Comparison of Compartmentalized Dynamic Model, HYDRUS, and Curve Number Methods for Estimating Drainage from Windrow Composting Pads

by

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(Under the direction of Ernest W. Tollner)

ABSTRACT

Design of containment facilities for runoff from windrow compost pads lacks suitable runoff prediction models for the unique surface consisting of gravel overlying compacted subsoil material. Models used were the curve number, a commercially available numerical computer model (HYDRUS®2-d), and a compartmental model developed on the Matlab-Simulink®platform based on rainfall-runoff data. The curve number model was based on infiltration, antecedent rainfall, and the percentage of pad coverage and led to a predicted vs. observed collection pond volume with a Percent Root Mean Squared Error (% RMSE) of 0.61 % compared to maximum pond volume. The prediction was relatively insensitive to deviation from the literature recommended value of 75. HYDRUS 2D applied vertical and lateral flow aspects to infiltration, storage, and subsurface transport, improving pond volume prediction with an %RMSE = 0.65 %. The Compartmental Model separately estimated outputs for infiltration, lateral seepage, and overland flow with an % RMSE = 0.76 %. Information from the compartment model can be used to develop an instantaneous unit hydrograph of compost pads and future applications for porous pavements.

Index words: Runoff Models, Compartmentalized Dynamic Model, Gravel Aggregate, Runoff Curve Number, Windrow Composting Pads, HYDRUS

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Chapter 1

INTRODUCTION

Open windrow compost pads are employed to allow organic waste to decompose in a controlled environment by placing the material in parallel piles on a sturdy surface that directs surface runoff parallel to the direction of the piles. The use of windrow compost pads has become increasingly popular due to their ability to allow organic material to decompose without affecting the surrounding environment. Compost material can typically contain organic matter including yard trimmings and animal waste. By placing the organic material in a controlled environment, organic waste is diverted from landfills while runoff that would normally be high in bio-solids is prevented from entering the watershed. An open windrow facility is exposed to atmospheric conditions such as extreme heat, extreme cold, and rainfall. During a storm the decomposing material comes in contact with the rainfall and may expose the rainfall to high concentrations of phosphorous, nitrogen, and bio-solids. This stormwater can potentially become runoff and is directed toward a containment pond to prevent water from entering the watershed. Runoff that occurs from open windrow composting can be affect surface-water quality but it has been reported that vegetative filter strip buffers can substantially reduce runoff and contaminants from the composting site (Webber et al., 2010). The surface of the compost pad is typically composed of a porous asphalt or gravel aggregate on top of a layer of compacted clay to provide a sturdy yet porous surface that can prevent a surplus of surface runoff. The porous surface acts as a filtration mechanism and helps to prevent a surplus of runoff.

Design restrictions on the compost pad and the containment pond (also referred to as collection pond) are instituted to regulate the rates of runoff and drainage from the pad along with preventing unwanted discharge. The curve number method is commonly used to estimate runoff from surfaces. With the different types of material along the vertical profile of the compost pad, discharge from the pad is most likely drainage rather than runoff causing estimation errors in the estimation of runoff using the curve number method. Current research on compost pads has shown a wide range of results for characterizing the storm water properties of the porous surface such as 44 based on the gravel base compostion by Wilson et al. (2004), 75 based on an effective curve number combining the gravel base and the windrow material by Kalaba et al. (2007), or a dynamic curve number with variations on effective rainfall or effective curve number by Tollner & Das (2004). This research presents a compartmentalized model, a two-dimensional HYDRUS model, and dynamic, asymptotic, and event based curve number approaches for predicting the amount of surface runoff, infiltration, and sub-surface seepage from windrow composting pads.

The test site is the compost pad at The University of Georgia Bioconversion Center in Athens, Georgia, with a crusher-run gravel aggregate surface. Previous research by Tollner & Das (2004) investigated using a Dynamic NRCS-CN approach to estimating runoff from the same site. Their collected data was evaluated using the dynamic Φ index and dynamic curve number that calculated runoff based on antecedent rainfall for 2, 7, and 14 days and the percentage of the compost pad covered with composting material and compared to the results of the storms collected during the time period of this current study. Tollner & Das (2004) found daily and monthly runoff was best modeled by the dynamic curve number equation with modified precipitation but tended to overpredict runoff at low precipitation values and required more data on the hydrophobic-hydrophilic transition of the windrows discussed in Kalaba et al. (2007). An uncovered windrow can release 15 to 20 % of rainwater as surface runoff, but accounting for experiments that have shown water leach from the toe of the pile after 48 hours or more, approximately 68 % of rainfall on saturated compost will end up as runoff (Kalaba et al., 2007).

The discrete time approach to curve number evaluations potentially obscures the analysis of flow dynamics that continuous time models can incorporate. The continuous time models featured in the current study assess computations at a shorter time increment during storm events that can provide a better understanding of the dominant water balance components such as direct runoff, infiltration, and storage.

To improve upon the findings of Tollner & Das (2004) and Kalaba et al. (2007) using curve number methodology, a compartmentalized dynamic model and the commercially available numerical computer model HYDRUS 2D were built to separately characterize each of the different layers of the compost pad surface to calculate the estimated amount of runoff based on continuous time rainfall data. Both models use a time series approach that will use the rainfall data gathered from a rain gauge connected to a data logger at the site as the input and evaluate storm water dynamics analytically. The governing concept of the compartmentalized model is based on solving a system of differential equations developed for flow through a system of interconnected tanks. To solve the developed equations, a model was built in Matlab-Simulink that processes the rainfall input and returns values for runoff, infiltration, and seepage as the output. The collection pond at the down slope end of the compost pad received all runoff from the pad and was monitored to compare the results of the prediction. HYDRUS-2D uses a two-dimensional approach that determines the distribution of water along the profile based on the series of evaluation nodes. Completion of this research provides users of open windrow composting facilities a more accurate approach to designing safety regulations.

Motivation for developing the compartment model in Matlab-Simulink was based on the potential for generating instantaneous unit hydrographs for a variety of infiltration conditions with largely uniform conditions over large areas. The instantaneous unit hydrograph is used to generate runoff hydrographs from design storms by a convolution process. The instantaneous unit hydrograph is the impulse response of a linear system. The Matlab-

Simulink platform provides excellent tools for linearizing processes about selected operating points and thus enables study of response to various rainfall inputs, given selected values for the model parameter set. The immediate goal is to develop and evaluate an accurate and validated compartmental model with needed design outputs and potential for providing the next step towards developing the instantaneous unit hydrograph representing the pad at a variety of physical parameters and rainfall amounts.

Chapter 2

LITERATURE REVIEW

Runoff Surplus

The hydrologic cycle describes the sequence of events water goes through in the atmosphere, the Earths surface, and in the soil. During a rain event, storm water can fall directly to the surface of Earth or be intercepted by vegetation. When it reaches the surface, the soil absorbs the water and it flows deeper into the aquifer as lateral flow or deep percolation. Runoff results when the rate of rainfall is greater than the rate of infiltration and the surface is no longer able to absorb water. Different characteristics of the soil type, soil cover, and land use cause the rate of infiltration to change in different watersheds. When runoff becomes excessive, flooding can occur that can damage the environment. The pollutants that occur from urban runoff can be attributed to the specific drainage catchments with different predominate land cover (Huang et al., 2007). The increases in flow rates and volumes along with the associated pollutant loads due to urbanization are severely degrading receiving waters (Thompson et al., 2008).

In urban environments, impervious surfaces leads to surface runoff and flooding. Metropolitan areas across much of the United States typically contain greater than 60 % impervious surfaces where 30 % of the impervious area is due to roadway pavement, 25 % due to parking lots, and 10 % due to driveways, sidewalks, and patios (Sansalone et al., 2008). From urban surfaces such as those mentioned, typical pollutants can be heavy metals, petroleum substances, organic matter, and suspended solids (Obropta & Kardos, 2007). The pollutants that leach from urban sources have shown trends that road runoff and tire wear debris is the dominant source of zinc, break wear is the dominant source of copper, and particles washed from rooftops contribute to the zinc and lead captured in an urban watershed (Casey et al., 2007).

The occurrence of surface runoff is a factor of many variables that include rainfall intensity and duration, land use, land cover type, soil moisture and slope (Elhakeem & Papanicolaou, 2009). In urban environments, the risk of high runoff loads and flooding, peak flow, and pollutant loads along with reduced time to groundwater recharge is increased (Bean et al., 2007). Developing better storm water prediction models can have a wide range of benefits including sewer overflow management, best management practice design, and total maximum daily load development (Obropta & Kardos, 2007).

Methods to Reduce Runoff

There are several methods for containing or preventing runoff. Best Management Practices (BMPs) include wet detention ponds, stormwater wetlands, sand filters, bioretention areas, and grassed swales (Bean et al., 2007). Stormwater ponds are developed to collect and store surface runoff from impervious surfaces, allow the water to slowly infiltrate into the watershed to prevent floods, and retain sediments (Casey et al., 2007). In urban landscapes, containment ponds are able to be installed without the need for removing or replacing structures that are already in place. The downside to containment ponds is that they do not reduce surface runoff; instead they collect the runoff that occurs and helps to filter contaminants.

Another option to reducing surface runoff is the installation of porous pavements (interchangeably referred to as porous concretes or porous asphalts). Porous pavements are defined as any paved surface that reduces runoff and allows infiltration into an underlying reservoir of sub-grade soil (Bean et al., 2007; Shirke & Shuler, 2009). The porous structure also acts as a filtration mechanism to reduce the amount of contaminants that reach local water bodies. Using permeable pavements can reduce runoff, filter and treat infiltrating runoff, reduce thermal pollution and temperature, and provide the load-carrying capacity of conventional rigid pavement (Sansalone et al., 2008). There are different types of porous pavements that can be used. Bean et al. (2007) compared results of 15 rainfall events of varying intensity; It was found that no runoff was reported for Permeable Interlocking Concrete Pavements and Concrete Grid Pavers while Plastic Reinforcing Grid Pavers (PRGP) with grass produced runoff five times and PRGP with gravel only produces runoff once (Bean et al., 2007). Unfortunately, current research on porous concretes lacks sufficient hydrologic information that the NRCS tabulated curve number method could use to more accurately estimate runoff loads.

Knowledge of storm water dynamics on porous pavements and porous aggregates is important because windrow composting pads institute porous aggregates in order to reduce the surface runoff that can occur. Composting pads are used to implement a safer method to decompose organic matter in order to avoid contaminants reaching water bodies and introducing toxins. To ensure that the base of a composting pad is sturdy yet pervious, it is typically composed of compacted gravel and rocks (Dorahy et al., 2009). Because the runoff from composting pads is high in organic matter, compost pads are built on a surface that is graded to ensure runoff is drained to a collection pond to prevent a surplus of contaminants entering the watershed (Wilson et al., 2004). Previous research on the estimation of runoff from windrow composting pads have found a runoff coefficient of 0.44, but the value has been based on the composition of the gravel base and not the compost pad as a whole (Wilson et al., 2004).

Instantaneous Unit Hydrograph

The purpose for establishing a rainfall-runoff relationship for a watershed is that a runoff hydrograph can be made available. The hydrograph is a graphical representation of runoff rate against time and can be plotted as a unit hydrograph representing one inch of runoff as done by Sherman (1932) or dimensionless as done by Commons (1942) (Schwab et al., 1993). Development of a unit hydrograph in beneficial especially for small catchments and the hydrograph can be generated from any volume of excess rainfall (Kalaba et al., 2007). Unit hydrographs are derived for a watershed representing a runoff volume of one inch from specified rainfall duration and must be done separately for all desired rainfall lengths (Viessman et al., 2009). The design hydrograph for a watershed is developed from the dimensionless hydrograph using conversion factors based on the peak flow and the runoff volume for the desired return period storm (Schwab et al., 1993).

Measuring Relevant Components of the Hydrologic Cycle

Rainfall

Rainfall simulators can be used to test the hydrologic properties of a surface under varying storm conditions without the need for weather to provide a source. The advantage of using a rainfall simulator is its ability to work on different sized plots. Rainfall simulators can be supplied water either through pumping or being gravity fed (Armstrong & Quinton, 2009). Elhakeem & Papanicolaou (2009) were able to use rainfall simulators to determine how rainfall intensity, soil type, soil moisture condition, tillage practice, and residue cover impact the runoff curve number. The applied volume of rainfall can be varied to test a range of storm sizes rather than relying on nature to provide the storm. It was found that the replication of the equivalent rainfall depth for a storm event of at least three hours was necessary to reach a steady state runoff rate (Elhakeem & Papanicolaou, 2009).

Real-time atmospheric rainfall data can be collected using tipping bucket rain gauges connected to data loggers. The use of a rain gauge is to measure the rainfall depth and rainfall intensity of rain on a flat surface but can sometimes include errors depending on the topography, nearby vegetation, and even the design of the gauge itself (Schwab et al., 1993). The rain gauge collects rainfall data by funneling any rainfall that falls within the area of the bucket into one of two collection pans balanced on a lever. The collection pans have a known maximum volume and when the rain into one of the pans reaches the maximum volume it is automatically tipped and emptied as the other pan begins to collect water. Each time one of the pans is tipped, a signal is sent to the data logger and the amount of rainfall for that time period is recorded.

Infiltration

The rate at which water can infiltrate into the surface affects the volume of storage and surface runoff. A porous medium transmits a liquid under a potential gradient but additional factors include geophysical logs, soil properties, and grain size (Lu, 2007). Infiltrometer tests are used to find the field range for the rate of infiltration and can relate infiltration to the hydraulic conductivity. Infiltrometers offer the ability to perform in-situ testing of the unsaturated and saturated hydraulic conductivity while providing a manageable level of hydraulic head. Hydraulic conductivity is essential for modeling groundwater flow and solute transport and is especially important in calculating the flow through porous pavements because it is generally controlled by grain size distribution and particle shape (Lu, 2007). After experimentally finding the rate of infiltration, Darcy's Law is used to calculate the discharge based on the hydraulic conductivity, hydraulic gradient, and the cross-sectional area through which flow occurs (Simpkins, 2006).

Different styles and models of infiltrometers have been fashioned that reduce errors that can occur from lateral seepage into the soil, leaking from the sides of the infiltrometer, falling head or constant head evaluation, or reading water level measurements. Double-ring infiltrometers have been found to be superior to single ring infiltrometers because the single ring tends to overestimate the vertical infiltration rates due to lateral divergence from capillary forces within the soil (Gregory et al., 2005). To overcome this problem, double-ring infiltrometers use the water level in the outer ring to force vertical infiltration of water in the inner ring. The set up of the infiltrometer is simple and includes two concentric rings and two water tanks to provide water to the rings. For a constant head test, an adjustable float valve can be added to the tap that provides water to each ring. The float valve can be set to close the tap when the level in the ring reaches the maximum allowable height and to open the tap when the water level decreases.

Runoff: Curve Number Method

Models that have been developed to predict storm water loads have been relied on by scientists, engineers, and policy makers seeking ways to measure the impact of water in the urban environment (Obropta & Kardos, 2007). One of the more popular methods for estimating the volume of runoff that occurs from a surface is the Natural Resources Conservation Service curve number method. The curve number method was originally conceived in the 1950s by the Natural Resources Conservation Service (NRCS) to estimate the direct runoff associated with a rainfall event (Hawkins et al., 2009). It has become widely used due to its simplicity and the limited number of parameters required for runoff prediction (Elhakeem & Papanicolaou, 2009). To estimate runoff, a value from the curve number table (dimensionless) CN is selected based on land use, land cover, and soil type and the value is substituted into Equation 2.1 to determine the potential maximum retention (mm) S, which is substituted into Equation 2.2 based on the magnitude of the rainfall (mm) P (Chong & Teng, 1986; Hawkins et al., 2009). The curve number method has typically been used to determine the rate of runoff for watersheds.

$$S = \frac{25400}{CN} - 254 \tag{2.1}$$

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \tag{2.2}$$

Where:

S = Maximum retention of the soil (mm)

Q = Runoff volume (mm)

The runoff curve number is used to estimate the runoff depth for a given storm event and drainage area (Ponce & Hawkins, 1996). The values of the curve number range from 30 to 100 and for a surface are based on the land use, permeability of the soil, and crop growth in the watershed. Decreasing values are for a surface that potentially abstracts all water and values increasing towards 100 describe a surface that is completely impervious and holds no water (Ponce & Hawkins, 1996). It has been found that the soil water retention is highly related to the saturated infiltration rate (Chong & Teng, 1986). The direct surface runoff produced in a watershed from a storm event that is larger than the critical value under a given Antecedent Moisture Condition is solely defined by the rainfall amount and not by the watersheds climatic conditions that govern initial abstraction (Mishra et al., 2008).

Runoff, infiltration, and soil retention will vary based on different types of soil and have an effect on the runoff curve number. To test soil properties such as porosity and particle size distribution, core samples of the soil can be taken and analyzed in the lab. A sieve shaker test can be used to determine the particle size distribution of the soil. A set of sieves are stacked on each other with decreasing pore sizes and the soil placed in the top sieve. As the stack of sieves is agitated, the soil can pass through each sieve until the particle size is larger than the pore size. The remaining mass in each sieve is plotted on a scale based on mass and particle size to determine the physical properties of the soil. A sieve analysis is beneficial over more modern optical particle measuring techniques because the sieve analysis presents the results as a percentage of the cumulative mass while image analysis does not express mass (Fernlund et al., 2007).

Several computer based simulation programs have been developed to determine storm water characteristics on different watersheds based on the runoff curve number. A common tool for quantifying the impact of land use and land cover change on watershed hydrology is the Soil Water Assessment Tool (SWAT). The SWAT tool is a conceptual, continuous-time model that can be used to assess the impact of management of water supplies and non point source pollution in watersheds and large river basins (Arnold et al., 1998).

Another computer based simulation program is the Soil-Plant-Atmosphere-Water (SPAW) tool. SPAW is able to use the inputs of soil type, crop rotation, weather data, and crop management to predict the water budget in a watershed. SPAW is also able to determine the water budget in watersheds with multiple field types. This is because watersheds have fields of different sizes that may have different crop types or a mixture of both urban and rural areas. In the SPAW model, a collection pond is simulated at the end of the watershed and can include details such as depth, surrounding vegetation, and whether the bottom is bare soil or contains a lining. Once the model has run, the resulting output shows the water budget for the collection pond and a budget of the amount of nitrogen and phosphorous from the watershed.

Runoff: Infiltration Process Models for Runoff Prediction

While the curve number method is based on calculating a solution for the volume of runoff, the Green-Ampt equation was developed as a process-based infiltration rate driven equation based on Darcys equation for hydraulic conductivity, effective porosity, and capillary potential (Hawkins et al., 2009; Schwab et al., 1993). The Green-Ampt equation approximates that the wetting front of infiltration into the soil is a square wave and proves to be accurate so long as the amount of water behind the predicted square front is equal to the amount of water behind the true wetting front (Radcliffe & Simunek, 2010). The wetting front is defined as the interface between wet soil that has come in contact with water and the unsaturated soil (Schwab et al., 1993).

HYDRUS is another such model that uses infiltration and soil physics to model the flow of water. The HYDRUS package is able to evaluate water flow through simulation and can predict runoff, infiltration, and drainage flow for the surface profile of the compost pad. The HYDRUS software package permits the evaluation of water flow, solute transport, and root water and nutrient uptake based on finite-element numerical solutions of the Richards' equation (Zhou et al., 2007). For water flow in HYDRUS 1D, a vertical profile is created that can have a depth the user defines. The soil materials within the profile can also be varied based on the type of soil and hydraulic conductivity. Provenzano (2007) found that the HYDRUS 2D model was able to assess the infiltration process around a buried emitter. The advantage of using a 2D model of HYDRUS over the 1D model was the ability to account for sub-surface lateral flow.

Runoff: Compartmentalized and Dynamic Models

Although SWAT and SPAW are powerful tools in determining runoff loads in watersheds, their reliance on the runoff curve number makes the models difficult to use when working with porous pavements. An alternative approach is to use the concept of the tank model for sediment yield developed by Lee & Singh (2005). The compartmentalized dynamic model is developed by relating each of the different layers in the soil profile to a conceptual tank that can receive, store, and release storm water. The benefit of the compartmentalized model is that it is based on a series of dynamic equations based on flow through a black box (tank) system whereas the curve number only provides a discrete time model. In a black box system, it is assumed that there are no external or unknown losses from the system so that the change in storage is equal to input flow minus output flow. In its development by Lee & Singh (2005), the tank model was a series of three interconnected tanks. The first tank represented the surface layer of the watershed and accepted rainfall as an input and the output was surface runoff and infiltration into the soil. The second tank represented the sub-surface soil of the watershed so it could received the infiltration that left tank one and was the output for interflow. The third tank represented the deep percolation layer of the watershed, received the infiltration from tank two, and was the output for groundwater runoff (Lee & Singh, 2005).

The concept of a compartmental model is useful due to the unique vertical profile of compost pads with the windrows of compost, covering of washed compost, gravel aggregate layer, and a compacted clay layer forcing lateral flow. Because of the piles of compost that cover a large portion of the upper section of the compost pad, the surface area of compartment one must be adjusted accordingly. This is because during rainfall events, the piles of compost initially react hydrophobically shedding much of the rain water. But as rainfall continues, the compost tends to reacting hydrophillically, accepting much of the storm water but not releasing it immediately. It has been found that water sprayed on compost windrows leached out over a period of 48 hours or more (Kalaba et al., 2007). The rates of infiltration and lateral flow through each of the tanks are dependent on the properties of the soil. The hydraulic conductivity of the soil will determine the rate at which its respective tank can remove water. For tank one, the depression storage of the washed compost will define the height at which surface runoff can occur. Below the height of the depressions, there will be no surface runoff and therefore no surface flow to the discharge. Aggregate size, pore size, slope, and sub-surface soil are all factors that affect the rate of infiltration through each tank and the holding time in tanks two and three (Lee & Singh, 2005). The outputs of the compartmental model can be calculated numerically to show the change in height of water in each tank with respect to time as well as the flow rates of overland flow, surface runoff, infiltration, and lateral flow.

Other water quality models developed include Areal Non-point Source Watershed Environment Simulation (ANSWERS), Chemicals Runoff and Erosion from Agricultural Management Systems (CREAMS), Groundwater Loading Effects of Agricultural Managemnet Systems (GLEAMS), and Erosion Productivity Impact Calculator (EPIC). A parsimonious watershed model was developed by Limbrunner et al. (2006) that based infiltration to the soil as the difference between effective precipitation and direct runoff to have a useful model that had only four adjustable parameters. Time dependent equations were developed that separately evaluated the unsaturated zone soil storage, groundwater storage, streamflow, and the flow through the network of stream channels (Limbrunner et al., 2006). A distributed large basin runoff model (DLBRM) was developed by DeMarchi et al. (2011) and found the approach worked well for most watersheds but performance declined in heavily urbanized watersheds where the most landscape change was observed.

Windrow Compost Pads

Open windrow compost pads allow organic material such as weeds, municipal lawn trimmings, and animal wastes to safely degrade without letting any hazardous material leach into the soil and affect the groundwater in the watershed. The composting material is contained in large mounds (windrows) that travel along the length of the pad. The environmental benefit of a composting facility is that it diverts the organic material from landfills to avoid impacting the environment with uncontrolled decomposition of organic material (Dorahy et al., 2009). For environmental safety concerns, design recommendations are instituted to ensure storm water drains from the pad quickly. The site should be set on a 1 - 2 % slope, the windrows should be placed parallel to the direction of the slope, and the surface should be made of asphalt, concrete, or gravel to encourage good drainage (Kalaba et al., 2007). The compost piles are mechanically turned periodically in order to prevent the material from settling and to allow uniform decomposition.

The purpose of using an open windrow composting facility is that the atmospheric rainfall provides a natural source of moisture to the composting material that promotes the decomposition processes. Because the open windrow is open to atmospheric conditions, the rainfall that comes in contact with it will become runoff that can be high in Biochemical Oxygen Demand (BOD) and nutrients where high quantities could have an adverse effect on any bodies of water it enters (Kalaba & Wilson, 2005). This makes it extremely hazardous for any wildlife it may come in contact with. To reduce surface runoff, the surface of the compost pad is made of a porous concrete or gravel aggregate. The allowed discharge of contaminated waters from facilities is highly dependent on the dilution of the effluent in receiving water bodies to meet water quality standards (Dow et al., 2009). The collection pond is used to collect all surface runoff and sub-surface runoff from the compost pad in order to filter out the contaminants. The bottom of the collection pond contains a lining that allows for minimal seepage. The pond must be designed based on the maximum potential volume of runoff that will be collected after a storm, which by Georgia guidelines means the volume of runoff that will occur in 24 hours from a storm with a 25 year return period (Kalaba et al., 2007).

Research on compost pads is still inconclusive on the methodology used to estimate runoff and drainage. Much discrepancy comes from the flow of storm water vertically through the piles of compost and the affect the change in the gravel surface characteristics has over time. The time of travel of precipitation for the paved portion of the compost pad can be minutes compared to the time of travel through the compost portion that can be measured in days (Kalaba et al., 2007). Normal methods do not account for whether the windrow will shed precipitation, absorb precipitation, or detain precipitation (Kalaba et al., 2007). There is still much research to be done on the runoff coefficient for the compost material and the coefficient can change depending on the stage of the composting process (Kalaba et al., 2007). Tollner & Das (2004) used a Dynamic Curve Number approach to calculate runoff from the compost pad at the UGA Bioconversion Center. The approach found that by using a curve number that accounts for antecedent rainfall and percentage of pad covered by compost material one could increase the accuracy of the standard curve number method.

Objectives

The purpose of this project is to investigate alternative methods for predicting runoff from a windrow composting pad and compare the results to the curve number method. This is done by (1) Collecting infiltration, rainfall, and runoff data using field equipment; (2) Testing and investigating alternative curve number runoff models; (3) Building a model in HYDRUS 1D and HYDRUS 2D that can evaluate the sub-surface flow dynamics of the compost pad; and (4) Developing a compartmentalized dynamic model as an alternative to the curve number that can predict runoff over a windrow compost pad. Each method is tested to check whether the estimated value of pond stage is reporting similar values to the observed pond stage to test whether each method is performing accurately with a hypothesis test.

Chapter 3

CURVE NUMBER APPROACHES TO ESTIMATE DRAINAGE FROM A YARD WASTE WINDROW COMPOSTING PAD

[1]

[1]Duncan, O.J., E.W. Tollner, H. Ssegane, S. McCutcheon. To be submitted to: Transactions of the ASABE.

Abstract

Estimation of runoff from windrow compost pads is a challenge due to the different hydrologic properties of the compost pad and moisture storage in the compost, both of which change with time. The surface of a compost pad is usually crushed rock on top of a compacted layer of clay and may contain a thin covering of washed compost over the gravel along with the mounds of compost extending above the surface. The curve number method is popular for evaluating runoff from rainfall, but because the porous aggregate promotes greater infiltration and drainage, a new approach was considered. Four curve number based methods are assessed for accuracy in estimating runoff on a windrow compost pad using 16 storm events occurring on a 7284 m^2 composting facility in Athens, Georgia. The methods include: (1) a tabulated effective curve number, (2) a dynamic curve number based on the magnitude of the rainfall, antecedent rainfall, and areal coverage of the compost piles, (3) an asymptotic curve number, and (4) an event-based optimized curve number. Using the NRCS effective curve number consistently under estimated event runoff ($r^2 = 0.92$). Using a dynamic curve number improved the runoff estimation ($r^2 = 0.98$). The asymptotic curve number method performed comparable to the effective CN method ($r^2 = 0.90$) while the event based optimization process only slightly improved over the curve numbers selected from the standard NRCS tables ($r^2 = 0.92$).

Introduction

Windrow composting pads allow organic waste to age in a controlled setting that minimizes environment impact. The environmental benefits of utilizing windrow composting include diversion of organic material from landfills and prevention of the uncontrolled decomposition and leaching of concentrated organic material (Dorahy et al., 2009). In an open windrow facility, the compost is exposed to rainfall from which surface runoff could transport organic material away from the controlled site. Surface runoff from the compost pad can be high in biochemical oxygen demand, suspended solids, and nutrients that may adversely affect surface and ground water (Kalaba & Wilson, 2005). Because windrow composting facilities are usually constructed in remote locations, runoff cannot be routed to a wastewater treatment facility. Instead, contaminated runoff must be collected (and treated) in a pond or other treatment process prior to release from the facility (Kalaba et al., 2007).

Sloped compost pads consist of a layer of concrete or porous gravel aggregate over a clay base that promotes infiltration and drainage towards a treatment pond. To achieve the necessary 1 % to 2 % design slope, windrows are normally placed parallel to the direction of the land surface slope, and a concrete or gravel aggregate to encourage good drainage (Kalaba et al., 2007). Designers determine the size of the pond using state and local specifications of a design event, which in Georgia is a 25-year 24-hour storm (17 cm). Estimating the amount of runoff is complex due to the different surfaces that designers use for the development of windrow compost pads and the wide range of compost.

During a storm, rainfall infiltrates the piles of compost or falls directly on the pad to become runoff or soil infiltration. The designer must accurately estimate the amount of runoff from a design event to size the collection pond. Methods of estimating runoff base measurements on different land use and land cover. However, variations of the curve number approach are the most widely used. The runoff curve number is selected from a table based on soil type, land cover, and land use (Hawkins et al., 2009). Along with characteristics of the surface, the runoff curve numbers exhibit strong dependence on the storm duration and thus can be better calculated using long term daily rainfall rather than a few selected extreme events (Mishra et al., 2008). The standard curve number method offers advantages such as simplicity and reliance on only one parameter; disadvantages are the absence of clear guidance on how to select the curve number for different antecedent moisture condition and variable accuracy for different land uses (urban, agriculture, rangeland, and forest (Ponce & Hawkins, 1996). Because the discharge from a compost pad is predominantly subsurface drainage, defining the curve number for drainage not only varies with season but also with rainfall amount (Yuan et al., 2001).

Although the standard curve number tables are based on runoff from many land covers and land uses, the method does not explicitly cover runoff from compost, gravel, or porous concrete. The relationship of accumulated subsurface drainage to accumulated infiltration have shown to be analogically similar to the rainfall-runoff relationship (Yuan et al., 2001). To improve the utility of the curve number method on porous surfaces such as compost pads, Tollner & Das (2004) developed a dynamic curve number method that accounts for antecedent rainfall and areal coverage of the compost piles. Hawkins (1993) introduced asymptotic curve numbers based on extensive observed rainfall and runoff finding three dominant watershed responses; (1) standard, (2) complacent, and (3) violent with 80 % of the watersheds having a standard response.

The objective of this paper is to compare the performance of these three curve number methods in addition to a curve number optimization to estimate runoff on a compost pad. The four approaches are use of the (1) tabulated effective curve number equations (Hawkins et al., 2009; Chong & Teng, 1986), (2) asymptotic curve numbers (Hawkins, 1993; Hawkins et al., 2009), (3) dynamic curve numbers (Tollner & Das, 2004), and (4) optimized curve numbers based on rainfall events at a site in Athens, Georgia. This paper also determines whether a single curve number can be used to estimate runoff for each type of windrow compost pad for all storm events or whether the curve number is a function of magnitude or frequency of the storm event with a threshold beyond which event magnitude is not relevant.

Methodology

Study Site

The compost pad used in this study is located at the University of Georgia Bioconversion Center in Athens, Georgia. The pad total surface area is 7284 m^2. During the test period, this investigation involved six mounds of compost placed approximately two meters apart. The mounds of compost were trapezoidal in shape and typically 1.5 m in width, 1.5 m in height, and extended the entire length of the compost pad (290 m). A truncated seventh row extended along the southeast edge of the pad (Figure 3.1). A sand-gravel aggregate surface of the compost pad with a thickness of 20 cm sits on top of a compacted clay layer. The clay minimizes deep infiltration into the watershed and promotes lateral flow. The pad is sloped 2.44 % along the length and 0 % along the width. The slope directs all drainage towards a catchment pond of 0.5 ha in area, 1.5 m deep, and less than 3.175 mm/day seepage due to an installed clay liner (Tollner & Das, 2004). Figure 3.1 shows the University of Georgia (UGA) Bioconversion Center. The measures that prevented most external storm water from surrounding sources from reaching the collection pond include the following. (1) The topography near the UGA Bioconversion Center has a slope that is directed towards the collection pond but a small curb travelling alongside the center access road inside the area was installed to direct runoff from the nearby land away from the compost pad and collection pond. (2) Rainfall from Center roofs was directed toward drains that kept water away from the composting pad. Nevertheless, during construction of the composting facility, six concrete test pads were installed next to the compost pad (Figure 3.1) with drains that flow directly to the collection pond. In addition, subsurface flow into the pond from the land application area was not investigated.

Data Collection and Preprocessing

This study recorded rainfall and pond volume from December 23, 2010, to June 21, 2011, using data logging equipment on site. Daily pond stage and rainfall data were also collected by Tollner & Das (2004) from 2000 to 2003 using daily weather station data for rainfall and staff gauge readings for pond volume. The rainfall and pond stage from both time periods were used to evaluate the curve number estimations. A HOBO Model number RGB-M002 tipping bucket rain gauge is located at the southwest end of the compost pad in a clearing that avoids interception from trees or splash from the ground. The collected water volume was estimated using two HOBO U20-001-04 pressure transducers (Onset Computer Corporation;

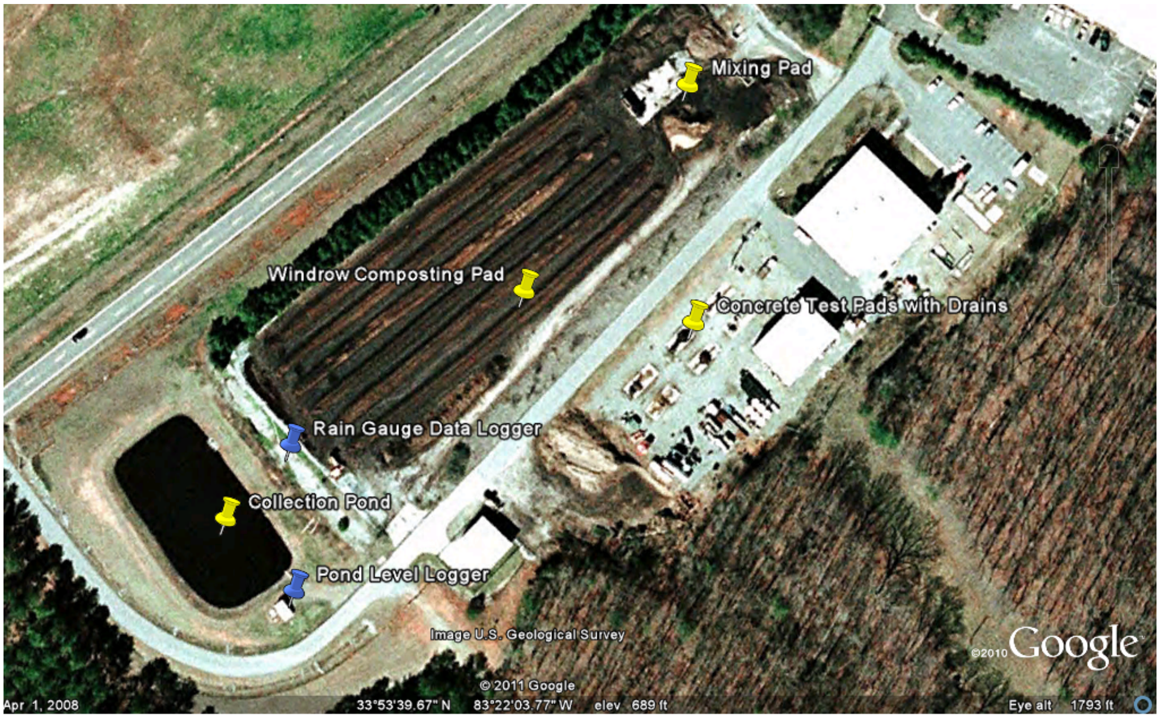


Figure 3.1: Google Earth (©2010) overhead view of the UGA Bioconversion Center showing the composting pad and collection pond.

Bourne, MA) placed in a well southeast of the pond. The transducers record average pond depth in the stilling well every 10 minutes. This study used one transducer suspended near the bottom of the well and above the floor of the pond to avoid siltation to measure the change in the pond depth while the second transducer is suspended just above the water level in the well to correct for the effect of atmospheric per HOBO recommendations.

After recording the rainfall and pond level, this study separated each storm event based on the amount of time between each recording of precipitation. Evaluation of the observed pond stage established that the change in pond level tended to decrease to zero within 24 hours of a storm. In addition, some methods typically calculate runoff on smaller catchments on the basis of 24 hours because evaporation and soil percolation are minimal. Thus, this study defined the beginning of a discrete rainfall event by the 12 hours of measurements before the first recording of precipitation and the end of runoff defined by the following 24 hours after rainfall ended. This study calculated the observed runoff volume as the difference in pond volume before and after a storm event. The observed volume included the direct rainfall onto the area of the pond, the volume of rainfall that occurs on six smaller concrete test pads that drain directly to the collection pond, and any infiltration from ground water minus the volume lost due to pumping to a nearby land application, and any evaporation or seepage from the pond. To ensure that the runoff calculated from change in pond was not biased, this study used a water balance to compare the volume of rainfall directly to the surface of the compost pad to the change in the volume of water in the pond minus rainfall directly onto the pond. After accounting for the direct rainfall to the pond, the comparison demonstrated that the volume of storm water was stored in the gravel and clay of the pad and the piles of compost 24 hours after the rainfall ended and this investigation concluded that because the rate of flow of the significant stored moisture to pond after 24 hours was insignificant, the slowly draining storage was not a significant source of error.

The interpretation of each test determined the calculated change in pond volume by using each curve number method to determine the volume of runoff that would occur and subtracting the pond seepage. The procedure then added calculated direct runoff from the compost pad (m^3) Q to the initial volume in the pond (m^3) V_i along with the volume of direct rainfall onto the pond, rainfall onto the concrete test pads, and rainfall onto the compost mixing pad (m^3) P_{ext} to complete the water balance (Equation 3.1).

$$Q = V_f - V_i - P_{ext} \tag{3.1}$$

where:

V_f = Final pond volume (m^3)

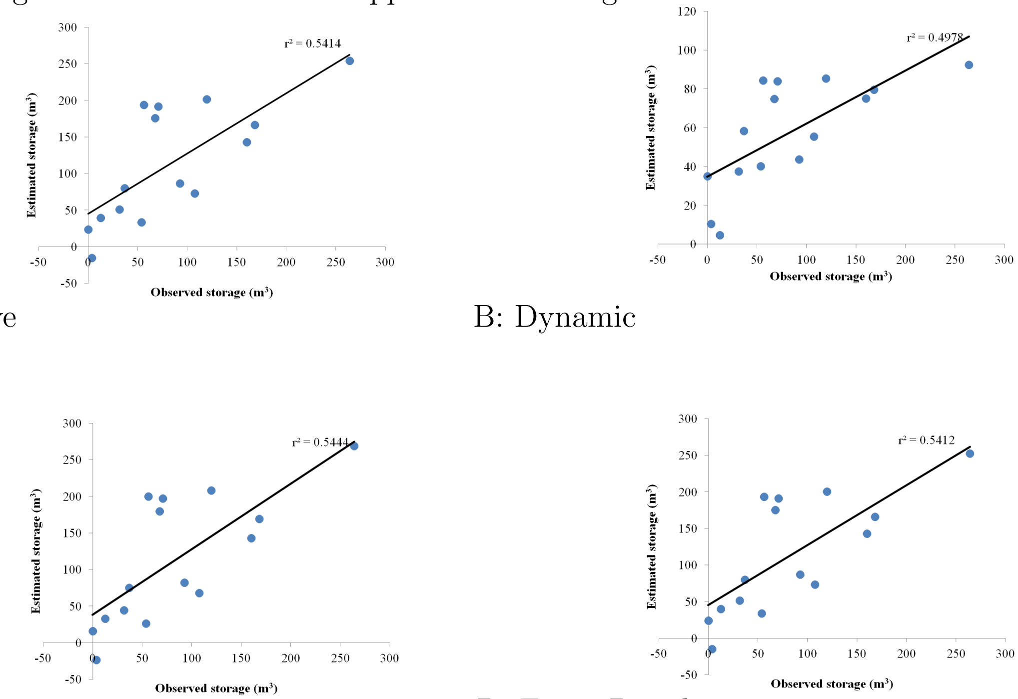
The amount of storage (m^3) S in the compost and pad for each of the recorded events is calculated by Equation 3.2.

$$S = P_{pad} - Q \tag{3.2}$$

where:

P_{pad} = Direct rainfall to the compost pad (m^3)

Figure 3.2 shows the amount of storage calculated from observations compared to volumes estimated using the four curve number approaches investigated.



A: Effective

B: Dynamic

C: Asymptotic

D: Event Based

Figure 3.2: Graphs of the comparison of observed against the estimated volume of storage using the different curve number approaches.

Tabulated Effective Curve Number

The value of the effective curve number is tabulated based on the affect each layer in the pad and compost influence the flow of storm water to the pond. To aid drainage of stored moisture to the pond, the vertical profile of the compost pad includes 15 cm to 20 cm of crushed rock between a thin layer of washed compost with the windrows above and compacted clay underneath. For rainfall directly onto the pad, an uncovered gravel surface can have a curve number as low as 44 and can range as high as 95 (Wilson et al., 2004). A range of 50 to 70 for compost windrows was used by Kalaba et al. (2007) based on laboratory experiments done by Wilson et al. (2004) where the value of 50 was most likely to represent drier compost conditions. Kalaba et al. (2007) showed that by using the curve number tables, the effective curve number for composting was 75. The curve number of 75 was an effective curve number based on the combination of asphalt and approximately 40 % of the pad being covered by compost in windrows (CN(asphalt) = 85 and CN(compost) = 60).

Dynamic Curve Number

Tollner & Das (2004) developed the dynamic curve number method to estimate runoff based on daily and monthly rainfall for the same compost pad used in this study (dynamic due to the fact that pad utilization changed over time due to seasonal deposition and seasonal differences in the makeup of the deposited compost). Tollner & Das (2004) revised the standard NRCS curve number equations for the fraction of the total pad that is covered by compost windrows (%) PadFract, antecedent rainfall for the past X days (mm) AntecedX, and magnitude of the monthly or daily rainfall (mm) P

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{3.3}$$

$$S = \frac{25400}{812PadFract + 9.002AntecedX + 623} - 13.9 \tag{3.4}$$

where:

Q = Runoff volume (mm)

S = Potential maximum retention (mm)

One dynamic approach used a constant curve number and varied the effect of rainfall magnitude on runoff for a given compost pile. A second dynamic approach used the actual rainfall and varied the effect of potential retention. The work done by Tollner & Das (2004) from 2000 - 2003 was evaluated again during this project to compare the differences between curve numbers calculated for new pads (referred to as 2000 to 2003) and more mature pads (referred to as 2010 to 2011).

Asymptotic Curve Number

The asymptotic approach independently ranks the rainfall and then the runoff series and calculates the curve number from the frequency matched pairs (Hawkins, 1993). The frequency matched rainfall-runoff pairs usually do not maintain the coherence of the observed rainfall and runoff for each storm, instead they preserve the assumption that similar storm sizes produce similar sized runoff events. After ranking and matching the rainfall and runoff by frequency, this method rearranged Equation 3.3 to calculate maximum potential retention S and the corresponding curve number (dimensionless) CN

$$CN = \frac{25400}{S - 254} \tag{3.5}$$

The relationship of storm event magnitude to calculated curve number for storm events with large rainfall depths approaches an asymptote taken to be the curve number CN_∞ for the particular surface or catchment of interest

$$CN(P) = CN_\infty + (100 - CN_\infty)\, e^{-kP} \tag{3.6}$$

where:

CN(P) = Curve number as a function of rainfall magnitude

k = An empirical fitting parameter determined from the series of rainfall and runoff

Storm Event Runoff Optimized Curve Number

The fourth approach was the event based optimization that estimates the event curve number as the optimum curve number that minimizes the runoff estimation error on an event basis. The optimization exhaustively searches through all curve numbers for each storm event to find the curve number that yields the minimum absolute percent error. This procedure calculates the error by comparing the observed to the calculated runoff volume (Equation (3.1) and Equation (3.3)). The approach then requires computation of the geometric mean of the event curve numbers and would conclude to be the curve number value for the compost pad.

Statistical Analyses

To evaluate the performance of each method, statistical evaluations compared the observed versus estimated results of pond stage. The methods used were a Percent Root Mean Squared Error (% RMSE) (Equation 3.8), Pearson correlation coefficient (r^2) test, and hypothesis t-test. The purpose of assessing the results with multiple statistical methods is because the data is evaluated using a small population size. To show whether each curve number method tested estimated results similar to the observed results, the r^2 correlation was calculated by comparing the observed against estimated pond stage. The % RMSE is a scaled value of the error that references the RMSE based on the maximum pond volume (m^3) V_{max} to numerically understand the scale with which each model is over- or under-predicting the pond stage. Lower values of % RMSE suggest a better fit of observed to predicted data. The hypothesis tests whether the dynamic, asymptotic, or event based curve number methods were able to significantly reduce the statistical error ($x - \widehat{x}$) in pond stage prediction compared to the use of an effective curve number. Hypothesis testing was performed using the SAS statistical package. The hypothesis tests adhered to the following assumption where the results of the statistical error from the effective curve number method (m^3) μ_1 will be compared to the statistical error by each of the alternative curve number methods (m^3) μ_2

using a significance level of $\alpha = 0.1$:

- H_0: $\mu_1 = \mu_2$
- H_a: $\mu_1 \neq \mu_2$
- $\mu_i = x - \widehat{x}$

$$RMSE = \sqrt{\frac{\sum (x - \widehat{x})^2}{n}} \tag{3.7}$$

$$\%RMSE = \frac{RMSE}{V_{max}} * 100 \tag{3.8}$$

Where:

x = Observed pond stage (m^3)

$\widehat{x}$ = Estimated pond stage (m^3)

n = Number of Observations (-)

Results and Discussion

Table 3.1 shows the calculated curve numbers for 2010 to 2011 using the four curve number approaches. The use of a tabulated effective curve number provided a baseline for how well the standard curve number method could characterize the drainage from windrow composting pads (% RMSE = 0.99 %). The tabulated effective curve number for the compost and pad is a singular 75. The tabulated effective approach (Kalaba et al., 2007) and the asymptotic approach only derive a singular curve number for all the events observed, thus reducing the variability of curve numbers seen in Table 3.1.

Curve numbers calculated from the event based approach varied within the range of 40 to 100 but reduced the root mean squared error based on observed versus estimated pond stage (% RMSE = 0.47 %). To develop a more defined curve number for the compost pad

Table 3.1: Curve numbers calculated using the dynamic curve number approach and event based curve number approach. The NRCS tabulated curve number was 75 and the curve number determined from the asymptotic method was 70.5. These 16 events were observed in 2010 to 2011 and geometric means are tabulated at the bottom.

Rainfall (mm)	Dynamic curve number	Event based curve number
11.2	95.03	52.4
27.2	94.99	97.0
7.9	97.06	63.2
5.1	94.99	62.5
26.8	94.99	96.0
91.6	97.03	100.0
6.7	99.77	60.5
6.1	94.99	89.3
24.2	95.53	96.1
1.4	96.87	88.5
10.4	95.12	83.1
28.5	94.99	91.9
12.0	97.13	80.9
19.3	94.99	72.5
22.8	94.99	65.0
38.6	94.99	42.2
AVERAGES		
14.1	95.8	75.4

using the event based approach, the geometric mean event based curve number was used (CN = 75.4, % RMSE = 0.98). Table 3.1 compares rainfall volume and optimized curve number.

The dynamic curve number method was able to better represent the calculated runoff from the compost pad (% RMSE = 0.61 %). As done in the testing of the event based approach, the geometric mean value of the dynamic curve number was also examined but there was no significant improvement in the results (% RMSE = 0.64 %). Figure 3.3 compares the absolute percent error from the four approaches for each of the 16 rainfalls in 2010 to 2011. Points closer to the center depict better performance while those close to the outermost circumference represent poorer performance. In Figure 3.4, the Pearson correlation coefficient (%) r^2 is tabulated. The r^2 value measures the linear dependence between the observed and estimated pond volume. High values of r^2 show a strong relationship between the two variables and suggest satisfactory curve fitting. Based on the r^2 values, the dynamic approach to the curve number shows the best performance for the storms occuring in 2010 to 2011.

Using the asymptotic approach to determine the curve number led to an asymptote that approached 70.5 for the compost pad for the 2010 to 2011 data (Figure 3.5, % RMSE = 1.05 %). Figure 3.5 also contains the rainfall to curve number relationship for the compost pad during the study in 2000 to 2003 for 44 storms provided by Tollner & Das (2004). A clear difference in asymptotes can be seen for the two different periods for the same pad. For 2000 to 2003 (Tollner & Das, 2004), the asymptotic curve number is 96 (% RMSE = 1.72 %). The curve number is a method to calculate storm direct runoff, but is also a reflection of a soils potential for retention, thus the decrease seen in the asymptotic curve number is most likely reflective of the compost incorporating into the rock media over the two different periods of study. During 2000 to 2003, the compost and pad still generated some flashy discharges, unexpected runoff occurred from surrounding areas, and the gravel was not fully compacted or had filled with the washed compost to retard drainage.

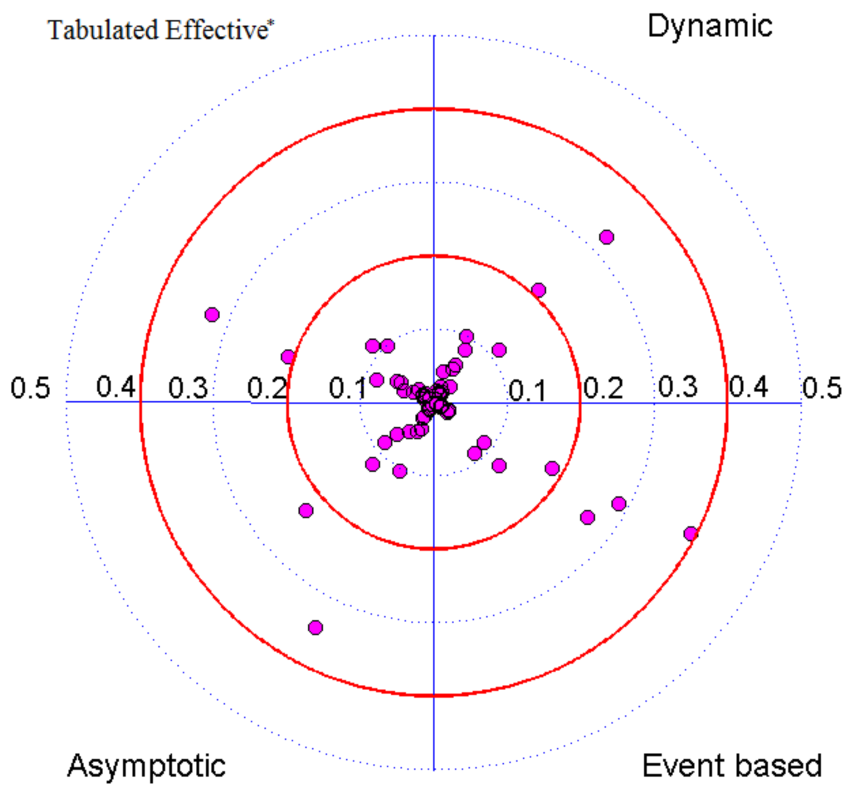


Figure 3.3: Fraction error from the calculation of runoff using the curve numbers based on NRCS tables, the dynamic approach, the asymptotic approach, and each individual event. *As calculated by Kalaba et al. (2007)

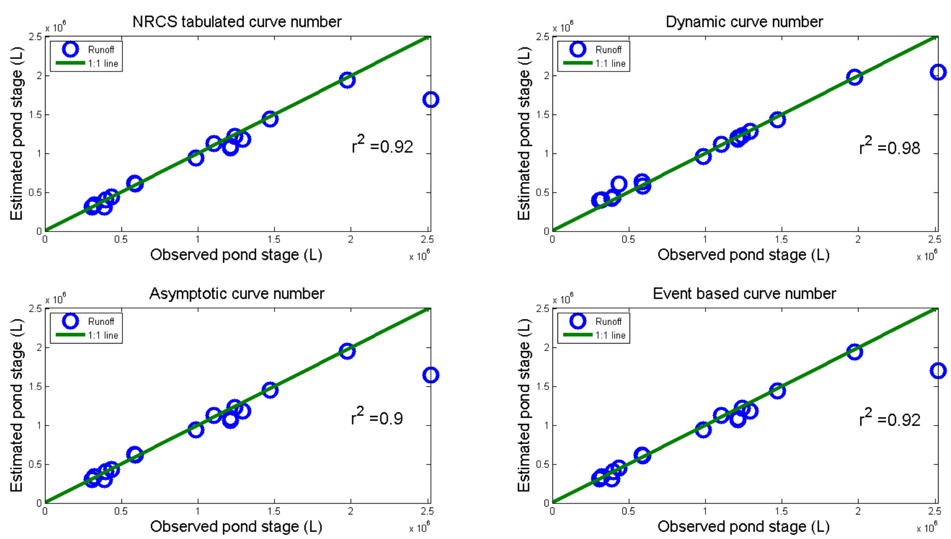


Figure 3.4: Estimated pond stage from the four different curve number methods compared to runoff observed in 2010 to 2011.

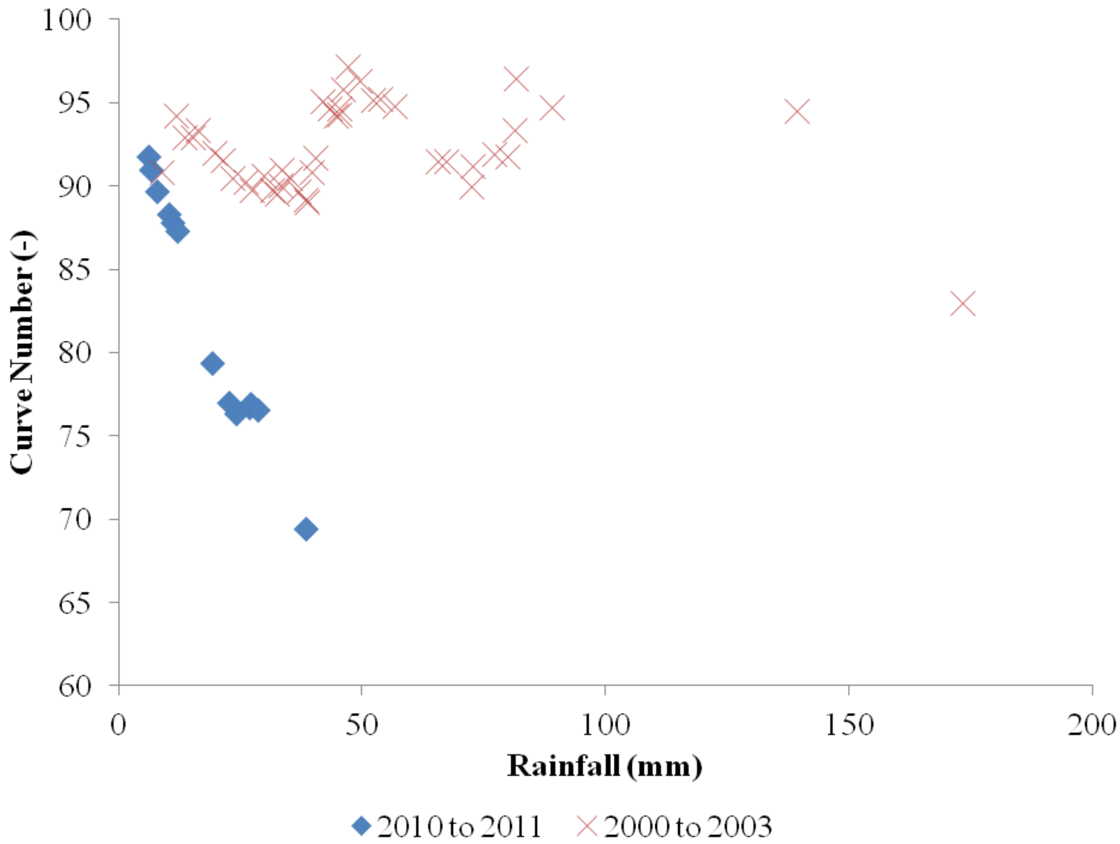


Figure 3.5: Calculated curve number versus rainfall for each event used to determine asymptotic curve numbers for the 2000 to 2003 storms (Tollner & Das, 2004) equal 96 and the 2010 to 2011 storms equal 70.5.

At $\alpha = 0.1$, the hypothesis test showed that the dynamic, asymptotic, and event based curve number methods were resulting in statistical error that was similar to the statistical error from the effective curve number method ($p_{Dynamic} = 0.2348$, $p_{Asymptotic} = 0.9721$, $p_{EventBased} = 0.9686$). Although each of the methods have similar performance in their results, each one provides a beneficial insight into the hydrologic conditions of a windrow composting pad.

Based on the two different curves that can be seen in Figure 3.5, there is an apparent change in how the surface of the compost pad transmits and releases storm water in its early stages (2000 to 2003) compared to later years (2010 to 2011). A high curve number of 96 during the 2000 to 2003 period suggest the pad is acting similar to a gravel parking lot where there is a more immediate response between rainfall and drainage. From 2000 to 2003 the pad was still in its early stages with a uniform gravel layer supporting the pad. As the years progressed, compost washed from the windrows and filled in pores in the gravel layer. The sand sized particles that comprise 34 % of the composition of the surface of the compost pad in the 2010 to 2011 data set increase the retention in the gravel layer during a storm. The difference in retention over the ten years separating study periods open to the theory that as the compost pad ages, the surface material takes on more of the characteristics of a soil than a pure gravel lot.

Conclusion

Observations of the windrow composting pad at the UGA Bioconversion Center in Athens, Georgia for the 2010 to 2011 data set established that a tabulated effective curve number based on studies by Kalaba et al. (2007) and Wilson et al. (2004) provided a curve number which typically under estimates runoff due to the varying surface characteristics of the compost pad (% RMSE = 0.99 %, CN = 75). In an attempt to improve runoff predictions, this study investigated three curve number modifications. Use of the dynamic curve number method, that varied the affect of soil retention, was able to slightly improve estimated runoff other methods (% RMSE = 0.61 %, $p = 0.2348$, CN = [94, 99]). Using the asymptotic approach, the curve number varied for smaller storm events but approached 71 and was similar to the NRCS tabulated curve number (% RMSE = 1.05 %, $p = 0.9721$, CN = 71). The event based optimization improved estimation of runoff, but the curve numbers for each rainfall varied within the entire range of curve numbers [30,100]; thus an average curve number was used (% RMSE = 0.98 %, $p = 0.9686$, CN = 78). Although each of the alternative curve number methods were able to slightly improve the prediction of pond stage, the hypothesis test fails to reject the null that the dynamic, asymptotic, or event based curve number offer a significant improvement compared to using the tabulated effective curve number ($\alpha = 0.1$). Based on the hypothesis test results, it can be understood that runoff from windrow compost pads is relatively insensitive to the curve number. Comparison of the runoff when the pad was new (2000 to 2003) and when the pad had aged (2010 to 2011) suggest runoff will reduce somewhat as windrow compost pads age. An asymptotic curve number was developed for the early and later stages of the compost pad and it was found that during the early years (2000 to 2003) the pad discharged drainage much like a gravel lot, while the aged pad (2010 to 2011) took on more of the properties of a soil with a higher retention.

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Chapter 4

COMPARISON OF COMPARTMENTALIZED DYNAMIC MODEL, HYDRUS, AND CURVE NUMBER METHODS FOR ESTIMATING DRAINAGE FROM WINDROW COMPOSTING PADS

[1]

[1]Duncan, O.J., E.W. Tollner, H. Ssegane. To be submitted to: Transactions of the ASABE.

Abstract

Compost pads are frequently constructed employing open windrows over a porous sand and gravel aggregate surface supported by compacted finer textured subsoil with limited infiltration capacity. Design of containment facilities and conveyance channels for runoff from windrow compost pads is hindered by a lack of suitable runoff prediction models. This research develops a compartmentalized dynamic model as an alternative to the limitations of the commonly used curve number method due to the dynamics of surface runoff and infiltration of storm water on the surface of a composting pad. The compartmentalized model offers the benefit of effectively evaluating the effects of different surface types have on the rate of infiltration on compost pads and their resulting impact on the partitioning of subsurface and surface runoff. Having a flow rate prediction in addition to volume predictions enables more precise conveyances between the pad and the containment as well as the total size of the containment. The accuracy of runoff predictions by the compartmentalized model were compared to the predicted pond stage based on runoff predicted by a Dynamic Curve Number (CN) method with a variation on effective rainfall and rate response from HYDRUS®(a commercially available numerical computer model). Percent Root Mean Square Errors (% RMSEs) were computed based on 16 runoff events between December 23, 2010, and June 21, 2011 and scaled to the maximum pond volume size. Results from 16 separate storm events based on the comparison of the observed runoff to the estimated runoff using the dynamic curve number method yielded % RMSE = 0.61 %; % RMSE = 0.78 using the compartmentalized dynamic model; and HYDRUS 2D®was able to predict within % RMSE = 0.65. Although the curve number and the dynamic models gave comparable results, the curve number method does not predict dynamic lateral flow.

Introduction

The composting process is an aerobic process used in the biological decomposition of organic materials (Kuhlman, 1990). The surface of a composting pad is typically compacted gravel and rocks to provide a sturdy and pervious base for the compost (Dorahy et al., 2009). The advantage of compost pads is the diversion of organic material from landfills and to avoid adversely affecting the environment with the uncontrolled decomposition of organic material (Dorahy et al., 2009). By instituting machine-turned windrows, it has been found that the composting procedure can be completed in one-third the time it would take for a static pile (Brodie et al., 2000). The design characteristics of the compost pad are instituted to ensure that storm water effectively drains from the pad quickly. It is recommended that the site should be set on a 1 to 2 % slope, the windrows should be placed parallel to the direction of the slope, and that the surface should be made of asphalt, concrete, or gravel to encourage good drainage (Kalaba et al., 2007).

Often, open windrow facilities are employed to allow direct rainfall on the compost material. The adverse effect of an open windrow facility is the resulting runoff that can leach contaminants and make the stormwater unsuitable for receiving water bodies (Wilson et al., 2004). To minimize drainage of contaminants surplus, compost pads are built on a surface that is graded to ensure runoff is drained to a collection pond (Wilson et al., 2004). Because an open windrow compost pad is open to the elements, the rainfall that comes in contact with it will become runoff which can be high in Biochemical Oxygen Demand (BOD), suspended solids, and nutrients (Kalaba & Wilson, 2005). These contaminants come from the compost material which are placed in trapezoidal shaped windrows with a base width of 3 to 5 m and a height of 2 to 3 m (Kuhlman, 1990). A collection pond is used to receive surface runoff from the compost pad in order to prevent any unwanted release of contaminated runoff. Ponds in Georgia are designed to contain a design storm such as the 25-year, 24-hour storm (P = 17 cm) as specified by the Georgia Department of Natural Resources (Kalaba et al., 2007). The design assumption was that virtually all the rainfall directly to the compost pad would be captured by the pond, which, for large installations may lead to over design. Knowledge of the partitioning of flow between surface runoff and subsurface flow (most of which usually reaches the pond at some time due to the compacted soil below the crusher run rock) is needed to properly design conveyances of the surface runoff from the pad to the containment. Because of the many different types of surfaces that can be used for the compost pad and the wide range of material that can be composted, it is currently difficult to get an accurate estimate of the amount of surface runoff. Tollner & Das (2004) attempted to fit the NRCS Curve model number to runoff data from a windrow pad and determined that using a curve number that varies dynamically based on antecedent rainfall and percentage of compost pad covered with windrows was able to better predict runoff compared to a constant curve number. The use of the curve number method is applied to the type of surface used but does not account for the compost, or the surface as modified by the compost.

Prediction of runoff, infiltration, seepage, and environmental impact of storm water can be made using runoff model programs such as HYDRUS-2D/3D, Soil-Water-Assessment-Tool (SWAT), Soil-Plant-Atmosphere-Water (SPAW), Groundwater Loading Effects of Agricultural Management Systems (GLEAMS), or Erosion Productivity Impact Calculator (EPIC). An alternative to these models is necessary because of issues such as affordability and the reliance of these models on the curve number. The curve number method is more widely used and estimates the runoff depth for a given storm event and drainage area Ponce & Hawkins (1996). The development of the curve number was derived from long term daily rainfall-runoff relationships and included factors for antecedent moisture condition (Mishra et al., 2008). While the curve number method offers advantages such as simplicity and reliance on only one parameter, it also has disadvantages such as the absence of clear guidance on how to vary antecedent moisture condition and varying accuracy for different ecosystems (Ponce & Hawkins, 1996). Runoff inaccuracies occur during the curve number method when trying to adjust the daily runoff curve number as a function of soil moisture content at the end of the previous day (Kim & Lee, 2008).

For a compost pad, the material and the degree of decomposition on sensitivity to antecedent condition is largely unknown. In some cases it has been found that water sprayed on a windrow has leached out over a period of 48 hours or more (Kalaba et al., 2007). This delay in transmission of water from the area of the compost pad can lead to large errors in calculation especially when storm events occur closely. The piles of compost material also create another difficulty; high volumes of leachate from the piles can be detrimental to the surrounding environment. Different surfaces have been examined to control the amount of contaminants that leach from a windrow compost pad. The type of aggregate used is typically crusher run. Current research on the surface of compost pads have shown a volumetric runoff coefficient of 0.44, but this value has been based on the composition of the gravel base and not the compost pad that contains residual compost material (Wilson et al., 2004). Porous pavements are asphalt or concrete surfaces that are designed to allow moisture to seep through the surface into an underlying reservoir or sub-grade soil (Beecham & Myers, 2007; Shirke & Shuler, 2009). Examples of porous pavements include permeable interlocking concrete pavements, concrete grid pavers, plastic reinforcing grid pavers (PRGP) with gravel, and plastic reinforcing grid pavers with grass (Bean et al., 2007). The uniform construction of the crusher run base overlying a compacted clay surface provides a uniform geometry and hydraulic system that lends itself to a hydraulic compartment model for the runoff process.

Kalaba et al. (2007) used a weighted average runoff coefficient of 0.75 because of significant differences between asphalt and compost material characteristics. Although the predicted data by Kalaba et al. (2007) using an empirical method fell within 5 % accuracy of the observed data, because they used a weighted average runoff coefficient the different dynamics in hydrology of the asphalt and compost material were not fully addressed. To fully address the different layers associated with the compost pad, we examined the predictability of a compartmentalized dynamic model and HYDRUS 2D and compared the results to the standard curve number method. The concept of the compartmental model was used by Lee

& Singh (2005) to examine the models ability to estimate sediment yield over a watershed. The use of the developed compartmental model can be adjusted to analyze the different surface types that make up the compost pad individually rather than as a lump sum. As a complement to the compartmental model, the 2D version of the HYDRUS software was examined to determine whether it would offer similar improvements to estimating the runoff from compost pads. The HYDRUS model offers the ability to evaluate the water flow dynamics along a 2-dimensional profile with different soil types. The output of the HYDRUS model can show the change in water content during the storm and direction of flow at any point within the soil profile.

One reason for the popularity of the curve number method is that it can be adapted to a large array of surface and subsurface conditions with the manipulation of one parameter as corrected for hydrologic condition, soil group, and antecedent rainfall. Actual available subsurface storage is not explicitly considered. In a situation like an engineered compost pad (or other engineered surfaces such as a porous pavement parking lot), the subsurface condition is relatively well known and reasonably uniform. Thus, we are designing a model that is more or less specific to the engineered situation found under a compost pad in hopes of improving on the Tollner & Das (2004) results. The objectives of this study were: 1) to develop a compartmentalized dynamic runoff model that modeled the amount of total runoff from rainfall events; and 2) to enable partitioning of direct surface runoff and runoff entering the containment via subsurface flow with the potential of further exploring the effect of parameters such as infiltration and rainfall amount on the instantaneous unit hydrograph.

Materials and Methods

Description of Composting Site

The compost pad in place in Athens-Clarke County was used to experimentally measure the runoff volume, seepage, and infiltration. The compost pad has an area of 7284 m^2 and is covered with a porous concrete aggregate underneath a thin layer of compost with an average thickness of five centimeters. Covering the pad are six to seven large mounds of compost running parallel to each other from the North to South end of the compost pad with an average length of 290 m and a thin covering of compost with an average depth of five centimeters covering the entire pad. Each large mound of compost averages 1.36 meters in width and are spaced an average distance of 1.27 meters apart. Of the total area at the surface of the compost pad, the windrows cover an average area of 2760 m^2 during the time period tested. The compost material typically shows properties of being hydrophilic as approximately 15 to 20 % of rainwater reaching a compost pile is released as surface runoff (Kalaba et al., 2007). The pad has a particle size concentration of 67 % gravel and 33 % sand on a tightly compacted Cecil sandy clay loam. This compacted soil is an average depth of approximately 20.32 cm below the surface (Tollner & Das, 2004). The pad has a downward slope of 2.44 % from the North to South end and level from the West to East end. At the South end of the compost pad is a pond that is used to collect water as it leaves the compost pad. All runoff is directed to the pond with a surface area of 1888 m^2. During construction, the collection pond included a clay lining to allow a maximum infiltration rate of 0.0132 cm/hr upon installation with 3:1 interior slopes which allowed for a straightforward conversion from depth to volume (Tollner & Das, 2004). Figure 4.1 below shows the composting facility along with the surrounding UGA Bioconversion Center.

Experimental Data Collection

Infiltrometers were placed at 12 key points covering the front, middle, and back sections of the compost pad to measure the potential rate of infiltration. Double ring infiltrometers were used to measure the rate of infiltration into the porous surface. The double ring is superior to the single ring infiltrometers because the single ring tends to overestimate vertical infiltration rates due to lateral divergence because of capillary forces within the soil (Gregory et al., 2005). The set up used a double ring infiltrometer with an inner ring diameter of 38.74 cm and an outer ring diameter of 53.98 cm. Both rings have a total height of 20.32 cm and were

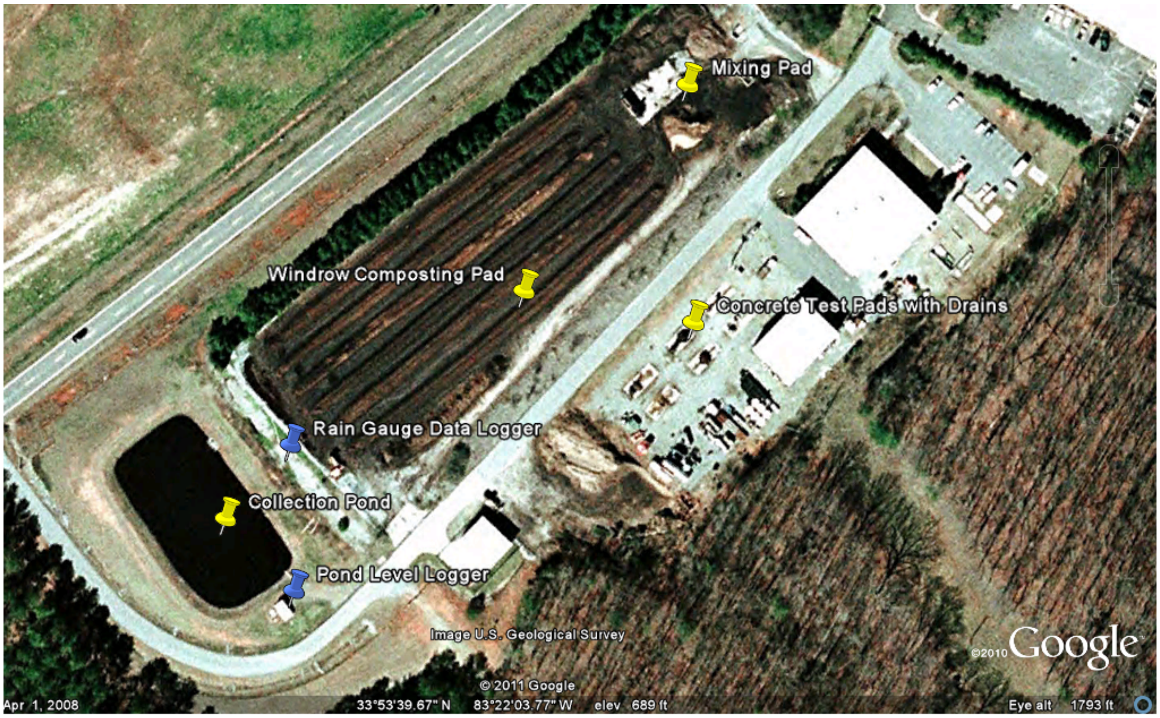

Figure 4.1: Overhead view of the composting facility and surrounding UGA Bioconversion Center using Google Earth ©2010.

driven into the ground approximately three centimeters to prevent any losses due to leakage from the sides. The height in the inner ring was controlled to maintain a constant head of approximately 4 cm by a float valve that can be adjusted to other heights when necessary. The water was supplied to the rings by two separate water tanks, one for the inner ring and one for the outer ring. The results of the infiltrometer tests found for the entire profile (both surface and sub-surface) an average effective saturated hydraulic conductivity of 7.1 cm/day with a maximum of 14.7 cm/day.

A second set of infiltrometer tests were performed on the compacted clay layer beneath the gravel aggregate layer to determine whether the clay layer allowed any deep infiltration that would be lost from the system. It was found that the clay layer allowed for minimal infiltration at a rate of 1.4 cm/day. This rate of infiltration shows that although most storm water will flow laterally and exits the compost pad, during large storm events the rate of deep infiltration can affect the volume of water that reaches the pond.

Pond Volume Sampling

The volume of water in the pond is monitored by two HOBO®U20-001-04 pressure transducer taking measurements at 10 minute intervals (Onset Computer Corporation; Bourne, MA). The logger is placed in a well next to the pond beneath the level of water. The barometric pressure is accounted for by a second pressure transducer being placed in the well above the height of the water. Variations in atmospheric pressure have shown that the pond level can vary by 1.2 cm during each logging interval. In the data collection process it is necessary to provide a reference height to the data logger from a staff gauge located in the pond with an error of 0.31 cm which interpolates to a possible error of 80.8 m^3 when determining pond volume.

Rainfall Sampling

A HOBO ®Model number RGB-M002 tipping bucket rain gauge data logger has also been placed on site to record the rainfall at one-minute intervals. The location of the rain gauge on a clearing of flat land between the compost pad and the collection pond was carefully chosen to avoid any inaccuracies in measurement due to interception from trees or splash resulting from any rain that directly hits the ground. To determine whether the storm water dynamics of the compost pad were a closed system (i.e. no external gains or losses through the sides or bottom), the rainfall data and pond volume data were used to establish a water balance. For the compost pad to truly be a closed system, the volume of rainfall directly to the surface of the pad must be equal to the change in pond volume for each storm event. It was found that in most cases there was a significant volume of storage in the sub-surface layer and the piles of compost material of the compost pad which must be accounted for in any model used. For each of the methods used the estimated change in pond volume was calculated by taking the sum of the estimated direct runoff from the compost pad, the direct rainfall onto the area of the pond, the volume of rainfall that occurs on the six smaller concrete test pads, volume lost due to pumping to a nearby land application sprayfield, and any evaporation or seepage from the pond.

Model Development

Rainfall data was collected for sixteen storms between December 23, 2010 and June 21, 2011. An individual storm was defined as the period beginning 12 hours before the logger first records rainfall and continues until the rainfall has ceased for 24 consecutive hours. The sum of rainfall during each rainfall event was used for the curve number method to predict the amount of runoff. Based on current research, a curve number of 75 was used, but due to differing curve number values between the compost piles, the bed of compost, and the porous surface of the pad, a more accurate value for the curve number is yet to be determined (Kalaba et al., 2007; Duncan, 2012; Wilson et al., 2004). The curve number method also did not account for any addition to the pond volume due to sub-surface lateral flow. The predicted change in pond volume was determined by first calculating the volume of runoff that would occur and subtracting the volume that would be lost due to deep infiltration. A detailed evaluation of the tested curve number models can be seen in Duncan (2012). To definitively find which method performs the best, four statistical evaluations were performed to compare the observed versus predicted results of pond stage. The methods used were a Percent Root Mean Squared Error (% RMSE) (Equation 4.2), Pearson Correlation Coefficient r^2 test, fraction error (%) Equation 4.3, and hypothesis t-test. The r^2 test gave insight into whether each method could estimate pond stage similar to the ovserved values, thus higher values of r^2 indicate a better fit model. The RMSE is a measure of the error that results between observed (m^3) x and estimated (m^3) $\widehat{x}$ values, thus a decrease in RMSE is a result in the decrease in error and a better fit model. The % RMSE is a scaled value of the error that references the RMSE based on the maximum pond volume (m^3) V_{max} to numerically understand the scale with which each model is over- or under-predicting the pond stage. The hypothesis tests will compare how well each method was able to reduce the statistical error (m^3) μ_2 compared to the statistical error that resulted from the effective curve number method (m^3) μ_1 for each storm ($\alpha = 0.10$).

- H_0: $\mu_1 = \mu_2$
- H_a: $\mu_1 \neq \mu_2$
- $\mu_i = x - \widehat{x}$

$$RMSE = \sqrt{\frac{\sum (x - \widehat{x})^2}{n}} \tag{4.1}$$

$$\%RMSE = \frac{RMSE}{V_{max}} * 100 \tag{4.2}$$

$$FractionError = \frac{x - \widehat{x}}{x} \tag{4.3}$$

Because factors such as rainfall intensity, antecedent moisture, and relative closeness of storms can affect how the hydraulic properties of the soil react during a storm, a sub-set of continuous storms was chosen from the total dataset of storms as a calibration set. This calibration set gave insight to how the adjustment of parameters can affect how well the model predicts results compared to the observed data. Due to the consistent intensity of the storms and lack of extreme weather events, the calibration period chosen was December 23, 2010 to January 30, 2011. The topography of the surrounding land at the UGA Bioconversion Center has a slope that is directed towards the collection pond but a small curb travelling alongside the road was installed to direct runoff from the nearby land away from the compost pad and collection pond. Rainfall from rooftops was directed toward drains that kept water away from the composting area. During construction of the composting facility, a set of six concrete test pads were installed next to the compost pad with drains that drain directly to the collection pond. The observed volume change of the collection pond for each storm reflected the volume of direct runoff from the compost pad, the direct rainfall to the area of the collection pond (cm^2) A_{pond}, the direct rainfall to the area of the concrete mixing pad and external drains (m^2) A_{ext} which have a combined total area of 1996 m^2, and the design rate of seepage and evaporation loss (m^3/min) P_{loss}.

A 2-dimensional HYDRUS model was chosen in order to reflect the lateral flow of storm water that occurs in the sub-surface layer of the compost pad that is not seen in a 1-dimensional model. With HYDRUS 2D it was possible to include the factor that over the length of the compost pad, the slope would cause the runoff to drain in a specific direction. The upper boundary condition was atmospheric boundary with surface layer, the upper elevation edge of the model was a no flux boundary, the down slope edge was free drainage, and the lower boundary was constant head (-100 cm). The soil physical properties used were based on the measurements found in infiltrometer tests for the surface and sub-surface materials in the model. The surface layer of washed compost was input to the model as a layer of sand with the saturated hydraulic conductivity adjusted to match field values for the 0 to 5 cm soil layer. The hydraulic properties of the gravel layer were developed based on 66 % gravel and 34 % sand and an effective hydraulic conductivity that reflected the infiltrometer test results in the 5 to 20 cm soil layer. A full explanation of the infiltrometer test and process for determining the saturated hydraulic conductivity can be found in Appendix B of Duncan (2012). Because the model was evaluated in a 2-dimensional domain, it was assumed that any water that escaped through the free drainage face (cm^3/hr) V_{lat} would be calculated as seepage to the pond and added to the calculated volume of surface runoff (rainfall (cm^3/hr) V_{rain} minus infiltration (cm^3/hr) V_{infil}). The value of discharge from the compost pad was added to the volume of water that was assumed to have come from the external sources based on the height of rainfall (cm) H_{rain} and the volume of any water pumped from the pond was subtracted ($1.5 m^3/min$) V_{pump}.

$$PV = (V_{rain} - V_{infil}) + V_{lat} - V_{pump} + (H_{rain} * A_{pond}) + (H_{rain} * A_{ext}) - P_{loss} \tag{4.4}$$

Where:

PV = Pond Volume (m^3)

The compartmentalized model was developed to quantify the impacts of surface runoff, infiltration, and lateral seepage by developing equations that separately evaluate the different sections of the compost pad. The developed model shown in Figure 4.2 represents how during a rainfall event the properties of the porous surface will determine the distribution of runoff and infiltration. This is analyzed as a conceptual system of three compartments derived from the model similar to the model developed to calculate the rate of runoff and sediment yield in a watershed (Lee & Singh, 2005).

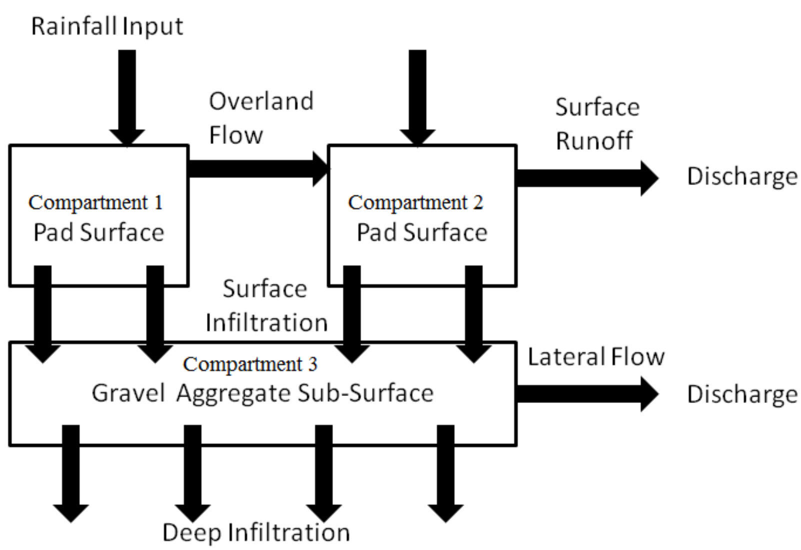

Figure 4.2: Storm water dynamics of porous pavements using the three compartment system used to analyze rates of surface runoff, infiltration, and lateral flow.

The first compartment receives the rainfall and represents the upslope surface of the compost pad (cm^2) A_1. At the bottom of the compartment is a discharge outlet representing infiltration and flows into the third compartment and the top is modeled as a weir representing overland flow leading to compartment two (cm^3/hr) $V_{Overland}$. The second compartment represents the down slope section of the surface that collects storm water due to the embankment (cm^2) A_2. The characteristics of the second compartment are similar to those of compartment one. The storm water will either infiltrate to compartment three or become overland flow leading to the discharge. The third compartment has a cross sectional area equal to that of the first compartment and second compartment combined (cm^2) A_3 and holds the water for a longer length of time representing the storage of water in the subsurface soil. At the downslope end of compartment three is an outlet that leads to the exit of the system and represents the rate of seepage through the soil (cm^3/hr) $V_{Lateral}$, and the bottom of compartment three allows minimal discharge due to deep infiltration into the compacted clay layer (cm^3/hr) V_{Deep}.

$$A_1 \frac{dh_1}{dt} = V_{Rain} - V_{Infil,1} - V_{Overland,1} \tag{4.5}$$

$$A_2 \frac{dh_2}{dt} = (V_{Rain} + V_{Overland,1}) - V_{Infil,2} - V_{Overland,2} \tag{4.6}$$

$$A_3 \frac{dh_3}{dt} = (V_{Infil,1} + V_{Infil,2}) - V_{Lateral} - V_{Deep} \tag{4.7}$$

Where:

$A_i \frac{dh_i}{dt}$ = Rate of change in volume of water in tank i (cm^3/hr)

The compartmentalized model depicts the rate of infiltration based on the measure of the hydraulic conductivity of the surface. The hydraulic conductivity describes the rate of loss from the bottom outputs of the first and second compartments because the conductivity of the soil determines the rate at which water can flow through the pores of the surface. The amount of water that is available for runoff is determined by how the hydraulic conductivity affects the initial abstraction. The conductivity is responsible for regulating the rate of holding and rate of release of storm water whether its over the top of the compartment or through the bottom. The rate at which storm water is released through the bottom compartment one is the measure of the rate of infiltration. The equation for calculating the resulting pond volume using the compartmentalized model is shown in Equation 4.8.

$$PV = (V_{Overland,2} + V_{Lateral}) - V_{pump} + (H_{rain} * A_{pond}) + (H_{rain} * A_{ext}) - P_{loss} \tag{4.8}$$

In Matlab-Simulink, the total model is broken down into three subsystems that return calculations for the three separate compartments. Simulink provides a graphic user interface to develop the equations for governing the flow in the compartments and simultaneously solving them. The input to the model is the rainfall data gathered from the rain gauge on-site and the initial water content in the surface and sub-surface soil. The initial water content is determined by the number of days after the preceding storm that the current storm occurs and the intensity of the previous storm. The output of the model is a trend-line of the rates of runoff and seepage and their effects on the height of ponded water.

While the parameters for the compartmentalized model found through field sampling were able to closely reflect the prediction of results, the major parameters were optimized using a Genetic Algorithm (GA) to find the combination of parameters that could best predict the pond volume. The GA is an optimization technique that searches through a search space of possible solutions using Darwins Theory of Evolution to repeatedly evolve the search space in order to find the most probable solution (Motoki, 2002; Shah, 2010). The consecutive storm data from December 23, 2010, to January 30, 2011, were used as the optimization set for the GA. The parameters investigated were depth of surface soil, depth of gravel layer, height of depression storage, height of embankment, saturated hydraulic conductivity of the surface and gravel layers, and initial water contents of the surface and gravel layers. During optimization, several steps were taken within the algorithm to ensure the results would fall within the range of observed parameters shown in Appendix B of Duncan (2012). The optimized parameters were compared to the parameters found at the composting site and the final parameters were determined based on how closely the optimized results reflected the real results.

The resulting flow data from the Matlab Simulink model are surface runoff, infiltration, and sub-surface lateral flow. The instantaneous heights given in Matlab Simulink are the surface and sub-surface storage. Because we assume a closed system with no unexpected losses, the input of rainfall over the affected area must equal the output of the model. After Matlab calculates the resulting pond volume from each individual rainfall event, the difference that results between each time step is calculated as the change in pond volume. The rate of overland flow accounts for the time of travel (hr) t_t from the farthest point along the length of the compost pad (cm) L. Darcy's Law is used to calculate infiltration based on the head of water (cm) h and depth of the wetting front (cm) Δx_i, the cross sectional area of the surface (cm^2) A_{ci}, and the saturated hydraulic conductivity of the surface (cm/min) K_{sat}. Lateral flow in the sub-surface region is also governed by the saturated hydraulic conductivity along with the width (cm) w and slope (%) s of the compost pad.

$$V_{Overland} = \frac{L_1}{t_t}\left[w\left(\frac{Q_{Rain} - Q_{Infil}}{A_1}\right)\right] \tag{4.9}$$

$$V_{Infil} = K(h)A_{ci}\left[\frac{h_i - \Delta x_i}{\Delta x_i} - 1\right] \tag{4.10}$$

$$V_{Lateral} = K(h)\left[h_i w s\right] \tag{4.11}$$

Where:

K(h) = Hydraulic Conductivity of Soil (cm/day)

K(h) = K_{sat} if $h \geq \Delta x_i$

K(h) = $K_{sat}e^{\alpha(\Delta x_i - h)}$ if $h < \Delta x_i$

Results

Curve Number Approach

At $\alpha = 0.1$, the hypothesis test failed to reject the null hypothesis that the dynamic, asymptotic, or event based curve number method reduces the statistical error of estimated pond stage significantly different than the effective curve number method ($p_{Dynamic} = 0.2348$, $p_{Asymptotic} = 0.9721$, $p_{Eventbased} = 0.9686$). Based on these results, each of the methods can be used as a viable drainage estimator for windrow composting pads. Using the tabulated effective curve number of 75, the resulting % RMSE was 0.99 %. The dynamic curve number performed the best with a % RMSE of 0.61 %. The asymptotic approach was able to characterize the curve number for each storm event but was unable to significantly improve the model with a % RMSE of 1.05 %. Finally, the event based optimized search method was able to perform similar to the effective curve number with a % RMSE of 0.98% (Duncan, 2012). Table 4.1 below shows how well the dynamic curve number method was at reducing the error in estimating the resulting pond volume compared to the observed values and other models used.

Table 4.1: Fraction error resulting from the curve number, HYDRUS 2D, and compartmentalized models. Results were determined based on the difference between the observed and estimated pond stage. (Duncan, 2012)

Date	Rain (cm)	CN Error (%)	HYDRUS Error (%)	CDM^1 Error (%)
12/25/2010	1.12	4.40	-15.59	-0.39
1/1/2011	2.72	11.39	-5.04	1.10
1/5/2011	0.79	1.58	-13.93	-4.45
1/17/2011	0.51	1.60	-5.43	1.48
1/24/2011	2.68	9.96	-17.74	-2.04
1/30/2011	9.16	32.58	2.27	25.05
2/9/2011	0.67	1.36	-10.25	0.05
2/24/2011	0.61	-1.82	-12.94	-3.38
2/28/2011	2.42	8.35	-1.86	-2.62
4/11/2011	0.14	-3.17	-5.81	0.54
4/15/2011	1.04	-5.87	-27.07	-15.45
4/21/2011	2.85	20.99	4.31	-12.98
4/27/2011	1.20	-1.51	-12.54	-16.04
5/26/2011	1.93	-5.23	-58.89	-14.87
6/9/2011	2.28	-0.51	-36.10	-17.46
6/15/2011	3.86	-2.30	-55.05	-35.18

CDM = Compartmentalized Dynamic Model

HYDRUS $2D^{®}$ Approach

The results of the pond volume trend predicted using HYDRUS 2D compared to the observed pond volume is shown in Figure 4.3. The data for surface runoff, infiltration, and bottom flux from HYDRUS are used to calculate the resulting trend for pond volume and the resulting fraction error can be seen in Table 4.1. The change in pond volume for each storm was determined by taking the sum of the volume surface runoff and deep drainage that occurred over the area of the compost pad that was not covered by compost piles. The total volume of runoff from the compost pad was added to the initial volume of the pond along with the volume of direct rainfall to determine the final pond volume. According to the results, the HYDRUS 2D model was able to predict the pond volume with a % RMSE of 0.65 %. This was due to the ability for HYDRUS to better determine the distribution of water that was stored in the farthest point from the seepage face along the profile of the compost pad. Table 4.2 below shows the parameters used for the HYDRUS 2D model. Using an $\alpha = 0.1$, it was found that the HYDRUS 2D model failed to reject the hypothesis that the resulting statistical error was significantly similar to the statistical error from the effective curve number method ($p = 0.0028$). The lower % RMSE and significantly different statistical error satisfy the hypothesis that the HYDRUS 2D model can provide better results for estimating pond stage than the effective curve number method.

Compartmentalized Dynamic Model Approach

The results in Figure 4.4 were able to reflect storage and flow rates for the calibration dataset. It was important that the compartmentalized model could calculate storage values per storm that were similar to the variables used in the curve number method. The similar trends for storage were necessary in proving that both methods were performing accurately because of the volume of water added to the collection pond from external sources. Figure 4.5 shows the comparison of the maximum storage calculated from the dynamic curve number method and the compartmentalized method. Table 4.3 shows the parameters found for the field testing

Table 4.2: Parameters used in the HYDRUS 2D model found using the calibration set of storms.

HYDRUS 2D Parameters	Value
Geometry	2D Vertical Plane XZ
X-Length (cm)	17068.586
Z-Length (cm)	16
Angle (cm/cm)	-0.0244
Main Process	Water Flow
Time Length	911 hours
Print times	10
Soil Material 1	Sand
Ksat 1 (cm/hr)	0.0359
Soil Material 2	Gravel
Ksat 2 (cm/hr)	38.3682
Top Boundary	Atmospheric Condition
Left Boundary	No flux
Bottom Boundary	Constant Head (-100 cm)
Right Boundary	Free Drainage
Initial Pressure head (cm)	-100

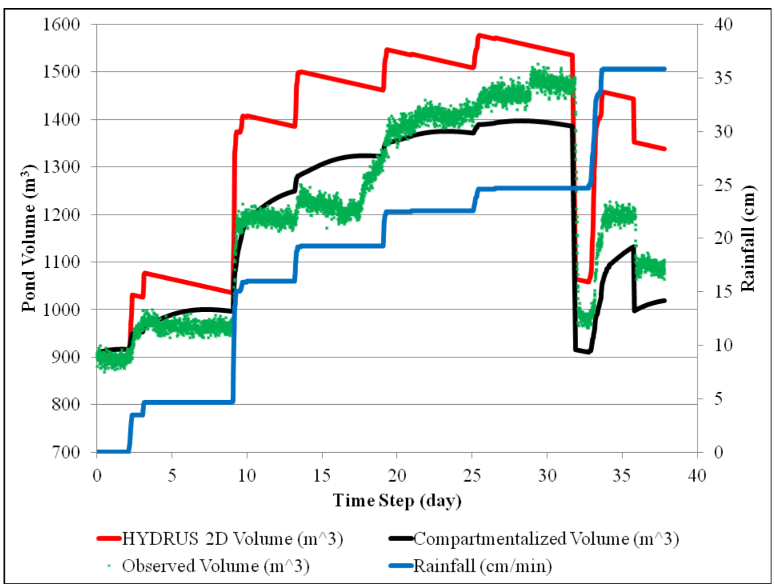

Figure 4.3: Observed (green) pond stage compared to the trend of estimated pond stage by the Compartmentalized Dynamic Model (black) and HYDRUS 2D Model (red) values for pond volume based on the cumulative rainfall (blue) using from December 23, 2010 to January 30, 2011.

and the comparison between the parameters found using the GA optimization and what was used for the compartmentalized model.

Table 4.3: Parameters used for the compartmentalized model as found through the calibration rainfall data collected from December 23, 2010 to January 30, 2011.

Parameters	Field[a]	GA[b]	CDM[c]
Areal Coverage (m^2)	4790.256	N/A	7431.525
Length of Compost pad (m)	110.050	N/A	182.924
Width of Compost pad (m)	43.528	N/A	40.626
Area of Compost piles (m^2)	2815.748	N/A	2815.748
Slope of Pad (cm/cm)	0.024	N/A	0.024
Ksat 1 (cm/hr)	N/A	0.016	0.036
Ksat 2 (cm/hr)	N/A	18.280	38.368
Keff (cm/hr)	5.505	0.198	0.43414
Depth of Surface (m)	0.025	0.020	0.020
Depth of Sub Surface (m)	0.152	0.225	0.225
Initial Surface Water Content (%)	N/A	87.859	1
Initial Sub Surface Water Content (%)	N/A	32.321	10
Depression Depth (m)	0.044	0.001	1.48E-03
Embankment Depth (m)	0.305	0.222	0.167

[a] Actual Field Parameters
[b] Genetic Algorithm Optimized Parameters
[c] Compartmentalized Dynamic Model Parameters

The equations that were developed for the compartment model was implemented using Matlab-Simulink 2010 to evaluate the time series rainfall data and is discussed in Appendix B of Duncan (2012). Using these criteria for the compartmentalized model, the predicted pond volume values have been plotted on the same graph as the observed pond volumes and the results (Figure 4.3) show a trend that is very similar. For all 16 storms, the resulting error from the observed versus predicted pond volume was compared in Table 4.1 to the other methods. This time series approach was able to improve the predictions of the model compared to the curve number method with a % RMSE of 0.78. At $\alpha = 0.1$, the hypothesis test showed that the statistical error resulting from the compartment model is significantly similar to using the effective curve number method (p = 0.2648).

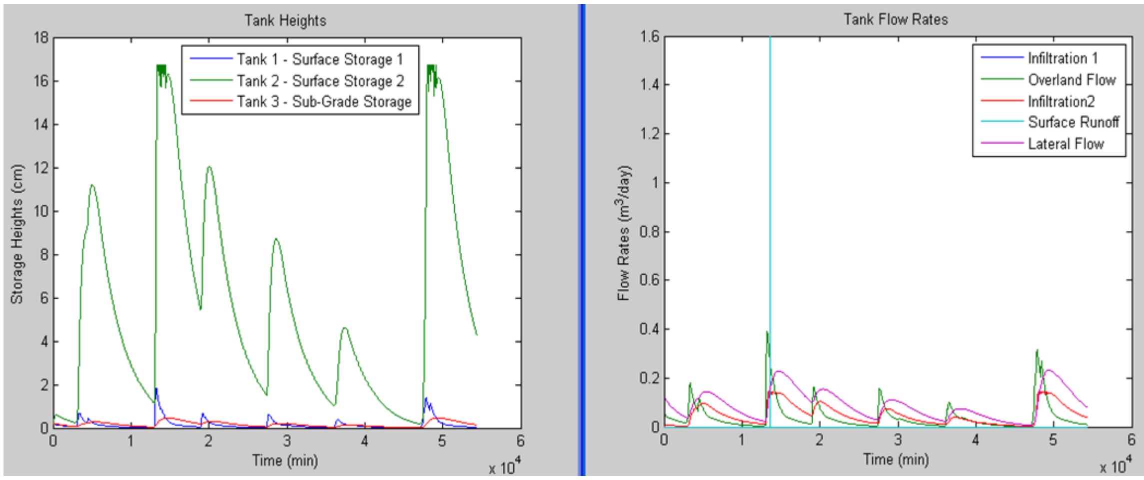

Figure 4.4: Matlab Simulink Graphs of flow rates and compartment heights. The above graphs show the expected relationship that as flow rates increase, the compartment heights properly respond with an increase as well. The parameters used were found using the Genetic Algorithm to search for the optimum parameters and discussed in Appendix B of Duncan (2012).

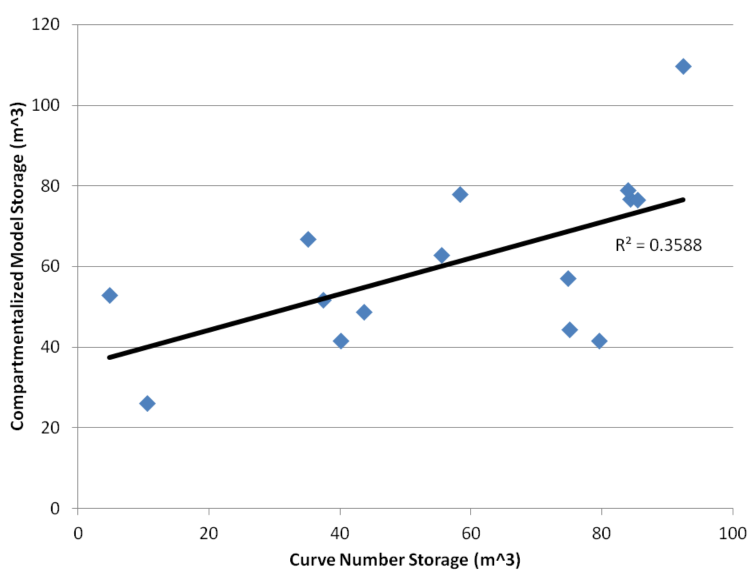

Figure 4.5: Comparison of the calculated volume of storage using the compartmentalized dynamic model and the curve number method.

Discussion

Accurate estimation of the runoff from windrow composting pads can be difficult due to how different the storm water acts with the windrows, washed compost, gravel, and clay in the vertical profile. The dynamic curve number method attempts to characterize all layers into one dynamically changing value ($r^2 = 0.98$). Results of the dynamic curve number prove to be superior to a single curve number value based on the premise that the area covered by windrows and antecedent rainfall can vary for similar sized events causing different runoff results.

Continuous time models were used to include the factor that storms of similar sizes can have different lengths of time, which the curve number does not include. The inclusion of time dependence was incorporated because the windrows of compost can initially react in a hydrophobic manner during a storm but can become hydrophilic as wetting continues. The amount of storage differs during the different wetting conditions. The HYDRUS 2D model was developed to account for surface storage and storage in the gravel layer ($r^2 = 0.98$). HYDRUS was able to provide feedback on how the storage changed in the gravel layer as the storm progressed. The compartmentalized dynamic model also included a direct calculation of surface runoff ($r^2 = 0.95$). Both dynamic models were used to create graphs of pond stage against time for a set of storms, which gives future users a better idea of how the design of the collection pond reacts to different sized storms over time.

Conclusion

At an $\alpha = 0.1$ significance level, it was found that all models were able to similar to the observed pond stage data collected at the University of Georgia Bioconversion Center Windrow Composting Pad. Although the dynamic curve number method was able to estimate the drainage from a windrow compost pad on a discrete time basis, the use of HYDRUS and the development of a compartmentalized model were able to evaluate the model using continuous time analysis that can give better insight into how storm water reacts with the compost pad with respect to time. HYDRUS and the compartmentalized dynamic model have significant advantages over the CN model including enabling a partition of surface runoff and subsurface runoff, which enables better knowledge of the design capacity for a conveyance from the pad to the containment pond. The HYDRUS model proved to be an accurate representation for the storm water characteristics and provided a graphic user interface that could show the wetting front of the surface for each time step. The results of the compartmentalized dynamic model have shown a predicted trend line for estimating the pond volume resulting from runoff on a windrow composting pad that is significantly similar to the observed pond volume. The compartmentalized dynamic model yields itself to further analysis of transfer functions of the runoff model using the developed model in Matlab-Simulink 2010 in order to create instantaneous unit hydrographs for a variety of infiltration conditions with largely uniform conditions over large areas. The Simulink feature of Matlab contains features which enables linearization of the model and analysis of transfer functions that may give further insight into the rainfall-runoff process where large areas have porous surfaces into a porous material overlying an impermeable layer.

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Chapter 5

CONCLUSION AND FUTURE DIRECTION

This project focused on investigating several different runoff calculation methods in order to determine the amount of runoff that would occur on a windrow composting pad based on different storm sizes. The runoff curve number method is a popular industry method and since its conception has received much scrutiny but has not incurred much change. This project inspected the reliability of the effective curve number method and compared it to an asymptotic method, a dynamic curve number with a variation on rainfall, a dynamic curve number with a variation on infiltration, and an event based optimized approach. While the variations on the curve number method helped to improve the reliability of predicting surface runoff, the wide range of curve number values that could describe different sized storm events leave a definitive value to still be determined. To help improve the results, a compartmentalized dynamic model and a HYDRUS model was used. The compartmentalized model uses the concept of flow through interconnected tanks to evaluate storm water flow through different sections of the soil profile. HYDRUS is a numerical computer model that can account for the different materials that may exist in the soil profile.

The curve number method was used to predict runoff for storm events that occurred on the windrow compost pad at the UGA Bioconversion Center. Characteristics for the site include six to seven large mounds of compost, a this film of washed compost material covering the surface of the pad, a sand and gravel aggregate structural surface, and a compacted clay layer beneath the surface. Using the curve number of 75 found from previous research typically resulted in an under prediction of runoff. The dynamic approach with a variation on effective curve number was able to improve on the prediction of runoff and could provide as a better method when investigating windrow compost pads (r^2 = 0.98, RMSE = 126 m^3, % Error = -6.07 %). The event based approach was able to search for the curve number that would most likely represent the characteristics of each storm and the average curve number value was taken (r^2=0.93, RMSE=200 m^3, % Error = 4.15 %). Although the predictability of the event based method could accurately characterize storm water dynamics of a windrow compost pad, the range of curve numbers found was so wide that the average curve number value performed similar to the effective curve number used.

Just like the compartmentalized model, HYDRUS 2D provided the ability to observe storm water dynamics based on the different layers in the soil profile. The 2D model looked at how runoff and infiltration reacted on the surface layer and the gravel layer of the compost pad. HYDRUS was able to account for the field measurements of infiltration, slope, and land cover that were not explicitly examined using the curve number. The analysis of the 2D model calculated total runoff from the pad only at the Southern end of the compost pad where the observed runoff went to the collection pond (r^2 = 0.98, RMSE = 135 m^3, % Error = -16.98 %).

The compartmentalized model was able to perform better than the effective curve number method because it was able to classify the different layers along the soil profile based on the hydraulic conductivity. Another improvement over the curve number method is that the compartmentalized model institutes a time series aspect to the analysis. Storms can vary in size along with the length of time the storm takes. Storms with similar rainfall depths but different time periods will have runoff dynamics that react differently because of how long it can take for the soil to become saturated. The compartmentalized dynamic model was able to predict the runoff from the storms similar to the runoff that was observed from the compost pad (r^2 = 0.95, RMSE = 163 m^3, % Error = -6.04 %). The compartmentalized model approach used for this project was done in Simulink because of the ability for Simulink to take the differential equations and use a transfer function that can relate rainfall with associated runoff. The rainfall-runoff relationship can then be used to create a unit hydrograph for windrow composting pads.

The purpose of developing a compartmental model on the Matlab-Simulink platform is Simulink's ability to work with differential equations and transform functions. The equations and system developed for the compartmental model that have been drawn in Simulink can lead to an instantaneous unit hydrograph for the material used on a windrow compost pad. Hydrographs relate time to runoff depth for a specific size storm. The development of a unit hydrograph uses the theory of convolutions in linear systems for its development by data from windrow composting pads is lacking. Thus using a linear transform function in the Simulink workspace allows the differential equations developed for the compartmental model to be linearized. The linear system can then be treated as a transfer function, and the impulse response determined. The system impulse response is taken to be the instantaneous unit hydrograph. The convolution approach can then be used to develop the runoff hydrograph based on excess rainfall from an arbitrary storm. The approach may be adapted to other stromwater management Best Management Practices such as porous pavement and other practices having uniform subsurface conditions over large areas.

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Appendix A

UGA BIOCONVERSION CENTER COMPOST PAD

Topography map

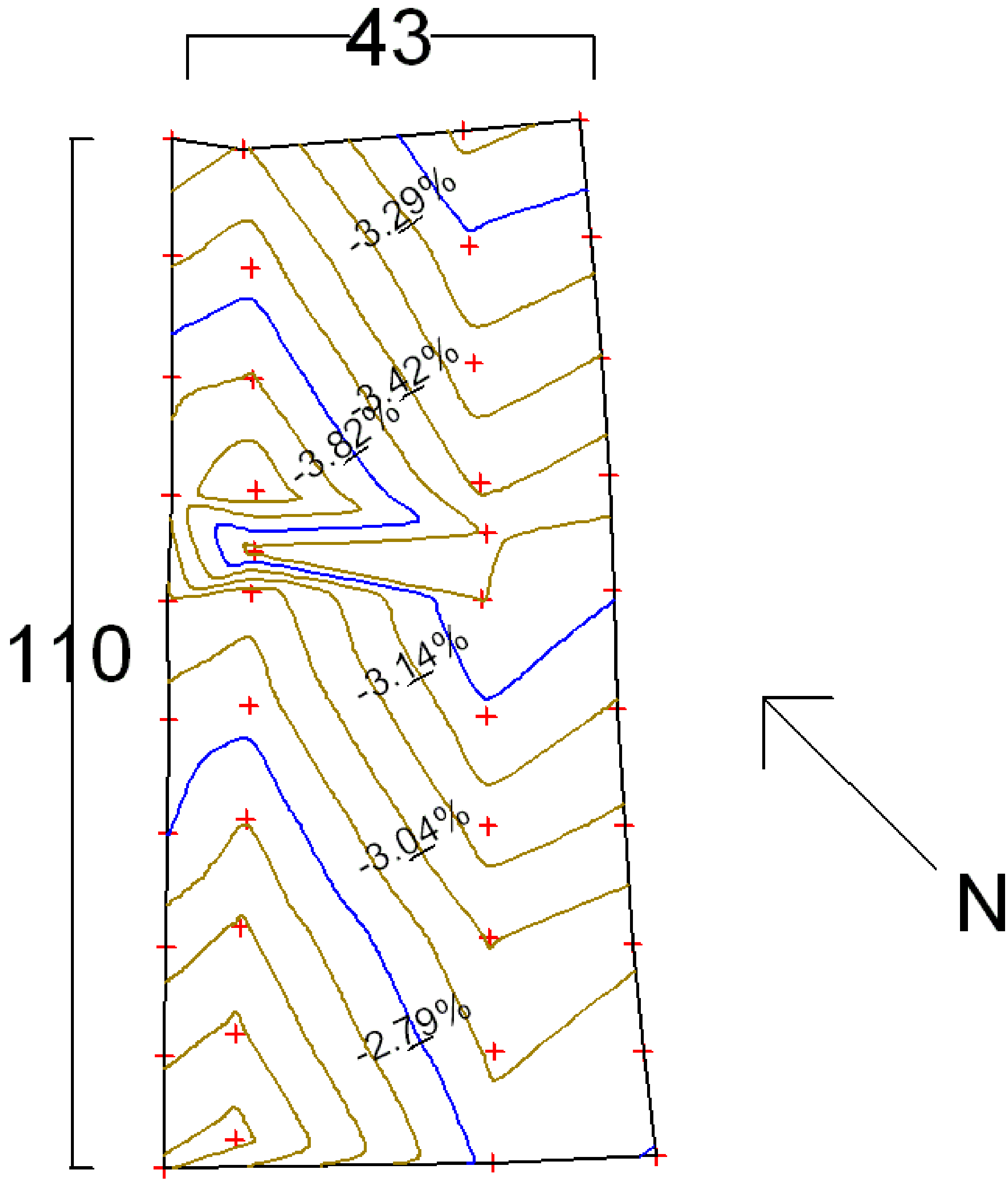

Figure A.1: Topography of the UGA Bioconversion Center Composting Pad. The direction of slope shown is the percent slope. The units for the length and Width of the Pad are in meters.

Surface storage

The embankment at the lower section of the compost pad causes a large volume of surface storage. Shown in Figure A.2 is the storage that can occur in the lower section of the compost pad due to the embankment. This large amount of storage that can occur can sometimes cause problems within the calculation for the curve number method.

Figure A.2: Surface storage that can occur at the lower section of the compost pad due to the embankment.

Compaction occurs on the surface of the compost pad due to machinery that crosses the compost pad in order to turn and relocate compost material. These machines can cause depressions on the surface that can collect storm water as seen in Figure A.3. The closer view in Figure A.4 and A.5 show that storage on the upper portion of the compost pad can reach 2 to 5 cm (1 to 2 in) within 6 hours after a small storm.

Figure A.3: Image of tire tracks that occur of compost pad. Storage shown in the depression of the tracks was found 6 hours after the previous storm.

Figure A.4: Image of the height of storage that can occur due to machinery on the compost pad. Storage shown in the depression of the tracks was found 6 hours after the previous storm.

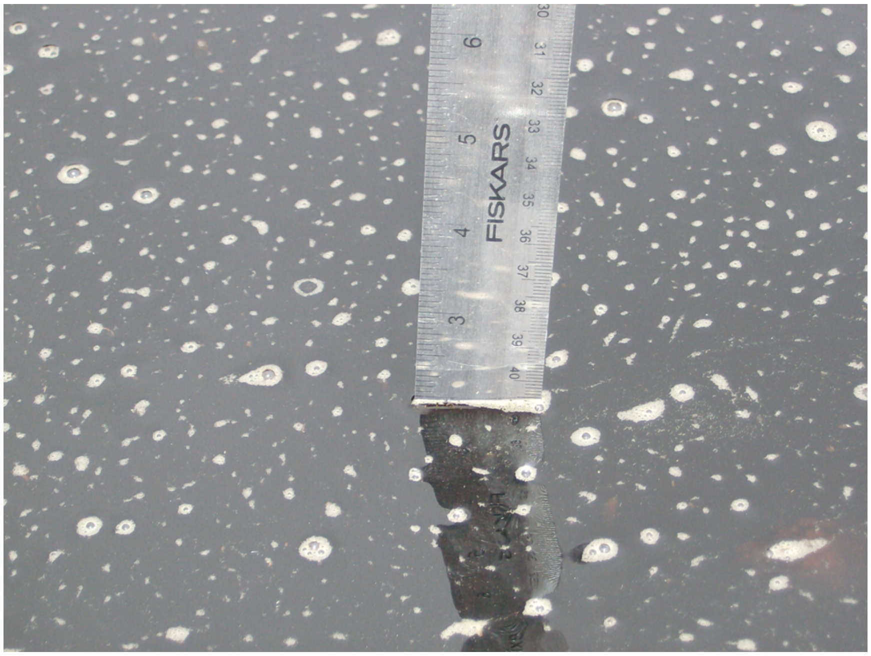

Figure A.5: A closer view of the height of storage that can occur due to machinery on the compost pad. Storage shown in the depression of the tracks was found 6 hours after the previous storm.

Collection Pond and External Sources

Throughout most of the year the level in the pond does not overflow but during times that rainfall becomes scarce the pond volume can reach very low levels (Figure A.6). The pond volume is determined by direct rainfall, runoff from the compost pad, the pumping from the well (Figure A.7), and the drainage from the concrete test pads (Figure A.8).

Figure A.6: The pond can reach extremely low heights in times of infrequent rainfall.

Figure A.7: Image of the pump that pumps water from the collection pond and uses it for spraying. The pump is rated to operate at 1516 L/min (400 gal/min).

Figure A.8: There are six concrete pads that contain small volumes of compost material that drain directly to the collection pond.

Appendix B

HYDRUS AND SIMULINK MODELING DETAILS

HYDRUS

1D Model Description

To compare the compartmentalized dynamic model to other dynamic models currently in use, a model was built in HYDRUS that provided a visual interface for analyzing the storm water dynamics. The first model was in HYDRUS 1-D that evaluated the flow of water along a vertical profile. The input properties of the material were calibrated to determine the best combination based on the same range of values as the compartmentalized model to maintain consistency in the comparison of the results. The same individual storm events were used and evaluated separately. The model was able to output the trend of surface runoff (cm^3/hr) V_{runoff}, infiltration (cm^3/hr) V_{infil}, and free drainage from the bottom of the profile (cm^3/hr) V_{drain}. Based on these values the estimated change in pond volume (total runoff) can be calculated by converting the height of surface runoff and free drainage to volumetric flow rates. Table B.1 shows the parameters that were used for the HYDRUS 1-D model. The parameters used were determined by calibrating the model based on a consecutive series of storms from December 23, 2010 to January 30, 2011. HYDRUS 1D used equation B.1 to calculate the pond volume at each time step and the results for the calibration time period are shown in Figure B.1. The results of using HYDRUS 1D were able to slightly improve the prediction of the models seen in the Curve Number, Compartmentalized Dynamic Model, and HYDRUS 2D (RMSE = 95.7 m^3, % Error = -11.2 %)

Table B.1: Parameters used in the HYDRUS 1D model. These parameters were found through the calibration dataset.

HYDRUS 1D Parameters	Value
Main process	Water Flow
Soil Materials	2
Depth of Profile	16 cm
Time length	911 hours
Hydraulic Model	van Genuchten-Maulem
Soil Material 1	Sand
Ksat1	0.0359 cm/hr
Soil Material 2	Gravel
Ksat2	38.3682 cm/hr
Upper Boundary	Atmospheric BC with Surface Runoff
Lower Boundary	Free Drainage
Depth of Surface	2.88 cm
Depth of Sub Surface	13.12 cm
Initial Pressure Head (cm)	-100 cm
Collection Pond Area (m^2)	1925.86
Area of Compost pad (m^2)	7431.53

$$PV = (V_{runoff} + V_{drain}) - V_{pump} + (H_{rain} * A_{pond}) + (H_{rain} * A_{ext}) - P_{loss} \tag{B.1}$$

2D Model Description

The output of HYDRUS 1-D created small error in interpolation because a 1-D model was used to calculate 2-D dynamics. HYDRUS 2-D is a computer program that can simulate two-dimensional dynamics of soil moisture by numerically solving the Richards equation based on finite element analysis (Zhou et al., 2007). One area of error occurred from the calculation of surface runoff. In a 1-D model, the height of surface runoff was interpolated over the entire surface area of the compost pad but in reality, the only surface water that was actually observed as surface runoff was what was lost over the embankment. Any surface

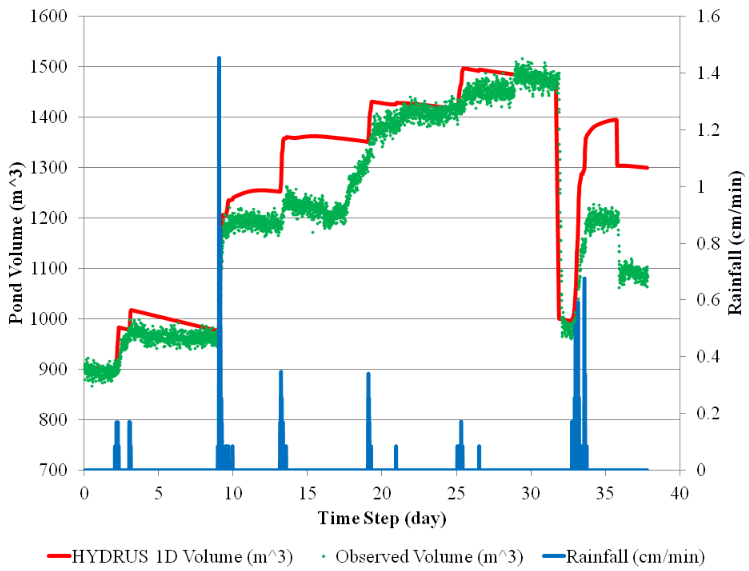

Figure B.1: Observed (green) and Predicted (red) values for pond volume based on rainfall (blue) during the calibration period using the HYDRUS 1D model.

water at the rear of the compost pad must first travel the length of the entire pad and avoid infiltration before it can actually be calculated as runoff. The other area of concern was the compacted clay layer. Because the 1-D model could not calculate for lateral flow, all vertical drainage was assumed to be sub-surface runoff. This does not accurately represent what was observed at the compost site. The clay layer allows for minimal infiltration but also forces most of the storm water to flow laterally towards the drainage pond. The use of HYDRUS 2-D allowed for runoff and lateral flow to be calculated along the vertical face of the profile.

Compartmentalized Dynamic Model

The compartmentalized model, originally described by (Lee & Singh, 2005), uses the idea of a system of interconnected compartments to describe the flow of storm water and sediment yield through a watershed. The parameters of the compartmentalized model are defined by the amount of rainfall, the height of depressions on the surface, and the rate of infiltration and lateral seepage. The structure of the originally conceived compartmental model was adjusted based on the structure and composition of the windrow compost pad that testing was done on. The surface of the pad was represented by a combination of the first and second compartments. This was because of the slope of the pad and the embankment at the bottom. The upper portion of the pad had small depressions that could hold surface storage and surface runoff could flow laterally to the lower section of the pad. The lower portion was stopped by an embankment that could hold back a larger quantity of water. The depressions of the upper section can be seen in B.2 and the lower section in B.3. Compartment one represents the surface of the upper portion of the compost pad and can receive rainfall as the input. Water that enters compartment one can either flow laterally to compartment two as overland flow or infiltrate into the sub-surface compartment three.

Figure B.2: Upper section of compost pad showing windrows and smaller depressions.

Unlike the surface compartments, compartment three represents the entire sub-surface layer. The composition of compartment three is a gravel and sand aggregate that extends a depth of 15-20 cm and can be seen in B.4. Compartment three has a cross sectional area equivalent to the total area of the compost pad. At the bottom of compartment three is the compacted clay layer that allows for minimal infiltration into the deep storage. The purpose of the clay layer is to force sub-surface water to flow laterally toward the discharge instead

Figure B.3: Image of the lower section of the compost pad with gravel embankment (left) where water has been found to pool as surface storage. This section is represented by compartment two in the compartmentalized model.

of vertically. Water is allowed to exit compartment three toward the southern end at a lower elevation.

Figure B.4: Profile view of the sub-surface gravel/sand aggregate layer of the compost pad. This layer extends from the surface of the compost pad down to the compacted clay layer.

The outputs of the compartmentalized model are numerical results that show the change in height of water in each compartment with respect to time (m^3/hr) $A_i\frac{dhi}{dt}$ as well as the flow rates of overland flow (m^3/hr) $V_{Overland,1}$ (compartment one to two), surface runoff (m^3/hr) $V_{Overland,2}$ (compartment two to discharge), infiltration (m^3/hr) $V_{Infil,i}$ (compartments one and two to three), lateral flow (m^3/hr) $V_{Lateral}$ (compartment three to discharge), and deep infiltration beneath the compost pad (cm^3/hr) Q_{Deep}. Figure B.5 gives a visual representation of how the compartmentalized model will be executed.

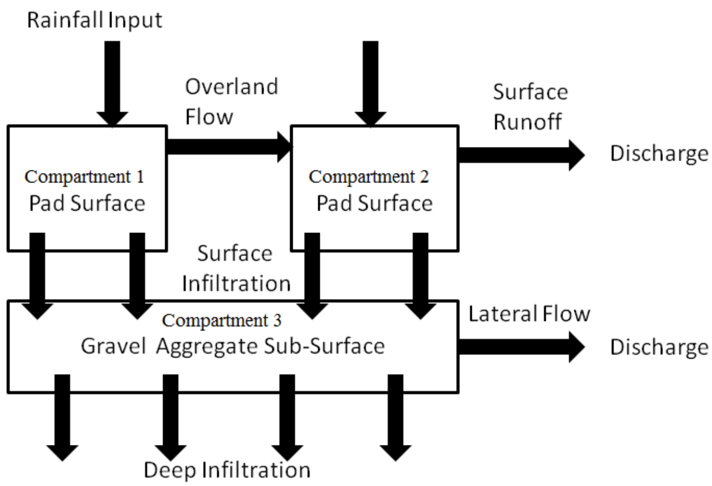

Figure B.5: Storm water dynamics of porous pavements using the three compartment system used to analyze rates of surface runoff, infiltration, and lateral flow.

$$A_1\frac{dh_1}{dt} = V_{Rain} - V_{Infil1} - V_{Overland} \tag{B.2}$$

$$A_2\frac{dh_2}{dt} = (V_{Rain} + V_{Overland}) - V_{Infil2} - V_{Runoff} \tag{B.3}$$

$$A_3\frac{dh_3}{dt} = (V_{Infil,1} + V_{Infil,2}) - V_{Lateral} - V_{Deep} \tag{B.4}$$

Rainfall and Pond Volume Data Collection

To determine the amount of rainfall that occurred during each storm, a HOBO Model number RGB-M002 tipping bucket rain gauge was installed at the site in August 2010 to collect rainfall data every minute (Figure B.6). The rain gauge was installed in a clearing between the compost pad and the collection pond in a location that would allow for the maximum collection of rainfall while avoiding any interception from the tree line or any splash from the ground. During the time period the data was collected, storm events were divided by the amount of time between each storm. A storm began 12 hours before the first recorded precipitation and extended until 24 consecutive hours after rainfall ceased. This time period was chosen to allow for any runoff from the compost pad that occurred during the storm to be accounted for.

Figure B.6: Tipping bucket rain gauge used at the UGA Bioconversion Center to measure the amount of rainfall.

A HOBO U20-001-04 (Onset Computer Corporation; Bourne, MA) pressure transducer was placed approximately 2 m below the water line in a well next to the pond in order to record the height of the pond every 10 minutes. Because of its trapezoidal design a direct relationship was used to convert the height of the pond to a volume. The staff gauge used to determine the reference height in the pond can be seen in Figure B.7 and the full pond can also be seen in Figure B.7. Initially a single pressure transducer was used to determine the pond level but it was found that due to variations in atmospheric pressure, inaccuracies occurred during calculation (Figure B.8). The inaccuracies lead to the installation of a second pressure transducer that was placed in the same well above the level of water to record the atmospheric pressure. After the data from the pressure transducers has been collected by the computer, the recorded height of the pond was converted to the equivalent volume by a regression equation (Equation B.5) based on the shape of the pond developed by the engineering team during the building stage of the site.

Figure B.7: (Left) Staff gauge used to determine the reference height in the collection pond. B. (right) Full view of the collection pond used to collect runoff from the compost pad.

$$V = 31,191 * H^2 - 8,051.6 * H + 121.01 \tag{B.5}$$

Infiltration

The rate of infiltration was determined experimentally through infiltrometer tests. It has been found that the permeability of a soil is heavily weighted on the finer grain sizes in soils (Lu, 2007). A double ring infiltrometer was used that received water through two water tanks and a constant head was maintained using a float valve. After the infiltration data was collected, the hydraulic conductivity was calculated using the spreadsheet developed. It was found that the hydraulic conductivity fell within the range of 7.09 to 14.66. By knowing the saturated hydraulic conductivity, the value can be included in the compartmentalized

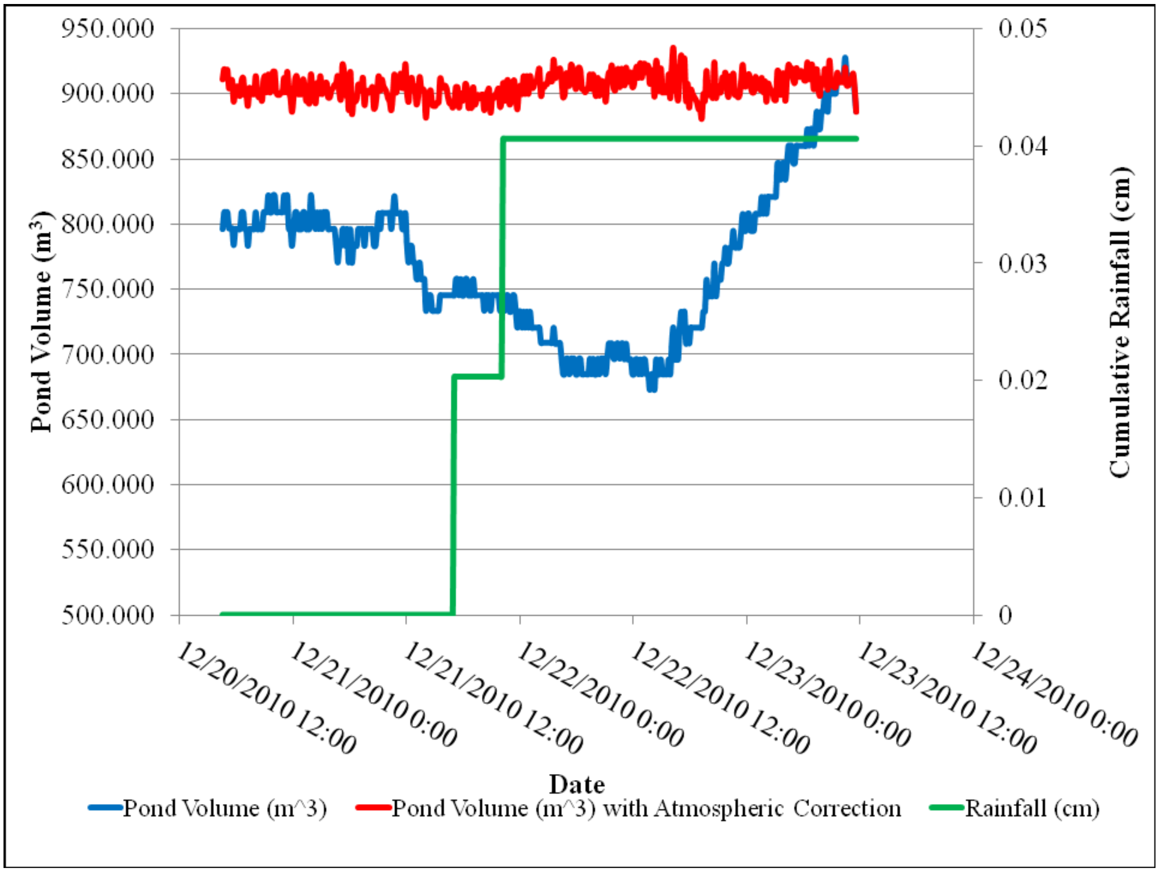

Figure B.8: A comparison of the error that can occur from the pond level logger when the impact of barometric pressure is not accounted for. During the rainfall event, changes in atmospheric pressure caused the logger to underestimate the level in the pond.

model equation and the rate of sub-surface lateral flow can be determined. Because the rate of infiltration into the clay subsurface of the compost pad was found to be negligible, any storm water that infiltrated from the surface was calculated as lateral flow (Equations (B.6) and (B.7)). Darcy's Law is used to calculate infiltration based on the head of water (cm) h and depth of the wetting front (cm) Δx_i, the cross sectional area of the surface (cm^2) A_{ci}, and the saturated hydraulic conductivity of the surface (cm/min) K_{sat}. Lateral flow in the sub-surface region is also governed by the saturated hydraulic conductivity along with the width (cm) w and slope (%) s of the compost pad.

$$V_{Infil} = K(h)A_{ci}\left[\frac{h_i - \Delta x_i}{\Delta x_i} - 1\right] \tag{B.6}$$

$$V_{Lateral} = K(h)\left[h_i w s\right] \tag{B.7}$$

Where:

K(h) = Hydraulic Conductivity of Soil (cm/day)

K(h) = K_{sat} if $h \geq \Delta x_i$

K(h) = $K_{sat}e^{\alpha(\Delta x_i - h)}$ if $h < \Delta x_i$

The following process was used in determining the rate of infiltration for the compost pad. The tests were set up according to Figures B.9 and B.10 and B.11. When the height of water in the rings reached its maximum height, the flow in stopped. Once infiltration caused the water level to decrease, the float valve would open the spout and let more water in from the holding tanks. Figure B.12

After the field data was collected, the results were input into a spreadsheet application in order to determine the resulting hydraulic conductivity for the compost pad. Table B.2 shows the input of time (min) ΔT and storage tank height (mm^3) ΔV and how that information is transformed into volume and infiltration based on the wetting front (mm) d. Converting the storage tank height into volume was done based on equations for a cylindrical trapezoidal tank and Equation B.8 is how the hydraulic conductivity was calculated. Once the table was

Figure B.9: After a proper location was found and extra debris was cleared away, the rings were placed in the ground at a depth that would prevent lateral loss.

Figure B.10: As an added precaution to prevent loss through the sides, the rings were surrounded by compacted clay.

Figure B.11: Water was supplied to the rings by a set of water tanks and measured at a constant interval using rulers.

Figure B.12: As the water level in the ring increased, a float valve was used to keep the head of water constant.

completed, an x-y plot of Time versus Hydrualic Conductivity was made and the point where the conductivity becomes constant was considered to be the saturated hydraulic conductivity (Figure B.13).

$$K(h) = \frac{\Delta V}{\Delta T} \frac{1}{\frac{d+h}{d}} \tag{B.8}$$

Table B.2: Table used to calculate hydraulic conductivity

Time (min)	Tank Height (cm)	Tank Volume (cm^3)	ΔV (cm^3)	K (cm/min)
0	49.5	89742.2	0.0	0.00
5	45.7	82039.3	7702.9	0.97
10	42.9	76184.2	5855.1	0.67
15	41.9	74217.6	1966.6	0.23
20	41.0	72243.5	1974.1	0.22
25	40.6	71583.7	659.7	0.07
30	40.3	70923.2	660.5	0.07
35	39.7	69599.6	1323.6	0.15
45	39.1	68272.7	1326.9	0.08
55	38.1	66276.0	1996.7	0.11
65	37.5	64940.7	1335.3	0.08
75	36.8	63602.0	1338.7	0.08

Runoff

When the maximum rate of infiltration is reached or the rate of rainfall is greater than the rate of infiltration, storm water is stored on the surface and can potentially become surface runoff. Surface runoff occurred when the height of surface storage became greater than the height of the depressions on the surface of the compost pad. To calculate the rate of surface runoff, the concept of a weir equation was useful because the flow rate was a direct relationship dependent on the height above the weir base. While the height of surface storage was below the depression depth, zero runoff would occur. When the height of water rose above five centimeters, runoff occurred. Although the two compartment model was an improvement compared to the curve number method in calculating runoff from the

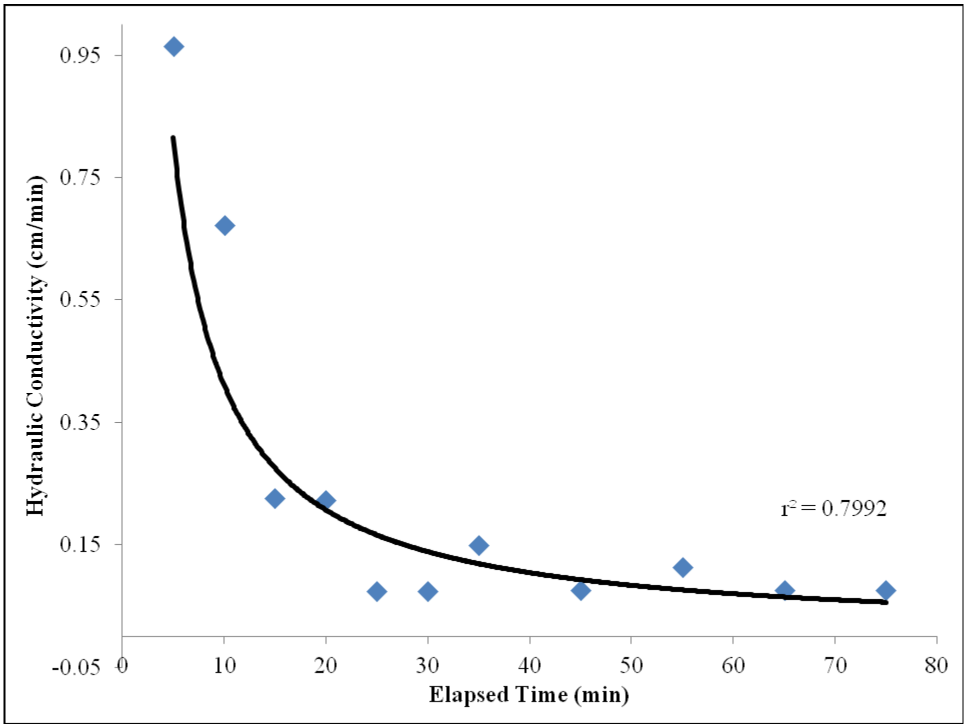

Figure B.13: Graph used to determine the hydraulic conductivity from the infiltrometer test performed in the area before windrow 1. The point at which the graph approaches a steady value is considered the hydraulic conductivity as demonstrated by the best fit line shown.

compost pad, it failed to account for the amount of storage on the Southern end of the compost pad due to less compacted material and an embankment. To correct this, a three compartment model was used. Compartment one was the upper portion of the compost pad. This area contained the compost piles and the majority of the washed compost material. Compartment two was the lower portion of the compost pad where the embankment would cause storm water to pond rather than immediately exit the compost pad as surface runoff. Compartment three was the subsurface material similar to the two compartment model.

Runoff was calculated by using the overland flow equation (Equation B.9). This equation starts by calculating the time of travel for the storm on the compost pad to determine the amount of time it would take for water from the furthest point on the compost pad to reach the end (hr) t_t where Manning's roughness coefficient (dimensionless) n and the slope (%)

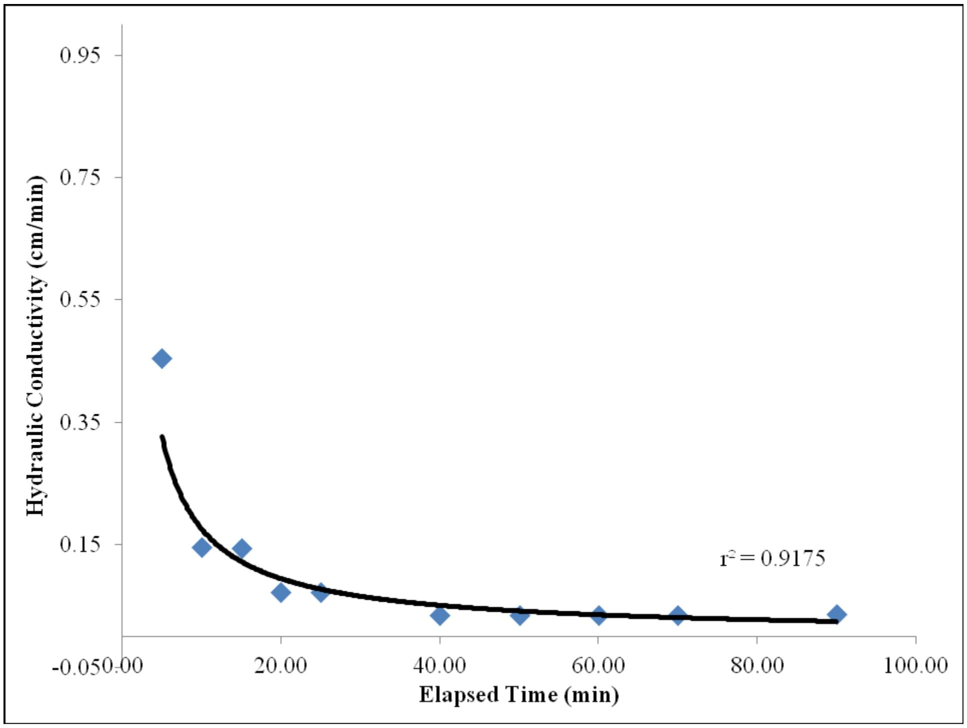

Figure B.14: Graph used to determine the hydraulic conductivity from the infiltrometer test performed in the area between windrows 2 and 3. The point at which the graph approaches a steady value is considered the hydraulic conductivity as demonstrated by the best fit line shown.

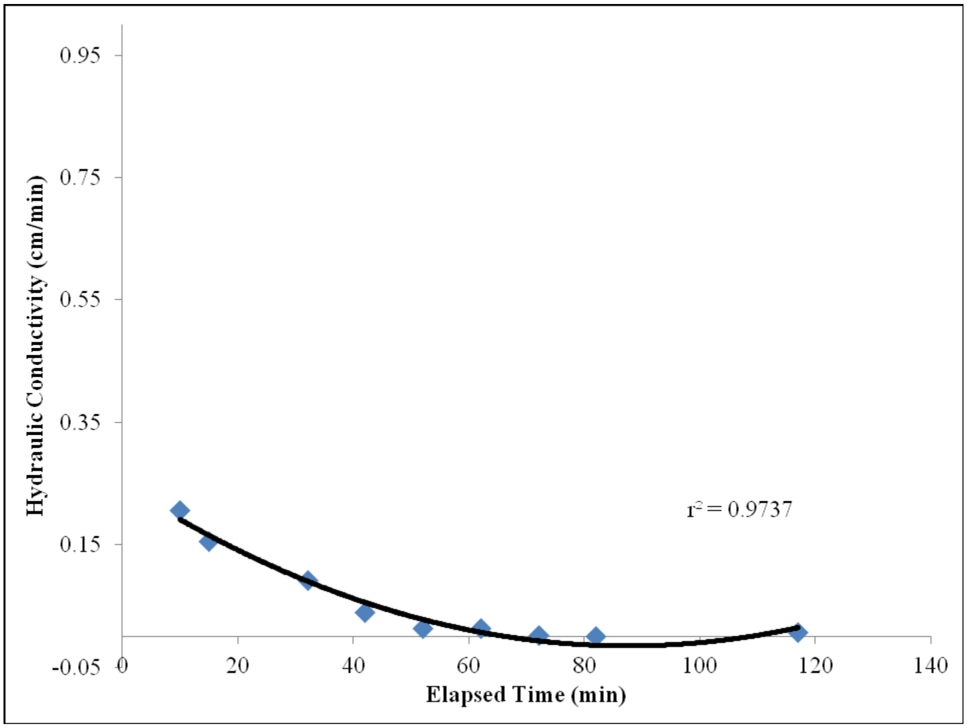

Figure B.15: Graph used to determine the hydraulic conductivity from the infiltrometer test performed in the area between windrows 4 and 5. The point at which the graph approaches a steady value is considered the hydraulic conductivity as demonstrated by the best fit line shown.

s are substituted. The volume of surface water on the compost pad is divided by the time of concentration to determine the volumetric flow rate of runoff. To prevent calculation of runoff when there is no surface storage, the overland flow equation was only used when the height of surface storage became higher than the height of depression on the surface; otherwise the runoff was zero.

$$V_{Overland,i} = \frac{L_i}{t_t}\left[w\left(\frac{V_{Rain} - V_{Infil}}{A}\right)\right] \tag{B.9}$$

Where:

$$t_t = \frac{0.93 * (L * n)^{0.6}}{\frac{Q_{Rain} - Q_{Infil}}{A}^{0.4} * s^{0.3}}$$

Application in Matlab-Simulink

To evaluate the differential equations of the compartmentalized model on a time series approach, the equations were developed as a Matlab-Simulink model. The model was developed to calculate and output the output flow rates and storage depths at each time step of the storm event. The full model used in Simulink is shown below in Figure B.16. The model receives rainfall and other variable inputs from the Matlab workspace.

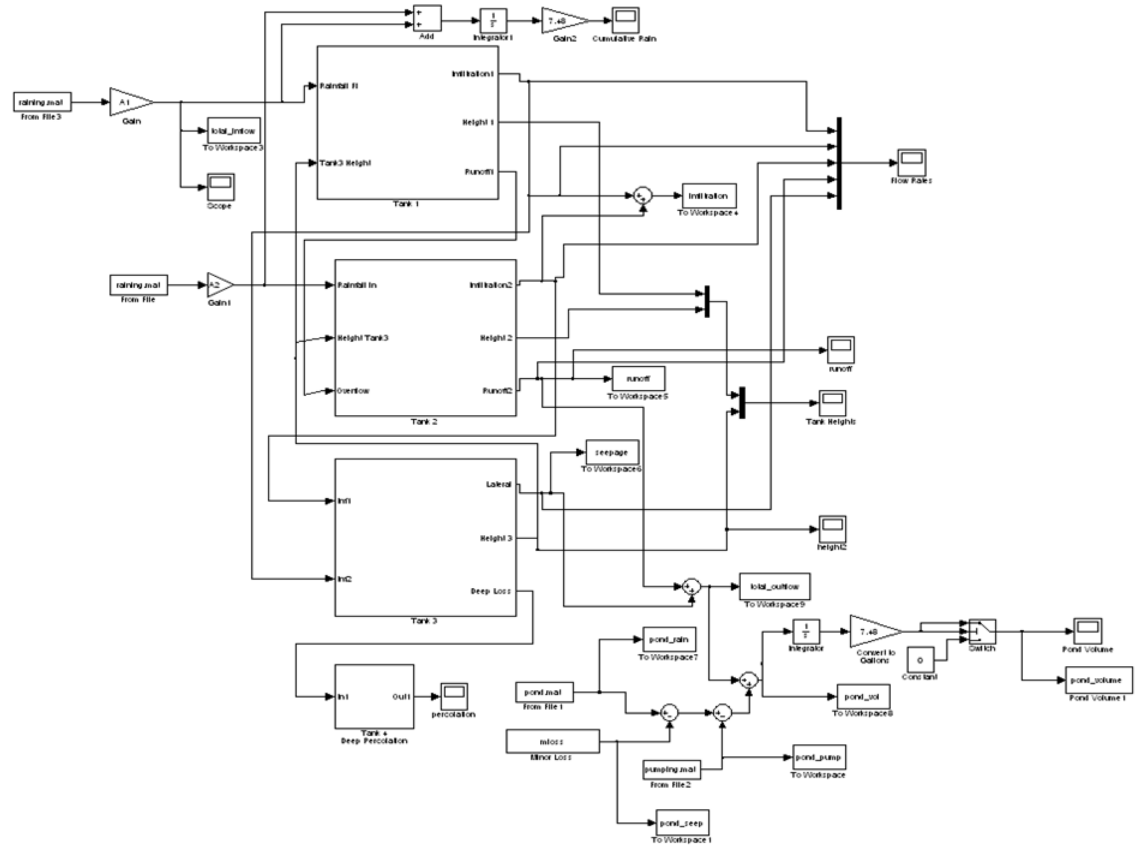

Figure B.16: Full compartmental model built in Simulink. The rainfall input as well as all variables are read from the Matlab workspace. At the end of the model, the rates of infiltration, runoff, storage for each tank and the resulting pond volume are exported to the Matlab workspace.

Compartment 1

Compartment one is used to calculate the flow dynamics over the upper portion of the surface of the compost pad. The input to compartment one is rainfall and the outputs are infiltration into compartment three and overland flow to compartment two. Figure B.17.

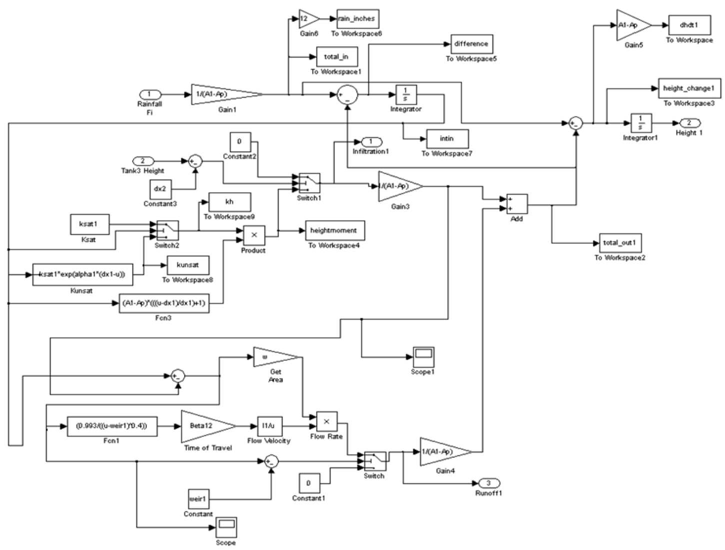

Figure B.17: Simulink Model of Compartment 1

Compartment 2

Compartment two is used to calculate the flow dynamics over the lower portion of the surface of the compost pad with the embankment stopping the flow. The inputs to compartment two are rainfall and overland flow from compartment one and the outputs are infiltration into compartment three and overland flow to the discharge. Figure B.18

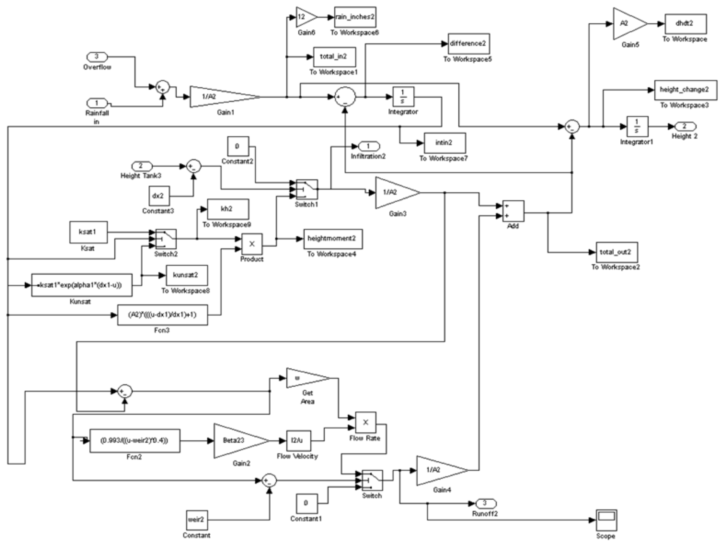

Figure B.18: Simulink Model of Compartment 2

Compartment 3

Compartment three is used to calculate the flow dynamics that occur in the sub-surface of the compost pad. Dynamics in this layer are different because the flow is lateral through porous media. The inputs to compartment three are the infiltration from compartments one and two and the output is deep drainage and seepage to the discharge. Figure B.19

After the equations had been developed, the next step was to determine the values for each of the variables. During the field tests for the rate of infiltration, the area, length and width of the compost pad, and the depths of each layer of soil in the soil profile, a range of values was found. For each parameter, a minimum and maximum was defined. It was important for the compartmentalized model that the parameters used would maximize the models ability to predict runoff, therefore the model needed to be calibrated. The calibration dataset was a series of consecutive storms from December 23, 2010 to January 30, 2011. This series of storms was chosen because they exhibited a moderate and consistent trend between rainfall and recorded runoff and did not contain any large events that could cause error to

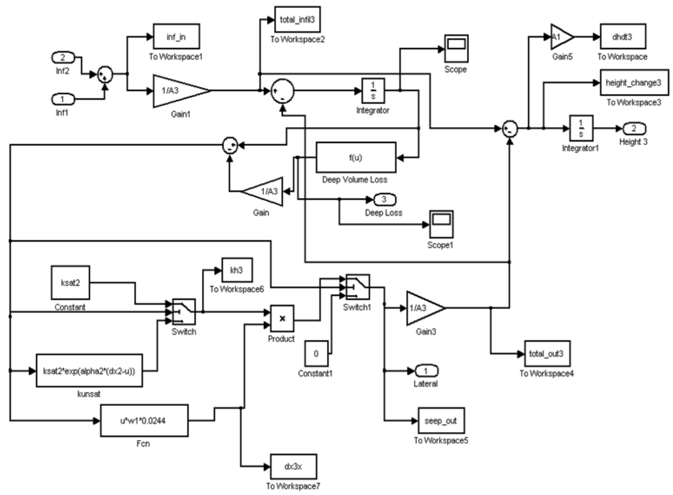

Figure B.19: Simulink Model of Compartment 3

the model.

A beneficial technique to searching for optimal settings is the use of Evolutionary Algorithms, particularly the Genetic Algorithm (GA). The GA provides a search technique that uses a population of search points and uses selection, crossover, and mutation to continuously evolve the population in search of a global maximum (Motoki, 2002). The major purpose of instituting the GA is its ability to use a large search space and adaptive search methods that perform a search in place of feasible candidate solutions in a limited amount of time (Alcala-Fdez et al., 2010). Several limitations were included in the GA search scheme to ensure the values found would fall within the range of real values. After the results were extracted from the GA, the parameters were adjusted to account for real-life factors that could not be examined in the search scheme and must be investigated personally. The levels of storage and rates of infiltration found in the field show patterns that can change based on how well the soil transmits water.

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