.18	1.18	sandy loam	56.3	3.1	40.6	sparse
	c	eliminated							
	a	3.75	1.09	1.34	sandy loam	70.0	3.7	26.2	thick
8	b	eliminated							
	c	eliminated							
	a	8.13	0.69	1.24	loamy sand	82.6	5.0	12.5	sparse
9	b	9.38	0.77	1.24	sandy loam	64.1	3.1	32.8	sparse
	c	10.63	1.24	1.24	sandy loam	70.0	3.3	26.7	sparse
	a	eliminated							
10	b	eliminated							
	c	eliminated							

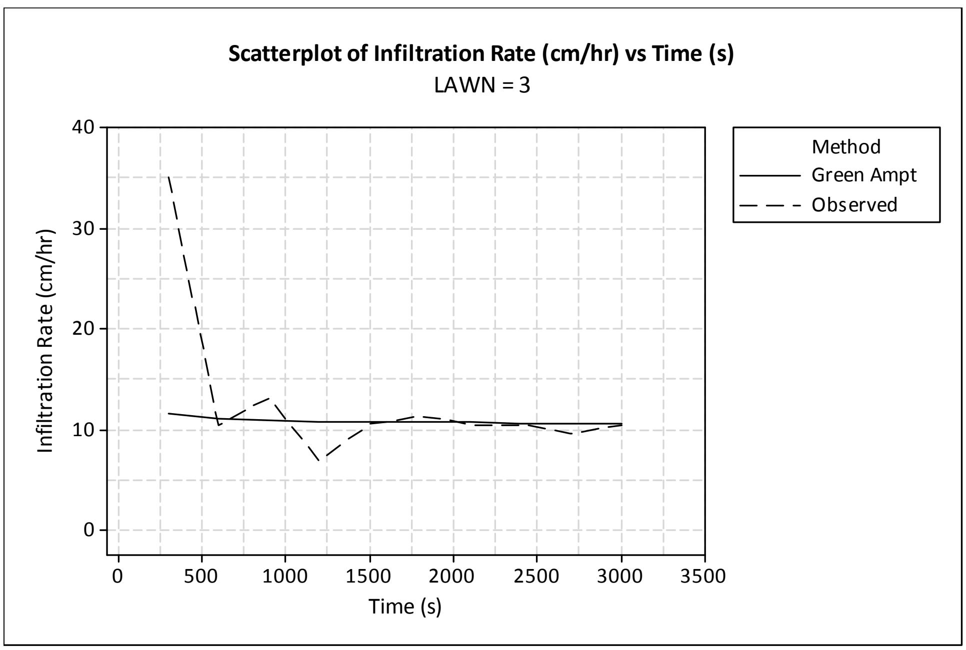
APPENDIX B VDF Curves

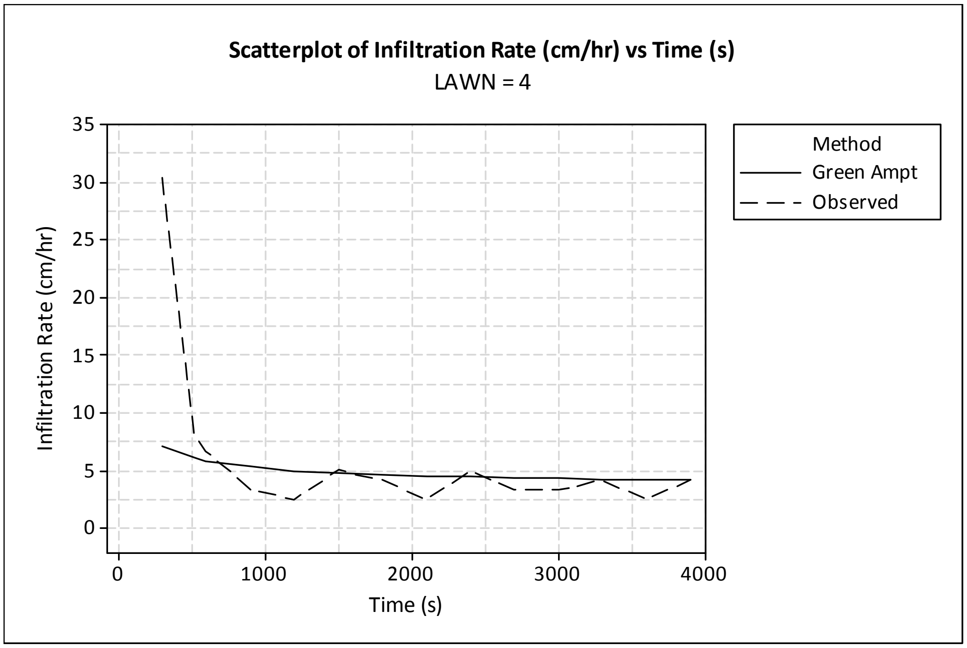


APPENDIX C Double-Ring Infiltrometer Data

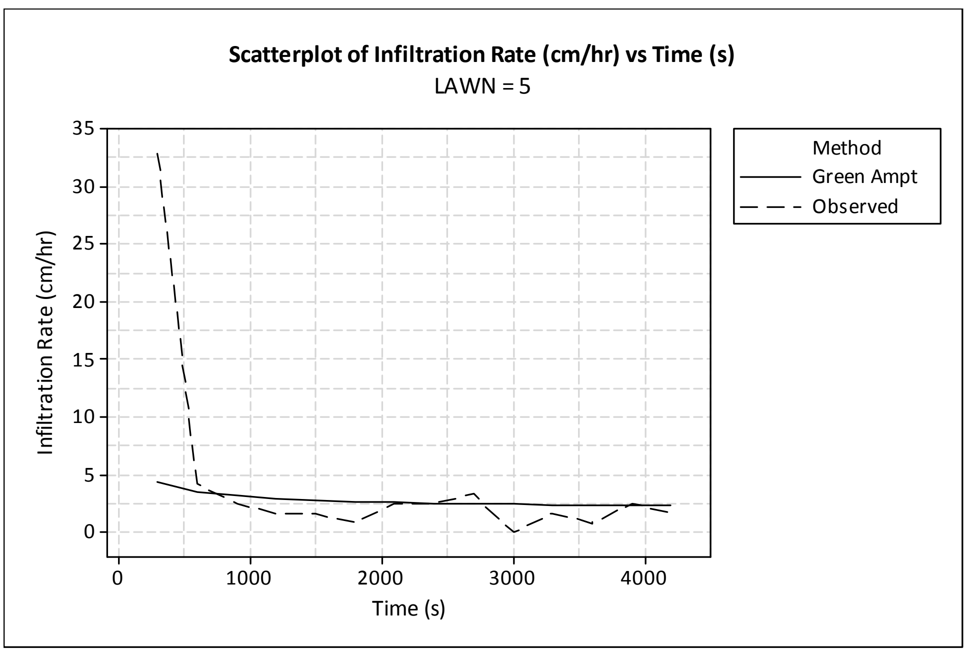



Scatterplot of Infiltration Rate (cm/hr) vs Time (s)
LAWN = 2
Infiltration Rate (cm/hr)
30
25
20
15
10
5
0
0
1000
2000
3000
4000
5000
Time (s)
Method
Green Ampt
Observed

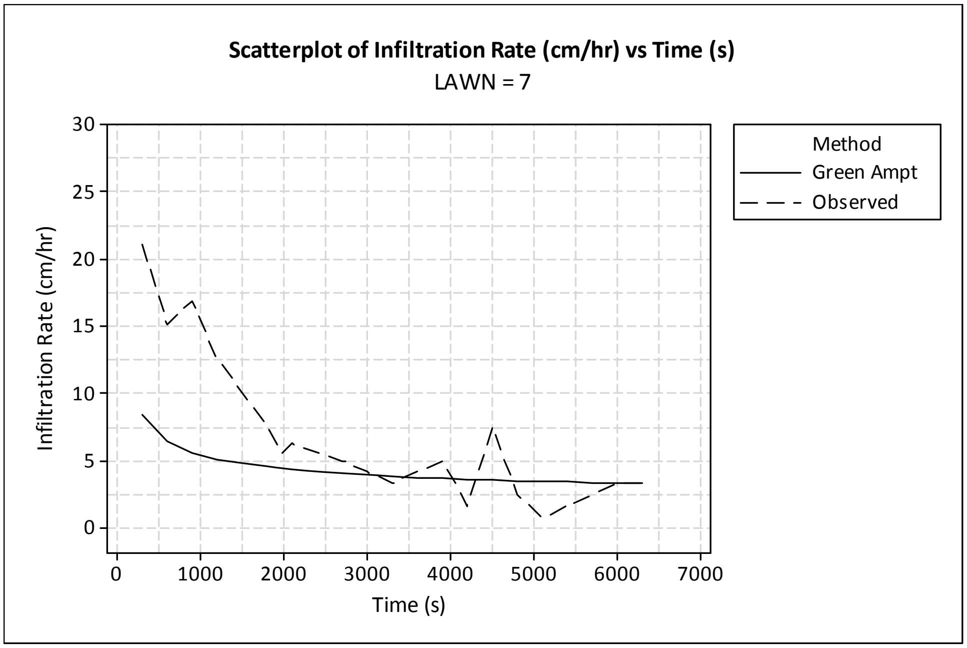

Scatterplot of Infiltration Rate (cm/hr) vs Time (s)
LAWN = 3
Infiltration Rate (cm/hr)
40
30
20
10
0
0
500
1000
1500
2000
2500
3000
3500
Time (s)
Method
Green Ampt
Observed



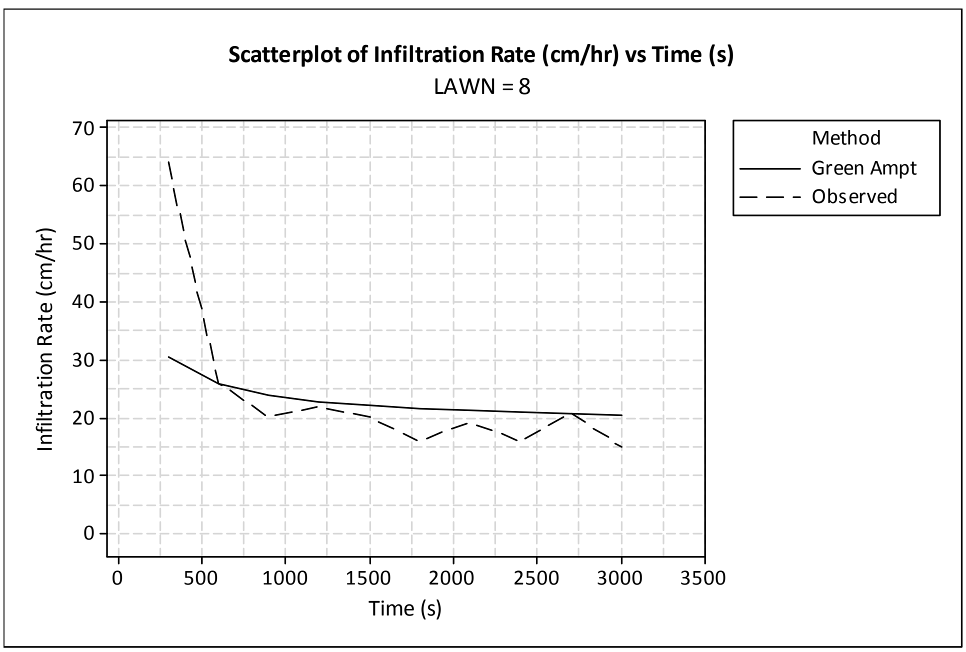
Scatterplot of Infiltration Rate (cm/hr) vs Time (s)
LAWN = 4
Infiltration Rate (cm/hr)
35
30
25
20
15
10
5
0
0
1000
2000
3000
4000
Time (s)
Method
Green Ampt
Observed



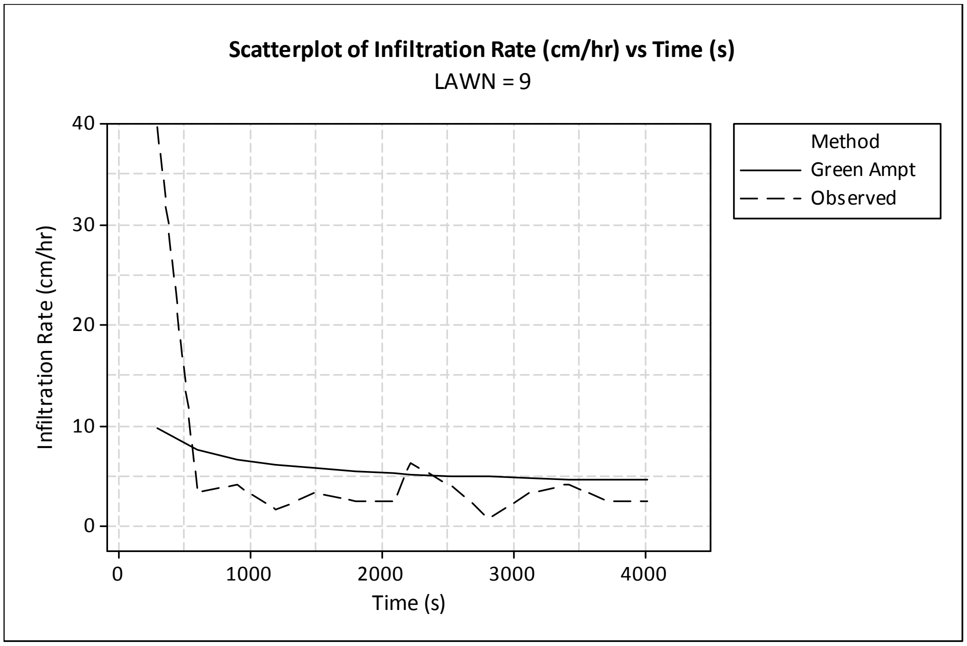
Scatterplot of Infiltration Rate (cm/hr) vs Time (s)
LAWN = 5
Infiltration Rate (cm/hr)
35
30
25
20
15
10
5
0
0
1000
2000
3000
4000
Time (s)
Method
Green Ampt
Observed



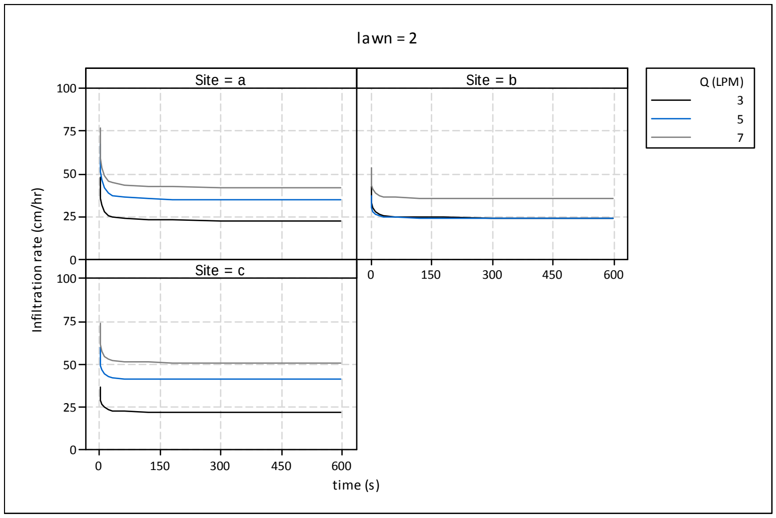
Scatterplot of Infiltration Rate (cm/hr) vs Time (s)
LAWN = 7
Infiltration Rate (cm/hr)
30
25
20
15
10
5
0
0
1000
2000
3000
4000
5000
6000
7000
Time (s)
Method
Green Ampt
Observed

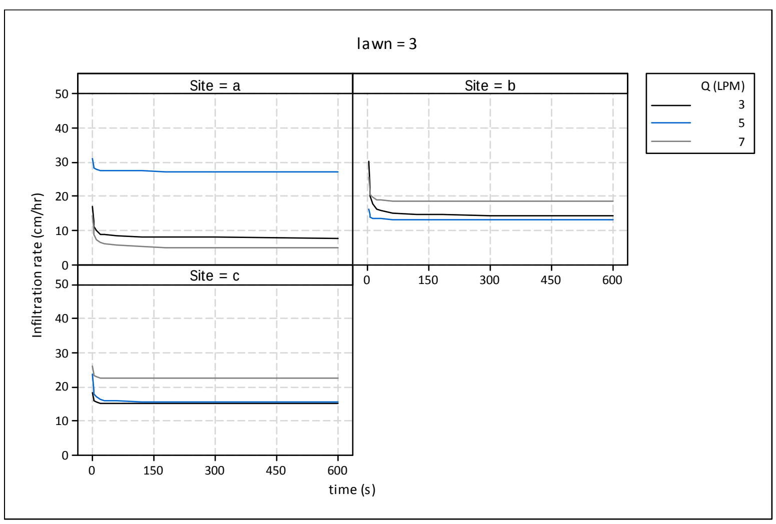


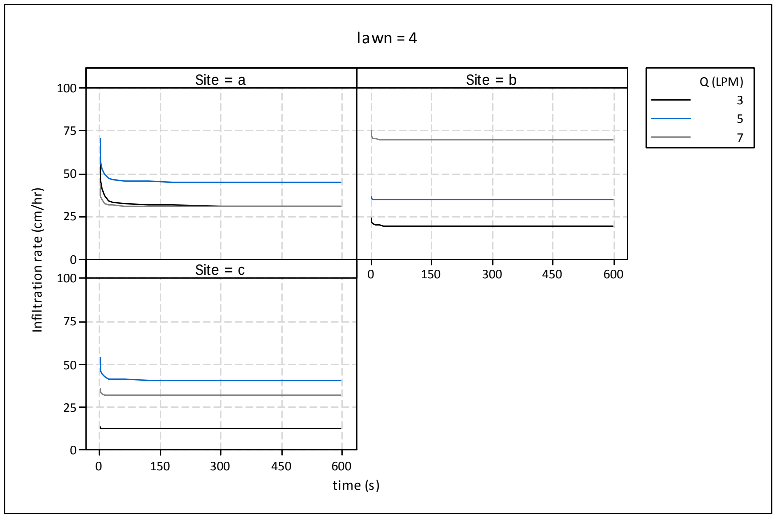
Scatterplot of Infiltration Rate (cm/hr) vs Time (s)
LAWN = 8
Infiltration Rate (cm/hr)
70
60
50
40
30
20
10
0
0
500
1000
1500
2000
2500
3000
3500
Time (s)
Method
Green Ampt
Observed

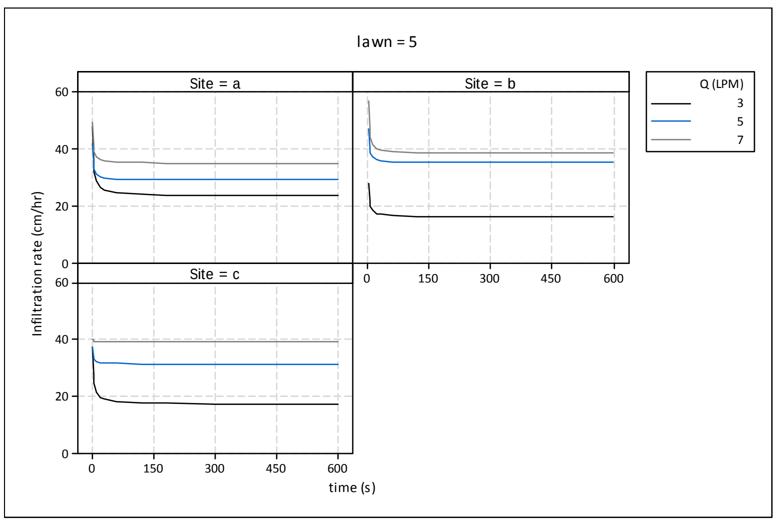

Scatterplot of Infiltration Rate (cm/hr) vs Time (s)
LAWN = 9
Infiltration Rate (cm/hr)
40
30
20
10
0
0
1000
2000
3000
4000
Time (s)
Method
Green Ampt
Observed

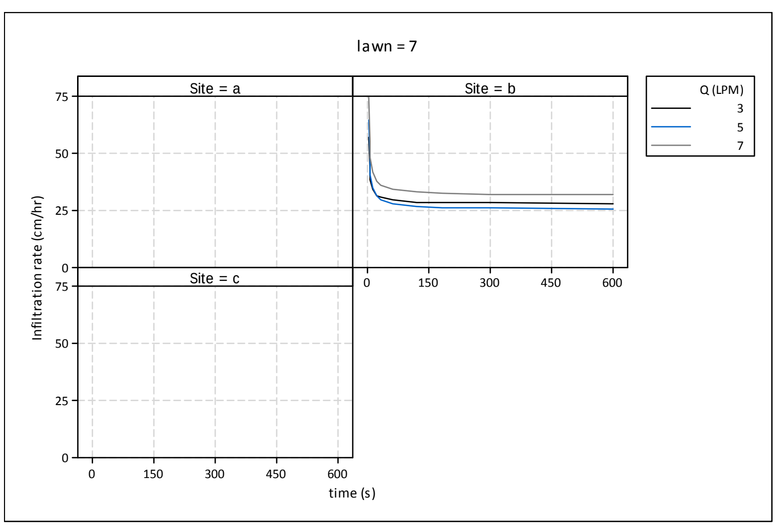
APPENDIX D Infiltration Capacity Curves

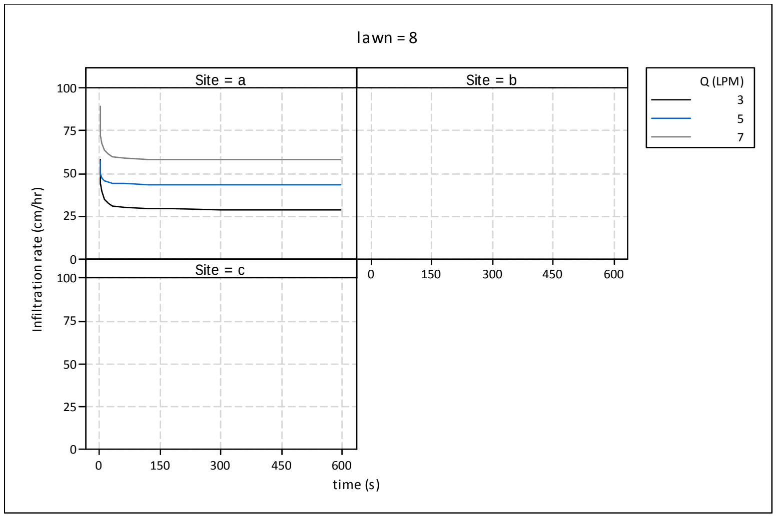


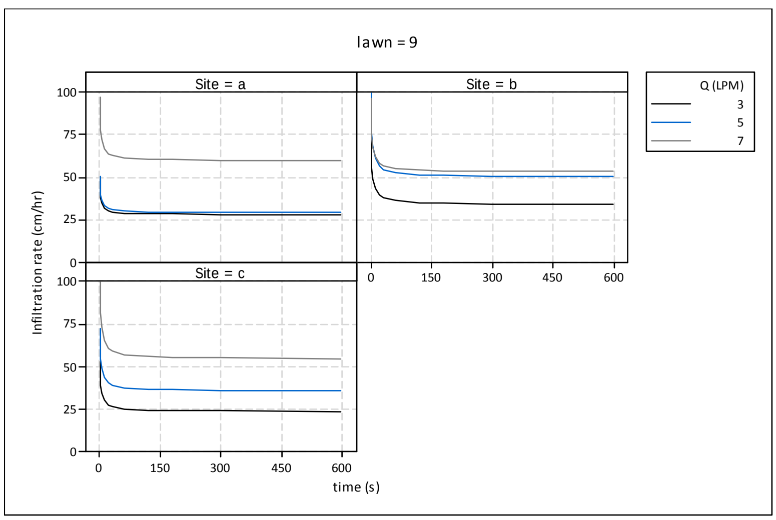



lawn = 4
Site = a
Site = b
Site = c
Q (LPM)
3
5
7
Infiltration rate (cm/hr)
100
75
50
25
0
0
150
300
450
600
time (s)


lawn = 5
Site = a
Site = b
Site = c
Q (LPM)
3
5
7
Infiltration rate (cm/hr)
60
40
20
0
0
150
300
450
600
time (s)


lawn = 7
Site = a
Site = b
Site = c
Q (LPM)
3
5
7
Infiltration rate (cm/hr)
75
50
25
0
0
150
300
450
600
time (s)


lawn = 8
Site = a
Site = b
Site = c
Q (LPM)
3
5
7
Infiltration rate (cm/hr)
time (s)


lawn = 9
Site = a
Site = b
Site = c
Q (LPM)
3
5
7
Infiltration rate (cm/hr)
time (s)

APPENDIX E Overland Flow Data

Lawn 2, Site A

Runon Application (L/min)	**Distance x (m)**	**Time (sec)**	**Velocity at Distance, V_x (m/s)**	**ΔV, V_0-V_x (m/s)**	**Acceleration, ΔV/Δt (m/s^2)**	**Continuous Slope**
3	0.3	22	0.014	-0.162	-0.007	0.050
	0.6	42	0.015	-0.161	-0.004	0.050
	0.9	58	0.016	-0.160	-0.003	0.057
	1.2	107	0.011	-0.164	-0.002	0.053
	1.5	132	0.012	-0.164	-0.001	0.052
	1.8	193	0.009	-0.166	-0.001	0.052
	2.1	239	0.009	-0.166	-0.001	0.057
	2.4	266	0.009	-0.166	-0.001	0.061
5	0.3	8	0.038	-0.254	-0.032	0.050
	0.6	18	0.034	-0.259	-0.014	0.050
	0.9	31	0.029	-0.263	-0.008	0.057
	1.2	56	0.022	-0.271	-0.005	0.053
	1.5	73	0.021	-0.271	-0.004	0.052
	1.8	106	0.017	-0.275	-0.003	0.052
	2.1	137	0.016	-0.277	-0.002	0.057
	2.4	151	0.016	-0.276	-0.002	0.061
7	0.3	6	0.051	-0.359	-0.060	0.050
	0.6	24	0.025	-0.384	-0.016	0.050
	0.9	37	0.025	-0.385	-0.010	0.057
	1.2	54	0.023	-0.387	-0.007	0.053
	1.5	69	0.022	-0.387	-0.006	0.052
	1.8	89	0.021	-0.389	-0.004	0.052
	2.1	105	0.020	-0.389	-0.004	0.057
	2.4	123	0.020	-0.389	-0.003	0.061

Lawn 2, Site B

Runon Application (L/min)	Distance x (m)	Time (sec)	Velocity at Distance, V_x (m/s)	ΔV, V_0-V_x (m/s)	Acceleration, ΔV/Δt (m/s^2)	Continuous Slope
3	0.3	23	0.013	-0.162	-0.007	0.070
	0.6	54	0.011	-0.164	-0.003	0.060
	0.9	103	0.009	-0.167	-0.002	0.067
	1.2	152	0.008	-0.167	-0.001	0.063
	1.5	190	0.008	-0.167	-0.001	0.064
	1.8	252	0.007	-0.168	-0.001	0.063
	2.1	288	0.007	-0.168	-0.001	0.061
	2.4	354	0.007	-0.169	0.000	0.061
5	0.3	11	0.028	-0.265	-0.024	0.070
	0.6	23	0.027	-0.266	-0.012	0.060
	0.9	42	0.022	-0.271	-0.006	0.067
	1.2	60	0.020	-0.272	-0.005	0.063
	1.5	76	0.020	-0.272	-0.004	0.064
	1.8	91	0.020	-0.272	-0.003	0.063
	2.1	104	0.021	-0.272	-0.003	0.061
	2.4	133	0.018	-0.274	-0.002	0.061
7	0.3	14	0.022	-0.388	-0.028	0.070
	0.6	25	0.024	-0.385	-0.015	0.060
	0.9	48	0.019	-0.390	-0.008	0.067
	1.2	60	0.020	-0.389	-0.006	0.063
	1.5	84	0.018	-0.391	-0.005	0.064
	1.8	100	0.018	-0.391	-0.004	0.063
	2.1	121	0.018	-0.392	-0.003	0.061
	2.4	133	0.018	-0.391	-0.003	0.061

Lawn 2, Site C

Runon Application (L/min)	Distance x (m)	Time (sec)	Velocity at Distance, V_x (m/s)	ΔV, V_0-V_x (m/s)	Acceleration, ΔV/Δt (m/s^2)	Continuous Slope
3	0.3	19	0.016	-0.159	-0.008	0.030
	0.6	50	0.012	-0.163	-0.003	0.040
	0.9	92	0.010	-0.165	-0.002	0.037
	1.2	132	0.009	-0.166	-0.001	0.035
	1.5	180	0.008	-0.167	-0.001	0.030
	1.8	226	0.008	-0.167	-0.001	0.027
	2.1	267	0.008	-0.167	-0.001	0.030
	2.4	327	0.007	-0.168	-0.001	0.033
5	0.3	12	0.025	-0.267	-0.022	0.030
	0.6	34	0.018	-0.274	-0.008	0.040
	0.9	58	0.016	-0.277	-0.005	0.037
	1.2	80	0.015	-0.277	-0.003	0.035
	1.5	126	0.012	-0.280	-0.002	0.030
	1.8	155	0.012	-0.281	-0.002	0.027
	2.1	194	0.011	-0.281	-0.001	0.030
7	0.3	5	0.061	-0.348	-0.070	0.030
	0.6	21	0.029	-0.380	-0.018	0.040
	0.9	45	0.020	-0.389	-0.009	0.037
	1.2	63	0.019	-0.390	-0.006	0.035
	1.5	81	0.019	-0.391	-0.005	0.030
	1.8	110	0.017	-0.393	-0.004	0.027
	2.1	134	0.016	-0.393	-0.003	0.030
	2.4	171	0.014	-0.395	-0.002	0.033

Lawn 3, Site A

Runon Application (L/min)	Distance x (m)	Time (sec)	Velocity at Distance, V_x (m/s)	ΔV, V_0-V_x (m/s)	Acceleration, ΔV/Δt (m/s^2)	Continuous Slope
3	0.3	8	0.038	-0.137	-0.017	0.100
	0.6	19	0.032	-0.143	-0.008	0.110
	0.9	32	0.029	-0.147	-0.005	0.113
	1.2	44	0.028	-0.148	-0.003	0.113
	1.5	58	0.026	-0.149	-0.003	0.104
	1.8	74	0.025	-0.151	-0.002	0.098
	2.1	95	0.022	-0.153	-0.002	0.100
	2.4	117	0.021	-0.155	-0.001	0.103
5	0.3	7	0.044	-0.249	-0.036	0.100
	0.6	18	0.034	-0.259	-0.014	0.110
	0.9	34	0.027	-0.265	-0.008	0.113
	1.2	46	0.027	-0.266	-0.006	0.113
	1.5	68	0.022	-0.270	-0.004	0.104
	1.8	90	0.020	-0.272	-0.003	0.098
	2.1	108	0.020	-0.273	-0.003	0.100
	2.4	142	0.017	-0.275	-0.002	0.103
7	0.3	4	0.076	-0.333	-0.083	0.100
	0.6	10	0.061	-0.348	-0.035	0.110
	0.9	18	0.051	-0.359	-0.020	0.113
	1.2	25	0.049	-0.361	-0.014	0.113
	1.5	34	0.045	-0.365	-0.011	0.104
	1.8	42	0.044	-0.366	-0.009	0.098
	2.1	47	0.045	-0.364	-0.008	0.100
	2.4	63	0.039	-0.371	-0.006	0.103

Lawn 3, Site B

Runon Application (L/min)	Distance x (m)	Time (sec)	Velocity at Distance, V_x (m/s)	ΔV, V_0-V_x (m/s)	Acceleration, ΔV/Δt (m/s^2)	Continuous Slope
3	0.3	6	0.051	-0.125	-0.021	0.070
	0.6	14	0.044	-0.132	-0.009	0.080
	0.9	21	0.044	-0.132	-0.006	0.087
	1.2	31	0.039	-0.136	-0.004	0.092
	1.5	41	0.037	-0.138	-0.003	0.096
	1.8	54	0.034	-0.142	-0.003	0.097
	2.1	66	0.032	-0.143	-0.002	0.097
	2.4	86	0.028	-0.147	-0.002	0.091
5	0.3	6	0.051	-0.242	-0.040	0.070
	0.6	13	0.047	-0.245	-0.019	0.080
	0.9	25	0.037	-0.256	-0.010	0.087
	1.2	36	0.034	-0.259	-0.007	0.092
	1.5	47	0.032	-0.260	-0.006	0.096
	1.8	57	0.032	-0.260	-0.005	0.097
	2.1	71	0.030	-0.262	-0.004	0.097
	2.4	89	0.027	-0.265	-0.003	0.091
7	0.3	3	0.102	-0.308	-0.103	0.070
	0.6	7	0.087	-0.322	-0.046	0.080
	0.9	14	0.065	-0.344	-0.025	0.087
	1.2	20	0.061	-0.348	-0.017	0.093
	1.5	27	0.056	-0.353	-0.013	0.096
	1.8	35	0.052	-0.357	-0.010	0.097
	2.1	46	0.046	-0.363	-0.008	0.097
	2.4	60	0.041	-0.369	-0.006	0.091

Lawn 3, Site C

Runon Application (L/min)	Distance x (m)	Time (sec)	Velocity at Distance, V_x (m/s)	ΔV, V_0-V_x (m/s)	Acceleration, ΔV/Δt (m/s^2)	Continuous Slope
3	0.3	4	0.076	-0.099	-0.025	0.130
	0.6	16	0.038	-0.137	-0.009	0.085
	0.9	36	0.025	-0.150	-0.004	0.093
	1.2	58	0.021	-0.154	-0.003	0.105
	1.5	85	0.018	-0.157	-0.002	0.100
	1.8	111	0.016	-0.159	-0.001	0.098
	2.1	138	0.015	-0.160	-0.001	0.101
	2.4	165	0.015	-0.161	-0.001	0.100
5	0.3	8	0.038	-0.254	-0.032	0.130
	0.6	15	0.041	-0.252	-0.017	0.085
	0.9	24	0.038	-0.254	-0.011	0.093
	1.2	35	0.035	-0.258	-0.007	0.105
	1.5	45	0.034	-0.259	-0.006	0.100
	1.8	58	0.032	-0.261	-0.004	0.098
	2.1	71	0.030	-0.262	-0.004	0.101
	2.4	86	0.028	-0.264	-0.003	0.100
7	0.3	5	0.061	-0.348	-0.070	0.130
	0.6	10	0.061	-0.348	-0.035	0.085
	0.9	17	0.054	-0.356	-0.021	0.093
	1.2	24	0.051	-0.359	-0.015	0.105
	1.5	34	0.045	-0.365	-0.011	0.100
	1.8	43	0.043	-0.367	-0.009	0.098
	2.1	52	0.041	-0.368	-0.007	0.101
	2.4	62	0.039	-0.370	-0.006	0.100

Lawn 4, Site A

Runon Application (L/min)	Distance x (m)	Time (sec)	Velocity at Distance, V_x (m/s)	ΔV, V_0-V_x (m/s)	Acceleration, ΔV/Δt (m/s^2)	Continuous Slope
3	0.3	17	0.018	-0.157	-0.009	0.050
	0.6	47	0.013	-0.162	-0.003	0.030
	0.9	73	0.013	-0.163	-0.002	0.037
	1.2	117	0.010	-0.165	-0.001	0.030
	1.5	155	0.010	-0.166	-0.001	0.030
	1.8	198	0.009	-0.166	-0.001	0.032
	2.1	301	0.007	-0.168	-0.001	0.030
	2.4	525	0.005	-0.171	0.000	0.029
5	0.3	10	0.030	-0.262	-0.026	0.050
	0.6	31	0.020	-0.273	-0.009	0.030
	0.9	58	0.016	-0.277	-0.005	0.037
	1.2	97	0.013	-0.280	-0.003	0.030
	1.5	118	0.013	-0.279	-0.002	0.030
	1.8	151	0.012	-0.280	-0.002	0.032
	2.1	179	0.012	-0.280	-0.002	0.030
	2.4	219	0.011	-0.281	-0.001	0.029
7	0.3	3	0.102	-0.308	-0.103	0.050
	0.6	14	0.044	-0.366	-0.026	0.030
	0.9	26	0.035	-0.374	-0.014	0.037
	1.2	42	0.029	-0.380	-0.009	0.030
	1.5	53	0.029	-0.381	-0.007	0.030
	1.8	67	0.027	-0.382	-0.006	0.032
	2.1	77	0.028	-0.382	-0.005	0.030
	2.4	88	0.028	-0.382	-0.004	0.029

Lawn 4, Site B

Runon Application (L/min)	Distance x (m)	Time (sec)	Velocity at Distance, V_x (m/s)	ΔV, V_0-V_x (m/s)	Acceleration, ΔV/Δt (m/s^2)	Continuous Slope
3	0.3	14	0.022	-0.154	-0.011	0.010
	0.6	23	0.027	-0.149	-0.006	0.060
	0.9	38	0.024	-0.151	-0.004	0.057
	1.2	62	0.020	-0.156	-0.003	0.060
	1.5	103	0.015	-0.161	-0.002	0.056
	1.8	127	0.014	-0.161	-0.001	0.058
	2.1	161	0.013	-0.162	-0.001	0.054
	2.4	203	0.012	-0.163	-0.001	0.050
5	0.3	6	0.051	-0.242	-0.040	0.010
	0.6	13	0.047	-0.245	-0.019	0.060
	0.9	22	0.042	-0.251	-0.011	0.057
	1.2	43	0.028	-0.264	-0.006	0.060
	1.5	72	0.021	-0.271	-0.004	0.056
	1.8	94	0.019	-0.273	-0.003	0.058
	2.1	121	0.018	-0.275	-0.002	0.054
	2.4	176	0.014	-0.279	-0.002	0.050
7	0.3	6	0.051	-0.359	-0.060	0.010
	0.6	19	0.032	-0.377	-0.020	0.060
	0.9	45	0.020	-0.389	-0.009	0.057
	1.2	72	0.017	-0.392	-0.005	0.060
	1.5	94	0.016	-0.393	-0.004	0.056
	1.8	112	0.016	-0.393	-0.004	0.058
	2.1	154	0.014	-0.395	-0.003	0.054
	2.4	191	0.013	-0.397	-0.002	0.050

Lawn 4, Site C

Runon Application (L/min)	Distance x (m)	Time (sec)	Velocity at Distance, V_x (m/s)	ΔV, V_0-V_x (m/s)	Acceleration, ΔV/Δt (m/s^2)	Continuous Slope
3	0.3	7	0.044	-0.132	-0.019	0.030
	0.6	45	0.014	-0.162	-0.004	0.060
	0.9	76	0.012	-0.163	-0.002	0.055
	1.2	98	0.012	-0.163	-0.002	0.050
	1.5	112	0.014	-0.162	-0.001	0.044
	1.8	123	0.015	-0.161	-0.001	0.048
	2.1	131	0.016	-0.159	-0.001	0.052
	2.4	137	0.018	-0.158	-0.001	0.047
5	0.3	7	0.044	-0.249	-0.036	0.030
	0.6	24	0.025	-0.267	-0.011	0.050
	0.9	48	0.019	-0.273	-0.006	0.050
	1.2	77	0.016	-0.277	-0.004	0.048
	1.5	99	0.015	-0.277	-0.003	0.042
	1.8	121	0.015	-0.277	-0.002	0.047
	2.1	139	0.015	-0.277	-0.002	0.050
	2.4	157	0.016	-0.277	-0.002	0.046
7	0.3	6	0.051	-0.359	-0.060	0.030
	0.6	18	0.034	-0.375	-0.021	0.050
	0.9	33	0.028	-0.382	-0.012	0.050
	1.2	49	0.025	-0.384	-0.008	0.048
	1.5	64	0.024	-0.386	-0.006	0.042
	1.8	74	0.025	-0.385	-0.005	0.047
	2.1	84	0.025	-0.384	-0.005	0.050
	2.4	95	0.026	-0.384	-0.004	0.046

Lawn 5, Site A

Runon Application (L/min)	Distance x (m)	Time (sec)	Velocity at Distance, V_x (m/s)	ΔV, V_0-V_x (m/s)	Acceleration, ΔV/Δt (m/s^2)	Continuous Slope
3	0.3	6	0.051	-0.125	-0.021	0.050
	0.6	16	0.038	-0.137	-0.009	0.035
	0.9	37	0.025	-0.151	-0.004	0.047
	1.2	60	0.020	-0.155	-0.003	0.038
	1.5	86	0.018	-0.158	-0.002	0.030
	1.8	119	0.015	-0.160	-0.001	0.032
	2.1	152	0.014	-0.161	-0.001	0.031
	2.4	175	0.014	-0.161	-0.001	0.033
5	0.3	7	0.044	-0.249	-0.036	0.050
	0.6	14	0.044	-0.249	-0.018	0.035
	0.9	22	0.042	-0.251	-0.011	0.047
	1.2	32	0.038	-0.254	-0.008	0.038
	1.5	44	0.035	-0.258	-0.006	0.030
	1.8	56	0.033	-0.260	-0.005	0.032
	2.1	74	0.029	-0.264	-0.004	0.031
	2.4	85	0.029	-0.264	-0.003	0.033
7	0.3	8	0.038	-0.371	-0.046	0.050
	0.6	15	0.041	-0.369	-0.025	0.035
	0.9	25	0.037	-0.373	-0.015	0.047
	1.2	34	0.036	-0.373	-0.011	0.038
	1.5	42	0.036	-0.373	-0.009	0.030
	1.8	53	0.035	-0.375	-0.007	0.032
	2.1	57	0.037	-0.372	-0.007	0.031
	2.3	73	0.031	-0.378	-0.005	0.033

Lawn 5, Site B

Runon Application (L/min)	Distance x (m)	Time (sec)	Velocity at Distance, V_x (m/s)	ΔV, V_0-V_x (m/s)	Acceleration, ΔV/Δt (m/s^2)	Continuous Slope
3	0.3	10	0.030	-0.145	-0.014	0.050
	0.6	23	0.027	-0.149	-0.006	0.050
	0.9	32	0.029	-0.147	-0.005	0.053
	1.2	43	0.028	-0.147	-0.003	0.045
	1.5	57	0.027	-0.149	-0.003	0.038
	1.8	81	0.023	-0.153	-0.002	0.032
	2.1	102	0.021	-0.155	-0.002	0.030
	2.4	135	0.018	-0.157	-0.001	0.029
5	0.3	12	0.025	-0.267	-0.022	0.050
	0.6	24	0.025	-0.267	-0.011	0.050
	0.9	42	0.022	-0.271	-0.006	0.053
	1.2	61	0.020	-0.272	-0.004	0.045
	1.5	90	0.017	-0.275	-0.003	0.038
	1.8	110	0.017	-0.276	-0.003	0.032
	2.1	152	0.014	-0.278	-0.002	0.030
	2.3	170	0.013	-0.279	-0.002	0.029
7	0.3	5	0.061	-0.348	-0.070	0.050
	0.6	17	0.036	-0.373	-0.022	0.050
	0.9	26	0.035	-0.374	-0.014	0.053
	1.2	36	0.034	-0.375	-0.010	0.045
	1.5	49	0.031	-0.378	-0.008	0.038
	1.8	62	0.029	-0.380	-0.006	0.032
	2.1	82	0.026	-0.383	-0.005	0.030
	2.4	101	0.024	-0.385	-0.004	0.029

Lawn 5, Site C

Runon Application (L/min)	Distance x (m)	Time (sec)	Velocity at Distance, V_x (m/s)	ΔV, V_0-V_x (m/s)	Acceleration, ΔV/Δt (m/s^2)	Continuous Slope
3	0.3	21	0.015	-0.161	-0.008	0.050
	0.6	37	0.016	-0.159	-0.004	0.030
	0.9	57	0.016	-0.159	-0.003	0.020
	1.2	75	0.016	-0.159	-0.002	0.030
	1.5	98	0.016	-0.160	-0.002	0.030
	1.8	114	0.016	-0.159	-0.001	0.030
	2.1	135	0.016	-0.160	-0.001	0.026
	2.4	177	0.014	-0.162	-0.001	0.026
5	0.3	9	0.034	-0.259	-0.029	0.050
	0.6	24	0.025	-0.267	-0.011	0.030
	0.9	34	0.027	-0.265	-0.008	0.020
	1.2	54	0.023	-0.270	-0.005	0.030
	1.5	69	0.022	-0.270	-0.004	0.030
	1.8	81	0.023	-0.270	-0.003	0.030
	2.1	96	0.022	-0.270	-0.003	0.026
	2.4	119	0.020	-0.272	-0.002	0.026
7	0.3	5	0.061	-0.348	-0.070	0.050
	0.6	12	0.051	-0.359	-0.030	0.030
	0.9	22	0.042	-0.368	-0.017	0.020
	1.2	33	0.037	-0.372	-0.011	0.030
	1.5	40	0.038	-0.371	-0.009	0.030
	1.8	48	0.038	-0.371	-0.008	0.030
	2.1	60	0.036	-0.374	-0.006	0.026
	2.4	73	0.033	-0.376	-0.005	0.026

Lawn 7, Site B

Runon Application (L/min)	Distance x (m)	Time (sec)	Velocity at Distance, V_x (m/s)	ΔV, V_0-V_x (m/s)	Acceleration, ΔV/Δt (m/s^2)	Continuous Slope
3	0.3	15	0.020	-0.155	-0.010	0.060
	0.6	43	0.014	-0.161	-0.004	0.065
	0.9	61	0.015	-0.160	-0.003	0.060
	1.2	93	0.013	-0.162	-0.002	0.068
	1.5	127	0.012	-0.163	-0.001	0.072
	1.8	148	0.012	-0.163	-0.001	0.073
	2.1	194	0.011	-0.164	-0.001	0.070
5	0.3	4	0.076	-0.216	-0.054	0.060
	0.6	9	0.068	-0.225	-0.025	0.065
	0.9	13	0.070	-0.222	-0.017	0.060
	1.2	20	0.061	-0.231	-0.012	0.068
	1.5	26	0.059	-0.234	-0.009	0.072
	1.8	34	0.054	-0.239	-0.007	0.073
	2.1	43	0.050	-0.243	-0.006	0.070
	2.4	51	0.048	-0.245	-0.005	0.068
7	0.3	4	0.076	-0.333	-0.083	0.060
	0.6	11	0.055	-0.354	-0.032	0.065
	0.9	17	0.054	-0.356	-0.021	0.060
	1.2	25	0.049	-0.361	-0.014	0.068
	1.5	33	0.046	-0.363	-0.011	0.072
	1.8	41	0.045	-0.365	-0.009	0.073
	2.1	48	0.044	-0.365	-0.008	0.070
	2.4	57	0.043	-0.367	-0.006	0.068

Lawn 8, Site A

Runon Application (L/min)	Distance x (m)	Time (sec)	Velocity at Distance, V_x (m/s)	ΔV, V_0-V_x (m/s)	Acceleration, ΔV/Δt (m/s^2)	Continuous Slope
3	0.3	12	0.025	-0.150	-0.013	0.060
	0.6	29	0.021	-0.154	-0.005	0.055
	0.9	95	0.010	-0.166	-0.002	0.043
	1.2	139	0.009	-0.167	-0.001	0.040
	1.5	220	0.007	-0.168	-0.001	0.038
	1.8	303	0.006	-0.169	-0.001	0.035
	2.1	434	0.005	-0.171	0.000	0.034
	2.4	644	0.004	-0.172	0.000	0.038
5	0.3	10	0.030	-0.262	-0.026	0.060
	0.6	35	0.017	-0.275	-0.008	0.055
	0.9	88	0.010	-0.282	-0.003	0.043
	1.2	129	0.009	-0.283	-0.002	0.040
	1.5	220	0.007	-0.285	-0.001	0.038
	1.8	260	0.007	-0.285	-0.001	0.035
	2.1	377	0.006	-0.287	-0.001	0.034
	2.4	523	0.005	-0.288	-0.001	0.038
7	0.3	3	0.102	-0.308	-0.103	0.060
	0.6	9	0.068	-0.342	-0.038	0.055
	0.9	33	0.028	-0.382	-0.012	0.043
	1.2	56	0.022	-0.388	-0.007	0.040
	1.5	87	0.018	-0.392	-0.005	0.038
	1.8	113	0.016	-0.393	-0.003	0.035
	2.1	155	0.014	-0.396	-0.003	0.034
	2.4	179	0.014	-0.396	-0.002	0.038

Lawn 9, Site A

Runon Application (L/min)	Distance x (m)	Time (sec)	Velocity at Distance, V_x (m/s)	ΔV, V_0-V_x (m/s)	Acceleration, ΔV/Δt (m/s^2)	Continuous Slope
3	0.3	20	0.015	-0.160	-0.008	0.080
	0.6	46	0.013	-0.162	-0.004	0.090
	0.9	78	0.012	-0.164	-0.002	0.083
	1.2	104	0.012	-0.164	-0.002	0.078
	1.5	133	0.011	-0.164	-0.001	0.082
	1.8	172	0.011	-0.165	-0.001	0.087
	2.1	202	0.011	-0.165	-0.001	0.080
	2.4	360	0.007	-0.169	0.000	0.081
5	0.3	4	0.076	-0.216	-0.054	0.080
	0.6	11	0.055	-0.237	-0.022	0.090
	0.9	19	0.048	-0.244	-0.013	0.083
	1.2	39	0.031	-0.261	-0.007	0.078
	1.5	84	0.018	-0.274	-0.003	0.082
	1.8	106	0.017	-0.275	-0.003	0.087
	2.1	132	0.016	-0.276	-0.002	0.080
	2.2	144	0.015	-0.277	-0.002	0.081
7	0.3	4	0.076	-0.333	-0.083	0.080
	0.6	12	0.051	-0.359	-0.030	0.090
	0.9	17	0.054	-0.356	-0.021	0.083
	1.2	26	0.047	-0.362	-0.014	0.078
	1.5	36	0.042	-0.367	-0.010	0.082
	1.8	42	0.044	-0.366	-0.009	0.087
	2.1	60	0.036	-0.374	-0.006	0.080
	2.4	77	0.032	-0.378	-0.005	0.081

Lawn 9, Site B

Runon Application (L/min)	Distance x (m)	Time (sec)	Velocity at Distance, V_x (m/s)	ΔV, V_0-V_x (m/s)	Acceleration, ΔV/Δt (m/s^2)	Continuous Slope
3	0.3	7	0.044	-0.132	-0.019	0.110
	0.6	13	0.047	-0.129	-0.010	0.090
	0.9	21	0.044	-0.132	-0.006	0.083
	1.2	38	0.032	-0.143	-0.004	0.090
	1.5	48	0.032	-0.144	-0.003	0.090
	1.8	61	0.030	-0.145	-0.002	0.098
	2.1	71	0.030	-0.145	-0.002	0.094
	2.4	85	0.029	-0.147	-0.002	0.094
5	0.3	8	0.038	-0.254	-0.032	0.110
	0.6	24	0.025	-0.267	-0.011	0.090
	0.9	37	0.025	-0.268	-0.007	0.083
	1.2	55	0.022	-0.270	-0.005	0.090
	1.5	69	0.022	-0.270	-0.004	0.090
	1.8	86	0.021	-0.271	-0.003	0.098
	2.1	111	0.019	-0.273	-0.002	0.094
	2.4	156	0.016	-0.277	-0.002	0.094
7	0.3	3	0.102	-0.308	-0.103	0.110
	0.6	8	0.076	-0.333	-0.042	0.090
	0.9	17	0.054	-0.356	-0.021	0.083
	1.2	37	0.033	-0.376	-0.010	0.090
	1.5	106	0.014	-0.395	-0.004	0.090
	1.8	120	0.015	-0.394	-0.003	0.098
	2.1	251	0.009	-0.401	-0.002	0.094
	2.4	349	0.007	-0.402	-0.001	0.094

Lawn 9, Site C

Runon Application (L/min)	Distance x (m)	Time (sec)	Velocity at Distance, V_x (m/s)	ΔV, V_0-V_x (m/s)	Acceleration, ΔV/Δt (m/s^2)	Continuous Slope
3	0.3	13	0.023	-0.152	-0.012	0.070
	0.6	32	0.019	-0.156	-0.005	0.095
	0.9	70	0.013	-0.162	-0.002	0.113
	1.2	103	0.012	-0.164	-0.002	0.123
	1.5	145	0.011	-0.165	-0.001	0.114
	1.8	203	0.009	-0.166	-0.001	0.112
	2.1	232	0.009	-0.166	-0.001	0.113
	2.4	264	0.009	-0.166	-0.001	0.106
5	0.3	8	0.038	-0.254	-0.032	0.070
	0.6	14	0.044	-0.249	-0.018	0.095
	0.9	24	0.038	-0.254	-0.011	0.113
	1.2	31	0.039	-0.253	-0.008	0.123
	1.5	39	0.039	-0.253	-0.006	0.114
	1.8	47	0.039	-0.253	-0.005	0.112
	2.1	56	0.038	-0.254	-0.005	0.113
	2.4	68	0.036	-0.257	-0.004	0.106
7	0.3	5	0.061	-0.348	-0.070	0.070
	0.6	15	0.041	-0.369	-0.025	0.095
	0.9	25	0.037	-0.373	-0.015	0.113
	1.2	35	0.035	-0.374	-0.011	0.123
	1.5	43	0.035	-0.374	-0.009	0.114
	1.8	56	0.033	-0.377	-0.007	0.112
	2.1	67	0.032	-0.377	-0.006	0.113
	2.4	75	0.033	-0.377	-0.005	0.106

APPENDIX F Delivered Runoff

date	lawn	site	Runon Q (L/min)	location
07/09/07	2	a	3	2A_3
07/30/07	2	a	5	2A_5
08/13/07	2	a	7	2A_7
07/31/07	2	b	3	2B_3
08/13/07	2	b	5	2B_5
07/09/07	2	b	7	2B_7
08/13/07	2	c	3	2C_3
07/09/07	2	c	5	2C_5
07/31/07	2	c	7	2C_7
07/30/07	3	a	3	3A_3
07/10/07	3	a	5	3A_5
09/22/07	3	a	7	3A_7
09/22/07	3	b	3	3B_3
08/16/07	3	b	5	3B_5
07/30/07	3	b	7	3B_7 (I)
07/10/07	3	b	7	3B_7 (II)
07/10/07	3	c	3	3C_3
07/30/07	3	c	5	3C_5
08/13/07	3	c	7	3C_7
07/31/07	4	a	3	4A_3
08/14/07	4	a	5	4A_5
07/10/07	4	a	7	4A_7
08/14/07	4	b	3	4B_3
08/16/07	4	b	5	4B_5
07/31/07	4	b	7	4B_7
08/16/07	4	c	3	4C_3

date	lawn	site	Runon Q (L/min)	location
07/31/07	4	c	5	4C_5
08/14/07	4	c	7	4C_7
08/15/07	5	a	3	5A_3
08/03/07	5	a	5	5A_5
07/11/07	5	a	7	5A_7
08/03/07	5	b	3	5B_3
07/11/07	5	b	5	5B_5
08/15/07	5	b	7	5B_7
07/11/07	5	c	3	5C_3
08/15/07	5	c	5	5C_5
08/03/07	5	c	7	5C_7
07/12/07	7	b	3	7B_3
08/01/07	7	b	5	7B_5
08/14/07	7	b	7	7B_7
08/14/07	8	a	3	8A_3
07/13/07	8	a	5	8A_5
08/02/07	8	a	7	8A_7
08/15/07	9	a	3	9A_3
07/13/07	9	a	5	9A_5
08/02/07	9	a	7	9A_7
08/02/07	9	b	3	9B_3
08/15/07	9	b	5	9B_5
07/13/07	9	b	7	9B_7
07/13/07	9	c	3	9C_3
08/02/07	9	c	5	9C_5
08/15/07	9	c	7	9C_7

APPENDIX G Hydrometer Analysis, Soil Particle Size Distribution

Lawn	Site	Replicate	% Sand	% Clay	% Silt
2	a	1	65.0	2.5	32.5
		2	77.6	2.5	19.9
		3	86.3	2.5	11.2
	b	1	57.5	2.5	40.0
		2	76.5	3.7	19.8
		3	85.1	2.5	12.4
	c	1	82.5	2.5	15.0
		3	87.5	3.1	9.4
3	a	1	51.2	5.0	43.8
		2	47.5	5.0	47.5
		3	37.9	3.7	58.4
		4	45.6	4.9	49.5
		5	45.0	6.3	48.8
	b	1	48.1	2.5	49.4
		2	52.5	3.8	43.8
		3	50.4	2.5	47.1
	c	1	56.0	2.5	41.5
		2	52.5	5.0	42.5
		3	42.3	5.0	52.7
		4	51.2	2.5	46.3
4	a	1	57.6	1.2	41.2
		2	53.8	3.7	42.5
	b/c	1	72.6	1.2	26.2
		2	77.5	1.3	21.3
		3	68.7	1.3	30.0

Lawn	Site	Replicate	% Sand	% Clay	% Silt
5	a	1	77.5	3.7	18.7
		2	77.6	2.5	19.9
		3	79.0	2.5	18.6
	b	1	80.0	2.5	17.5
		2	75.2	3.7	21.1
	c	1	76.3	2.5	21.2
		2	69.8	5.0	25.1
7	a	1	66.3	3.7	30.0
		2	53.7	5.0	41.3
	b	1	60.0	2.5	37.5
		2	52.5	3.8	43.8
	c	1	60.2	2.5	37.3
		2	55.1	3.7	41.2
8	a	1	67.5	3.8	28.8
		2	65.0	3.7	31.2
		3	67.3	3.8	28.9
9	a	1	72.5	3.8	23.8
		2	57.6	6.2	36.1
		3	72.5	2.5	25.0
		4	67.8	2.5	29.7
	b	1	67.3	2.5	30.1
		2	62.5	3.8	33.8
		3	62.5	3.1	34.4
	c	1	72.5	1.2	26.2
		2	62.5	3.8	33.8