SIMULATION OF RUNOFF AND POLLUTANT LOSS IN URBANIZING WATERSHEDS

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Abstract

The effect of urbanization on previously agricultural watersheds is an increasingly important issue for watershed planners. Urbanization increases runoff and pollutant loadings to the watershed outlet. Watershed planners in areas that previously had little impervious cover must now consider the effects of new roads and buildings on hydrologic processes. The ANSWERS-2000 watershed model was modified to simulate watersheds with mixtures of agricultural and urban areas. In addition, components were added to simulate atmospheric deposition and urban management practices, including wet ponds, dry ponds, and infiltration trenches.

The modified model was evaluated on two watersheds in Blacksburg, Virginia, including a subwatershed of Stroubles Creek and a large parking lot on the Virginia Tech campus with a dry pond at its outlet. The model predicted the hydrology and pollutant losses for the year 1999 from the Stroubles Creek watershed within 50% of the observed values after calibration. Prediction errors were much higher for the parking lot and dry pond simulation of the period of time from August 1995 to February 1996. For the parking lot inflow to the dry pond, errors ranged from 0 to 100%. For the dry pond effluent, errors for runoff and sediment losses were –11.5 and 60.1%, respectively, and nutrient losses were poorly predicted (greater than 100% error). There was considerable uncertainty as to the quality of the observed data and this may account for some of the predicted sediment and nutrient loss errors. The modified model was applied to the Battlefield Green Watershed in Hanover County, Virginia to demonstrate the watershed response to development in that watershed. As simulated, sediment and nutrient losses were 30 to 50 times higher after development.

The model is intended for use on watersheds with an impervious cover of 30% or less, due to the increased difficulty in accurately quantifying the hydrology of highly urbanized watersheds and

because of uncertainty in atmospheric deposition rates on such watersheds. The pond subroutines are very simplified, and limit simulation to ponds with simple geometries.

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Chapter 1. Introduction

From 1992 to 1997, a total of 9,653,000 acres of cropland, pastureland, and forestland in the United States were converted to urban land uses (NRCS, 2000c). Watershed planners in agricultural watersheds often neglected urban areas as they comprised an extremely small portion of the total watershed. However, with urbanization increasing in agricultural areas, watershed planners must now consider the effects of the increasing urban area in predominately agricultural watersheds. Most water quality assessment tools (models) have been created for either developed or undeveloped watersheds. In addition, most water quality planners are accustomed to working in either developed or undeveloped watersheds. Consequently, there is a need for new assessment tools that can be used to analyze both rural and urban watersheds and those that are in transition.

Several models exist for analyzing urban watersheds, including the stormwater management model (SWMM) (Metcalf & Eddy Inc., 1971); the Illinois urban drainage simulator (ILLUDAS) (Noel & Terstriep, 1982); and the storage, treatment, overflow, and runoff model (STORM) (US Army Corps of Engineers, 1977). These models were created specifically for use with developed watersheds and give little detail to the undeveloped areas of the watershed. The non-urban areas are represented simply as 'pervious' areas and are assigned a curve number or other runoff coefficient to partition rainfall into runoff and infiltration. Consequently, these models have difficulty simulating diverse agricultural practices, such as terracing and crop rotations; they cannot effectively simulate different crops. For watersheds with diverse agricultural and urban land uses (such as those which exist in Blacksburg, VA, where the university's cropland, turf, and pastures are interspersed through the town), more detailed modeling is required than the current urban models allow.

Other models exist to quantify and determine the quality of runoff from pervious areas. However, these models were not developed to simulate urban land uses, and their use in urban areas has generally not been validated. Furthermore, most existing agricultural watershed models are not well suited for the addition of an urban component. For example, the annualized agricultural nonpoint source model (AnnAGNPS) does not route flow from cell to cell (although it is a distributed parameter model) but instead routes all losses from a cell directly to a stream reach within each cell, thus making it impossible to simulate the spatial character of some urban best management practices (BMPs) (Cronshey and Theurer, 1998). Some models are capable of modeling pervious and impervious areas but are not in the public domain (e.g., MIKE SHE).

In order to properly simulate a mixture of developed and undeveloped areas, a model must be able to represent different land use conditions intermingled together. This is facilitated by the use of a distributed parameter model, which is also useful in representing the spatial nature of urban BMPs. Many such BMPs focus on breaking up the impervious areas to reduce runoff and peak flows, and to detain some of the sediment and nutrients washed off the land. A distributed parameter model can simulate the location of pervious areas inserted to break up the impervious land, and thus can determine where pervious BMPs need to be located and their effectiveness in reducing runoff, sediment, and nutrient losses. A lumped parameter model is incapable of doing this because it cannot consider the spatial placement of BMPs. The existing urban water quality models are lumped in that they break down watersheds into fairly large subwatersheds. In addition to the distributed parameter requirement, in order for the model to be useful in simulating the effects of management decisions over the long term, a continuous simulation model is required. A continuous simulation model accounts for moisture loss in the soil between storm events and is capable of simulating multiple storm events, which enables it to make long-term predictions. By contrast, a single-event model is useful for estimating the loads on a structure for a design storm, but does not provide the long-term interactions that would be necessary to quantify long-term response to changes in watersheds that might affect hydrology and pollutant loss. The single-event model does not account for hydrologic processes between storm events and thus cannot provide an accurate long-term representation of the watershed.

1.1 Objectives

The overall goal for this research project was to develop a model to simulate runoff and pollutant losses in urbanizing watersheds better than currently available models. The model chosen for this development is ANSWERS-2000, a continuous simulation, distributed parameter model developed for water quality planning in predominately agricultural watersheds. ANSWERS-2000 has never been validated in urban watersheds and it would benefit from the addition of new submodels to simulate urban hydrologic processes.

The specific objectives of this research were:

1. To develop an improved model for simulating the effects of urban best management practices on water quality and runoff in urbanizing watersheds.
2. To evaluate the model and determine if it is sufficiently accurate for water quality planning purposes.
3. To demonstrate how the model can be used for water quality planning in urbanizing watersheds.

In order to accomplish the above objectives, the following tasks were necessary:

1. Improve the capability of the ANSWERS-2000 model to simulate impervious areas and other urban land uses such as lawns.
2. Improve the ability of the ANSWERS-2000 model to simulate flow over non-erodible surfaces and in non-erodible channels.
3. Improve the ability of the ANSWERS-2000 model to simulate urban BMPs used for water quality management in urbanizing watersheds.
4. Investigate the sensitivity of the model to new model input parameters.
5. Evaluate the model using observed data from urban and urbanizing watersheds and determine if model accuracy is adequate for planning purposes in urbanizing watersheds.
6. Run the model on an urbanizing watershed for pre- and post-development conditions to demonstrate the intended use of the model.

Chapter 2. Literature Review

2.1 Introduction

The literature was reviewed to investigate the effects of urbanization on watershed hydrology and water quality and to review the methods used by models to represent impervious land uses. First, the impacts of urbanization were reviewed and the extent of urbanization in the United States was quantified. Next, a review of urban best management practices and their designs and effects was conducted. Finally, the methods used by different watershed models that might be capable of representing a mixed agricultural and urbanized watershed were considered.

2.2 Urbanization Impacts

Urbanization, from a hydrologic perspective, can be defined as the addition of impervious area to a watershed. Impervious area includes, but is not limited to, structures such as roads, houses, parking lots, and industrial buildings. Commonly, cities are referred to as 'urban' and towns have the distinction of being 'rural'; however, in this context urbanization refers to the addition of impervious areas to a watershed regardless of scale. Urbanization of watersheds causes drastic effects on hydrology (Rao and Rao, 1977). These changes come in the form of increased runoff (50% or more), increased peak flows (two to fivefold increase), and up to 50% decrease in time of concentration (Whipple *et al.*, 1981; NVPDC, 1992; Schueler, 1987; Prasad and Olson, 1995; Whipple *et al.*, 1983; Berger and Jensen, 1980). Runoff increases are a result of the increase in impervious area and resulting decrease in infiltration; and the elimination of storage associated with depressions in the natural land, interception from plant leaves, and retention by organic matter (Schueler, 1987). A distinction can be made between total and effective impervious area. Total impervious area includes any surface through which water cannot infiltrate. Effective impervious area disregards impervious areas that are not directly connected to receiving waters via other impervious areas and/or a constructed conveyance system. Any impervious area whose runoff flows to a pervious area is disregarded in the effective impervious area assessment (Booth and Jackson, 1997). The effective impervious area is the area that will have the most impact on the hydrology of a watershed, and thus whether or not impervious area drains directly to the receiving stream should be addressed when considering watershed hydrology (Booth and Jackson, 1997).

Another effect of the increased runoff that accompanies urbanization is the widening of stream channels. Before urbanization, channels tend to erode at a very slow rate (on the order of hundreds of years). However, the increased flows that accompany urbanization cause stream banks to erode at a much faster rate (Whipple *et al.*, 1981). The annual number of floods increases, as does the magnitude of flooding (Whipple *et al.*, 1981; Schueler, 1987; Oslin *et al.*, 1988; Whipple *et al.*, 1983).

According to a study performed by the United States Executive Office of the President's Council on Environmental Quality, 80% of the urban areas studied had impaired water bodies due to nonpoint source pollution (i.e., urban runoff) (Colston, 1975). Many urban watershed models seem to focus on predicting the loading effects on the existing human-made drainage systems, and focus less on the effects of nonpoint source pollution (Terstriep *et al.*, 1990; Grayman *et al*., 1982). However, in addition to hydrologic effects on the watershed, urbanization affects water quality.

The filtering effect of vegetation is lost when runoff from impervious areas is transported directly to streams via the stormwater conveyance system (NVPDC, 1992). The increased rates of runoff result in fewer particles settling out of the water stream before it reaches a receiving water body; thus, suspended sediment is a major pollutant of urban runoff (NVPDC, 1992; Whipple *et al.*, 1983). However, the introduction of paved or otherwise nonerodible area that accompanies urbanization may actually decrease upland sediment loss (Cohen *et al.*, 1993).

The major sources of pollution in urban areas include litter, dustfall, septic tanks, pet excretions, chemicals (fertilizers and deicers), and wastes from cars (Guy, 1975; APWA, 1969). Many urban models use some form of exponential decay equation to relate the cumulative pollutant washoff as time progresses to the initial amount of pollutant on the surface at the beginning of the storm (Huber *et al*., 1981). This form of equation does not consider the energy imparted to the particles by raindrop impact and surface runoff, which are needed for accurate simulation of pollutant detachment and washoff (Angelotti, 1985).

Atmospheric deposition of sediment occurs at varying rates according to time, climate, and location (Stevens, 1999). Atmospheric deposition of sediment can be a significant source of sediment transported to receiving water bodies (Guy, 1975; Stevens, 1999). In a 10-acre plot in Chicago, Illinois, dust and dirt accounted for 64% of the street sweepings (Guy, 1975). The amount of sediment deposition varies widely; however, there is an order of severity that can be assumed: gravel and dirt road areas have more sediment deposition than paved areas, which in turn have more sediment deposition than natural areas (Stevens, 1999). Stevens (1999) reported a median rate of dust and dirt deposition from the air in an area surrounding gravel and dirt roads that was 106 times larger than that deposited 500 feet away (an area assumed to be a 'reference' site); in addition, the sediment deposition near gravel and dirt roads was 39 times as large as that near paved roads. Sediment-bound chemicals are associated with the sediment in urban runoff, and make up the majority of the chemicals found in urban runoff (Stevens, 1999). The pollutants on roads tend to accumulate near the curbs, which is why urban-associated pollutant loads are often expressed as a function of length of curb (Terstriep *et al*., 1990).

2.3 Magnitude of Urbanization

The rate of urban expansion in the United States has increased over the last 20 years. During the period from 1982 to 1992, the average annual increase in developed areas was 1.4 million acres. From 1992 to 1997, that figure increased to 2.2 million acres/year (NRCS, 2000a). The highest rate of development during the 1992-1997 period occurred in Texas, at nearly 180,000 acres/year. Virginia came in 11th place at just under 70,000 acres/year (NRCS, 2000b). The national area in crop or pastureland decreased from 508,362,700 to 496,989,900 acres between 1992 and 1997. During the same period, there was a corresponding increase in developed land: from 87,034,700 to 98,251,700 acres (NRCS, 2000c). As evident from the above figures and from those in Table 1, urban areas are expanding at an increasing rate.

Table 1. Acreage and Percentage of Non-Federal Land Development[1]

	Year	Developed Area (acres)	Developed Area (percent)
Virginia	1982	1,841,300	8.2
	1987	2,080,400	9.2
	1992	2,282,300	10.1
	1997	2,625,800	11.7
United States	1982	73,245,800	4.9
	1987	79,504,500	5.3
	1992	87,034,700	5.8
	1997	98,251,700	6.6

[1]Excerpt from table 5846 (NRCS, 2000d).

2.4 Urban Best Management Practices

Best Management Practices (BMPs) for urban areas fall into two general categories: structural (or conventional) and nonstructural (Young *et al.*, 1996; Tsihrintzis and Hamid, 1997). The primary pollutants that urban BMPs seek to control are phosphorus and sediment, although other nutrients and toxics are present in the runoff and are also treated by the BMPs (NVPDC, 1992). Some common structural BMPs are infiltration trenches, porous pavement, dry wells, infiltration basins, grass swales, constructed wetlands, wet detention/retention ponds, sand filters, and oil/water separators (Tsihrintzis and Hamid, 1997; Huber, 1988; WEF, 1998; NVPDC, 1992; Young *et al.*, 1996). These methods are termed 'structural' because an actual physical entity exists that directly treats or collects the runoff. The goal of structural BMPs is to detain or impede runoff so that pollutants can settle out, be filtered out through a medium, or be detained long enough for degradation or other biological transformation to occur (Young *et al.*, 1996). Nonstructural (or source control) BMPs, by contrast, are not associated with a physical structure. Their purpose is to prevent the pollution from entering runoff in the first place (Young *et al.*, 1996). Nonstructural BMPs include public education, street sweeping, traffic control, fertilizer and herbicide treatment controls, use of non-hazardous products in street maintenance, and prevention of illegal connections to storm drains (Tsihrintzis and Hamid, 1997; Huber, 1988; WEF, 1998; Young *et al.*, 1996).

The most common urban BMPs in the Fairfax County, Virginia database of stormwater management facilities are wet ponds, dry ponds, and infiltration trenches (Fairfax, 2001). Wet ponds are distinguished from dry ponds by their maintenance of a permanent pool level. Additional volume is available to accommodate stormwater runoff. Resuspension of deposited pollutants does not occur as frequently in a wet pond as in a dry pond because of the permanent pool (NVPDC, 1992). Typical removal efficiencies for wet ponds are 74% for sediment, 49% for total phosphorus, and 34% for total nitrogen (Young *et al.*, 1996). Wet ponds have emergency overflow devices as well as a primary spillway at the permanent pool level (NVPDC, 1992).

Extended detention dry ponds, in contrast to wet ponds, are designed to release all the water they retain within a designated amount of time. Dry ponds are designed with two purposes in mind. The first is to detain the water for a time before releasing it downstream. This reduces the energy (and erosivity) of the runoff, and also decreases the potential for flooding. A second purpose is to settle out sediment and other pollutants to improve the downstream water quality (NVPDC, 1992). Typical removal efficiencies for extended detention dry ponds are 60-90% for sediment, 42-50% for total phosphorus, and 28-40% for total nitrogen (Young *et al.*, 1996). Dry ponds have outlet devices that are designed to release the water from the pond at a certain rate. Several openings in the side of an outlet riser may exist to accommodate storms of various sizes (NVPDC, 1992).

Infiltration trenches are large trenches, generally filled with a coarse stone aggregate and lined with filter fabric. They are designed to capture runoff and allow it to infiltrate and not enter the downstream environment (NVPDC, 1992; Young *et al.*, 1996). Typical removal efficiencies for infiltration trenches are 75-99% for sediment, 50-75% for total phosphorus, and 45-70% for total nitrogen (Young *et al.*, 1996). Regular maintenance is required for infiltration trenches to ensure that they do not clog with the sediment they remove from runoff (Young *et al.*, 1996; NVPDC, 1992). This maintenance may include excavation of the trench in order to unclog it (Young *et al.*, 1996). Infiltration trenches do not have outlet structures, but may have specially designed overflow devices.

2.5 Watershed Simulation Models

There are many sources of error associated with the hydrologic modeling process. Some of these sources are the result of assigning too much confidence to a model, using overly complex equations for simple situations, or using a model that is not applicable to the situation being analyzed (Caraco *et al.*, 1998). In light of these common sources of error, a review of watershed models that may be suitable for use in urban areas is necessary.

The **S**torm**w**ater **M**anagement **M**odel (SWMM) (Metcalf & Eddy Inc., 1971) is one of the most commonly used models for urban watersheds. It has been used extensively in the United States, Canada, Europe, and Australia and is intended for use by engineers and scientists familiar with urban hydrology (CHI, 2001). The latest version includes the ability to set a cap on infiltration, a routine to simulate bridges, more possible orifice shapes, increased array dimensions, and additional printing options (CHI, 2001). Most of the new changes found in the latest 4.4h edition are found in the submodel EXTRAN (the dynamic hydraulic routing block) (ORST, 2001). Computational Hydraulics, Int. provides support for the latest version of SWMM (CHI, 2001).

The Stormwater Management Model can be used as a single event or a continuous simulation model (ORST, 2001; CHI, 2001). SWMM is a lumped parameter model, representing urban areas as a percentage of the total area and modifying the equations to represent averaged values based on the percent urban and agricultural areas (Metcalf & Eddy Inc., 1971). For example, the following modification is made for Manning's n (Metcalf & Eddy Inc., 1971):

$$\frac{1}{n} = \frac{x}{n_p} + \frac{(1-x)}{n_i} \qquad (1)$$

Where: x = the fraction impervious area;

n_i = Manning's n for impervious area = 0.014;

n_p = Manning's n for pervious area = 0.35;

n = Manning's n for use in the model.

A glossary of the variables for all equations used in this thesis is included in Appendix A.

An executive program links together a number of separate components that are used by SWMM (Whipple *et al*., 1983). Each submodel handles a different aspect of the watershed – runoff, transport, etc. Manning's equation is used to compute flow velocity and the continuity equation to determine the depth of water flow for overland and gutter flow phases (Metcalf & Eddy Inc., 1971). St. Venant's equations are used to simulate flow routing in major storm sewers and can account for backwater effects (CHI, 2001). From inputs of rainfall hyetographs, SWMM outputs runoff hydrographs and pollutant loadings (Whipple *et al.*, 1983). The majority of the pollution considered in SWMM is from dust and dirt deposited on roads; each day without a storm receives an equal amount of deposited sediment (Halverson *et al.*, 1982). The SWMM model has been calibrated and evaluated on several watersheds, generally performing well (Tsihrintzis and Hamid, 1997). The model is being updated at Oregon State University. The Danish Hydraulic Institute has created a proprietary GIS interface for SWMM called MIKE SWMM (DHI, 2001c).

The **H**ydrological **S**imulation **P**rogram – **F**ortran (HSPF) is a derivative of the Stanford Watershed Model (Whipple *et al.*, 1983). Hydrocomp, Inc. developed the original Stanford Watershed Model, which evolved into three models: HSP (**H**ydrocomp **S**imulation **P**rogram), ARM (**A**gricultural **R**unoff **M**anagement Model, and NPS (**N**on**p**oint **S**ource Pollutant Loading Model). In 1976, Hydrocomp, Inc. combined these models into one program, HSPF, an event or continuous simulation model for simulating one-dimensional flow in streams (Hydrocomp, 1999a; Whipple *et al.*, 1983; Tsihrintzis and Hamid, 1997). The model is lumped, but is capable of dividing a basin into smaller subwatersheds, each having its own lumped parameters (Hydrocomp, 1999b).

A quasi-kinematic wave equation is used in HSPF to route surface water, and the model can simulate interactions between surface and ground water (Whipple *et al.*, 1983), based on a calibrated parameter that apportions percentages of the infiltrated water to different sinks. The HSPF model can represent both pervious and impervious land uses (Tsihrintzis and Hamid, 1997). The current version of HSPF simulates the fate of pollutants such as pesticides and fertilizers well (Tsihrintzis *et al.*, 1997), but calibration is required. Two different techniques can be used to calculate sediment detachment and transport from impervious areas, although the designers have expressed doubts about the reliability of the two methods (Johanson *et al.*, 1980). Upon visual inspection of the current source code (USGS, 2000), it was discovered that the same two equations are still used in the current model, and from the comments in the code it is evident that there are still concerns with the equations used. Geographical information system (GIS) interfaces have been developed for use with HSPF to simulate runoff from urban areas (Tsihrintzis *et al.*, 1997). The most well known GIS interface for HSPF is BASINS (**B**etter **A**ssessment **S**cience **I**ntegrating Point and **N**onpoint **S**ources) (Shoemaker *et al.,* 1997). The United States Environmental Protection Agency (EPA) supports and distributes HSPF (USEPA, 2002).

The **S**imulator for **W**ater **R**esources in **R**ural **B**asins (SWRRB) was originally developed for ungaged watersheds to assist in management decisions by analyzing changes in watershed erosion and runoff as a result of different management practices (Bingner, 1990). It is a continuous model requiring continuous climatological and management data records (Bingner, 1990). All slope and soil characteristic information is assumed uniform in the analysis area for SWRRB, but it is capable of dividing a watershed into subcatchments of homogeneous characteristics (Bingner *et al.*, 1992). The Soil Conservation Service (SCS) curve number method (SCS, 1990) is used to simulate runoff, adjusting the S value (the maximum potential difference between rainfall and runoff) according to the water content of the soil. The SWRRB model uses Ritchie's method (Ritchie, 1972) to compute evapotranspiration and MUSLE (Williams, 1975) to calculate soil erosion (Savabi *et al.*, 1988; Bingner, 1990). Processes simulated by SWRRB include meteorology, hydrology, crop growth, sedimentation, and nutrient and pesticide movement (Tsihrintzis and Hamid, 1997). The model was tested on 11 watersheds associated with eight Agricultural Research Service sites across the United States and was found to 'realistically' simulate the conditions at each site (Arnold and Williams, 1987). The only problem was the model's inability to estimate snowmelt, which caused the model to be less accurate in Vermont (Arnold and Williams, 1987).

The **S**oil and **W**ater **A**ssessment **T**ool (SWAT) was developed by combining SWRRB and ROTO (**R**outing **O**utputs **t**o **O**utlet) (TAMUS, 2001a). This model uses the Penman-Monteith equation to compute evapotranspiration and either the curve number approach or the Green and Ampt equation to calculate infiltration (TAMUS, 2001a). It uses MUSLE to calculate sediment yield and GLEAMS methods (Leonard *et al.*, 1987) to calculate nutrient and pesticide transport. The model is also capable of simulating irrigation and fertilizer applications (TAMUS, 2001d). Interfaces for SWAT are available in Windows, GRASS, and ArcView, and SWAT was recently integrated into BASINS (TAMUS, 2001a). The model has been evaluated on a small watershed and on a river basin scale (TAMUS, 2001b). It has the capability to simulate urban areas through a fractional representation of the amount of impervious area present and to represent a watershed on a grid cell basis (TAMUS, 2001c; TAMUS, 2001e). There is a 2000 version of SWAT currently available. The model is supported by the USDA Agricultural Research Service at the Grassland, Soil and Water Research Laboratory in Temple, Texas.

The **Ag**ricultural **N**on**p**oint **S**ource (AGNPS) model (Young *et al.*, 1987) began as a single event, distributed parameter model for use in Minnesota (Wu *et al*., 1993; Bingner, 1990). It is now a system of computer models and has been modified for continuous simulation and renamed AnnAGNPS (Needham and Young, 1993). The combined models now simulate weather, sediment and other pollutant losses (nitrogen, phosphorus, and organic carbon) from fields, channel erosion, in-stream habitat, riparian zones, and lakes. Runoff is calculated using the SCS curve number method. Peak runoff is calculated using TR-55 (NRCS, 1986). Sediment delivery is calculated using an altered form of the USLE (Wischmeier and Smith, 1978). Water input in AGNPS can come from snowfall, rain, irrigation, and point sources (NSL, 2001). The most current version of AGNPS does not route flow from cell to cell but instead calculates total losses from a cell and deposits them directly to a stream reach (Cronshey and Theurer, 1998).

The AGNPS model has been tested on several watersheds, including the St. Esprit watershed in Quebec (Perrone and Madramootoo, 1997). It adequately predicted surface runoff and sediment yield, but greatly overestimated peak flows and performed less well during complex climatic events and during colder months (Perrone and Madramootoo, 1997). The National Sedimentation Laboratory (USDA-ARS) at the University of Mississippi maintains and distributes AGNPS (NSL, 2001).

The **S**torage, **T**reatment, **O**verflow, **R**unoff **M**odel (STORM) (US Army Corps of Engineers, 1977) was developed and is maintained by the U.S. Army Corps of Engineers' Hydrologic Engineering Center and is intended primarily for use as an urban model (Whipple *et al.*, 1983; Tsihrintzis and Hamid, 1997). It is a continuous lumped parameter model, simulating a watershed by percent of land in each land use type (Whipple *et al.*, 1983; Tsihrintzis and Hamid, 1997). Runoff is routed first to treatment, then storage, and then any excess is modeled as overflow (Whipple *et al.*, 1983). The STORM model uses a modified rational method (DCR, 1999) to compute runoff in developed areas and the SCS curve number method to compute runoff in undeveloped areas (Whipple *et al.*, 1983). Suspended solids are computed using the USLE and pollutant buildup is estimated with an exponential decay equation. The model runs on a one-hour time step to match hourly National Weather Service data (Whipple *et al*, 1983). Numerous watersheds have been used to test STORM, including one reported by Warwick and Wilson (1990) in Dallas, Texas. The users had difficulty determining the appropriate daily accumulation rates for total suspended solids (among other water quality components) needed for input to the model. As a result, the runoff quality computations did not match observed data as well as they expected (Warwick and Wilson, 1990).

MIKE **E**uropean **H**ydrological **S**ystem (MIKE SHE) (Wicks *et al.*, 1992) is a distributed parameter model that focuses on modeling interactions between surface and ground water (UTEXAS, 1998) and is typically used in agricultural areas (DHI, 2001a). Its primary modules are evapotranspiration, unsaturated zone flow, saturated zone flow, overland and channel flow, and irrigation (DHI, 2001b). The equations used by MIKE SHE include the kinematic wave approximation of Saint-Venant's equation to model overland flow, either the Kristensen and Jensen or Penman-Monteith method to calculate evapotranspiration, and Boussinesq's equation to model groundwater flow (Jacobsen, 1999). The model has a GIS interface for input and output (UTEXAS, 1998). The Danish Hydrologic Institute in Hørsholm, Denmark originally developed and currently maintains MIKE SHE.

The **Auto**mated **Q**uality-**I**llinois Urban Drainage Simulator (AUTO-QI) was derived from the Q-ILLUDAS model, a continuous simulation water quality model (Noel and Terstriep, 1982). The results of Q-ILLUDAS were similar to those obtained using SWMM, but the model was much less difficult to run (Noel and Terstriep, 1982). The Q-ILLUDAS model considered three types of land: connected paved, supplemental paved, and contributing grassed areas. It used a daily time step on days without precipitation and a one-hour time step on days with precipitation. When precipitation occured, the time step was defined by the user, usually on the order of minutes (Noel and Terstriep, 1982).

The AUTO-QI model retains the three land use types and most of the equations of Q-ILLUDAS and adds continuous simulation of soil moisture and modifications for use on a regional level. The model includes a GIS interface called RUNIT and a program called QIMENU helps produce input files. There are three sections of AUTO-QI; data are passed from one section to another in sequential order, with additional user input required at each step. The three parts are HYDRO, LOAD, and BMP. The first part, HYDRO, simulates soil moisture and runoff. Next, LOAD computes the pollutant loadings for the runoff from HYDRO. Then BMP modifies the quality of runoff and pollutants based on the user-input reductions for the effects of each BMP. The AUTO-QI model does not simulate BMP effects; it only reduces runoff and pollutants by the user-specified percentage for each BMP (Terstriep *et al.*, 1990).

The **A**real **N**onpoint **S**ource **W**atershed **E**nvironment **R**esponse **S**imulation (ANSWERS-2000) model (Bouraoui, 1994) is a further development of a hydrologic model developed in 1966 by L.F. Huggins (Huggins and Monke, 1966) as a dissertation project. The 1966 version was written in FORTRAN IV and named “Mathematical Model of a Small Watershed.” The original model was a distributed parameter, single event model developed for simulating the hydrologic response of small agricultural watersheds. Erosion and water quality were not simulated. In the late seventies, Beasley *et al.* (1980) added components to the model to simulate sediment loss, tile drainage, and the effects of selected agricultural BMPs on runoff and sediment loss. Baun *et al.* (1986) used ANSWERS to evaluate sediment loss in Minnesota. They reported that the model poorly predicted sediment loss in Minnesota, but subsequent study revealed that they had used 40-acre cells that violated the model developer's maximum recommended cell size of 2 to 5 acres. Baun *et al.* (1986) concluded that a new sediment transport model was needed as well as software for creation of input files and analysis of output files and an improved users manual. The sediment model at that time used the following equations to calculate sediment detachment and transport (Beasley and Huggins, 1980):

$$D_F = 6.83 \cdot C \cdot K \cdot A \cdot SL \cdot Q \qquad \text{for flow detachment} \qquad (2)$$

$$D_R = 0.82 \cdot C \cdot K \cdot A \cdot R^2 \qquad \text{for splash detachment} \qquad (3)$$

Where: D = detachment, kg/min;

C = USLE C factor;

K = USLE K factor;

A = area, m^2;

SL = slope steepness;

Q = flow rate per unit width, m^2/min;

R = rainfall intensity during the time interval, mm/min.

$$T_F = 161 \cdot SL \cdot \sqrt{Q} \qquad Q \le 0.046 \, m^2/min \qquad (4)$$

$$T_F = 16320 \cdot SL \cdot Q^2 \qquad Q > 0.046 \, m^2/min \qquad (5)$$

Where: T_F = transport capacity, kg/min-m;

SL = slope steepness;

Q = flow rate per unit width, m^2/min.

The ANSWERS model was modified almost continuously during the next two decades. Additions included improved sediment (Dillaha and Beasley, 1983), phosphorus (Storm *et al.*, 1988), and nitrogen (Bouraoui and Dillaha, 2000) transport submodels. A major advancement for the model occurred in 1994 when the model was modified for continuous simulation, and components were added for crop growth, improved simulation of the infiltration process, and simulation of nitrogen and phosphorus losses (Bouraoui, 1994; Bouraoui and Dillaha, 1996, 2000). At this time the model was renamed ANSWERS-2000. Byne (2000) replaced the sediment detachment submodel with critical shear stress components from the WEPP model (Alberts *et al.*, 1995) and added a channel erosion component. Shortly thereafter, QUESTIONS, an ArcInfo-based user interface written in Visual Basic, was developed for ANSWERS to simplify data file creation (Veith *et al.*, 2002).

In the mid-1990s two subroutines, STRUCT and IMPOND, were added to ANSWERS-2000 in 1995 and 1994, respectively. Subroutine STRUCT simulates terraces, ponds, and grassed waterways in individual cells. This is done by applying a percentage decrease in runoff for the cells of concern. Subroutine IMPOND simulates impoundments at the outlet of the watershed. These ponds cannot be present elsewhere in the watershed. There is no documentation on these subroutines except the limited comments in the model code.

The ANSWERS-2000 model is a continuous, distributed parameter model used for watershed analysis of runoff, sediment loss, and nutrient loss. The hydrologic model acts on the assumption that, during a rainfall event, infiltration, interception, surface detention, surface retention, and subsurface drainage all contribute to the routing of flow (Collett and Punthakey, 1989). Infiltration is calculated using the Green and Ampt approach. Depression storage is filled before runoff begins. Subsurface drainage is calculated using a relationship determined by Huggins and Monke (1966). Sediment detachment occurs through rainfall impact and overland flow. Sediment transport is calculated using Yalin's equation (Byne, 2000). These and other equations used in the model are well documented in the literature (Huggins and Monke, 1966; Huggins *et al.*, 1973; Huggins *et al.*, 1976; Beasley *et al.*, 1980; Dillaha and Beasley, 1983; Bouraoui and Dillaha, 1996, 2000; Byne, 2000). The major inputs to ANSWERS-2000 are related to crop rotations and soil types. A breakpoint weather file is also required, and a fertilizer file is optional. The program takes this information and processes it for the intended period of time to produce daily and yearly output of runoff, sediment loss, and nutrient losses. This model is maintained and distributed by the Biological Systems Engineering Department at Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

2.6 Summary

From the literature, it is evident that urbanization is a problem that current and future watershed planners must consider. Water resources planning in urbanizing watersheds requires models that can simulate a mixture of agricultural and urbanized areas, as the urbanizing areas are taking over the formerly agricultural areas of the country. Review of existing models has shown that few models exist that can quantify both agricultural and urban runoff. The SWMM model is intended for simulating urban land use practices. Changing this model would be very complex, as a whole new series of equations would be needed to quantify flow from pervious areas that is currently ignored by the model. The HSPF, SWRRB, and STORM models are lumped parameter models incapable of representing the spatial placement of BMPs in watersheds. The two existing models that are capable of simulating a combined agricultural and urbanized watershed have limitations that make them unsuitable for modification to simulate urban BMPs. One model that is capable of simulating a watershed of combined urban and agricultural land use practices is MIKE SHE, which is not a public domain model. It is not available for modification and would be less desirable for use of the target audience – researchers and watershed planners. The second model, AnnAGNPS, though distributed, does not simulate the interactions of pollutants with the cells between the contributing cell and the stream reach. Therefore, it cannot simulate the effects of urban BMPs that are used to promote infiltration and break up directly connected impervious areas. The ANSWERS-2000 model does not currently simulate impervious areas and urban stormwater detention facilities; however, it is continuous, distributed, and routes overland flow from cell to cell as it progresses to the stream. It is thus able to simulate the effects of BMPs that reduce overland flow and disrupt directly connected impervious areas. It is also in the public domain. It is difficult to use in urban areas because it lacks an urbanization component to simulate atmospheric deposition, impervious surface processes, infiltration structures, and impoundments. In spite of these limitations, ANSWERS-2000 was found to be the most suitable existing model for modifying to simulate the effects of BMPs in urbanizing watersheds because of its continuous and true distributed parameter approach. The next chapter describes how ANSWERS-2000 was modified to better simulate hydrology, pollutant transport, and common BMPs in urbanizing watersheds.

Chapter 3. Model Development

3.1 Introduction

From the review of the literature, ANSWERS-2000 was chosen as the model to modify for this research. It is a distributed parameter model capable of representing up to 35,000 cells (or more if the array dimensions are increased in the source code). These cells, also called elements, make up a grid representing the watershed area. It is a continuous simulation model and freely available to the public. It is lacking in several areas, including representation of impervious and nonerodible surfaces, but with modification, it has the potential to represent combined urban and agricultural watersheds in detail.

Several different submodels were developed to achieve the desired goal of using a distributed parameter model to represent urban BMPs in an urbanizing watershed. First, a submodel was needed to simulate urban BMPs for stormwater detention and/or treatment. Second, a submodel to represent nonerodible impervious surfaces was needed; this subroutine is referred to as the URBANIZED subroutine. Third, an atmospheric deposition subroutine was needed to approximate the deposition of sediment and nutrients that is significant in urban areas. In addition, modifications were made to the ANSWERS-2000 user interface, QUESTIONS, to accommodate the new input parameters, numerous utilities were developed to facilitate data file creation, and an irrigation subroutine was developed to represent irrigation of lawns and golf courses. Discussion of these last features is included in Appendix B, as they were not directly part of the research conducted.

3.2 Best Management Practices

The BMPS subroutine was written to simulate wet ponds, dry ponds, and infiltration trenches. Other types of BMPs, such as infiltration basins, can be simulated as a dry pond without an outlet structure. There are two basic assumptions common to all ponds and infiltration trenches simulated by ANSWERS-2000. First, each structure is approximated as a rectangular pond or trench with vertical walls. Second, if an element contains a pond or infiltration trench, it is assumed that all runoff entering the element flows into the pond or infiltration trench. Water entering a wet or dry pond can exit in one of four ways: through the principal spillway, through the emergency spillway, via infiltration, or via evaporation. The principal spillway consists of a riser with inlets at the top and on the side (Figure 1).

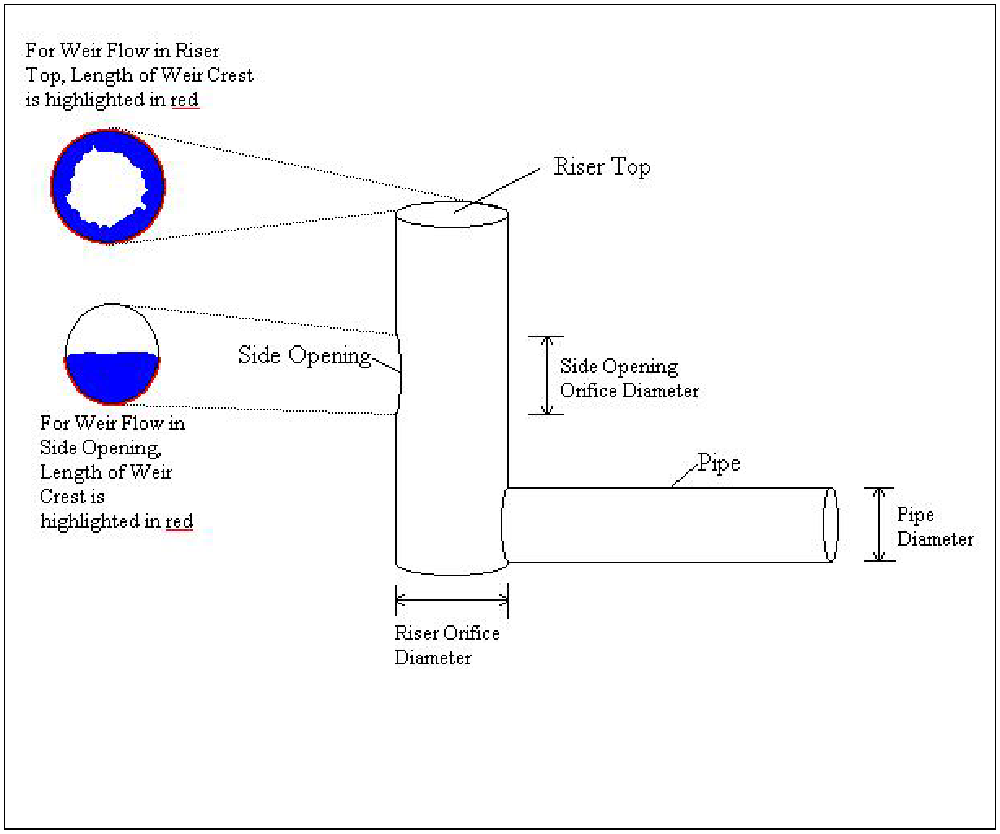

Figure 1. Diagram of outlet structure and dimensions used in flow equations.

Flow through the principal spillway is a function of the depth of water above each outlet and the dimensions and characteristics of the outlets. The height of the water in the pond determines which spillways are discharging. The water level must be higher than the lowest orifice for discharge to occur through the side opening on the riser; it must be higher than the riser top to discharge through the top of the riser; and it must be higher than the base of the emergency spillway to leave via the emergency spillway. For ponds with a permanent pool, the elevation of the top opening of the riser is the permanent pool level.

Three types of equations govern the flow through the primary spillway: weir flow, orifice flow, and pipe flow. The stage-discharge relationship for an example pond is shown in Figure 2.

Weir flow may occur through a nonsubmerged opening on the side of the riser and at the riser top. The equation is (converted from the equation for English units) (DCR, 1999):

$$Q = 0.0283 * 3.1 * \left(L_{crest} * 3.281\right) * \left(h * 3.281\right)^{1.5} \quad (6)$$

Where: Q = flow rate, m³/s;

L_{crest} = length of weir crest, m;

h = height of water above weir, m.

The length of the weir crest is the length of the wetted perimeter for the side opening and the circumference of the riser for the top opening.

Orifice flow may occur through a submerged opening on the side of the riser and at the outlet pipe in the bottom of the riser. The equation is the same in both cases (DCR, 1999):

$$Q = 0.6 * a_{orifice} * \sqrt{2gh} \quad (7)$$

Where: Q = flow through the orifice, m^3/s;

$a_{orifice}$ = orifice area, m^2;

g = acceleration due to gravity, m/s^2;

h = height of water above centerline of orifice, m.

Pipe flow occurs in the outlet pipe connected to the bottom of the riser. The equation for pipe flow is (Schwab *et al.*, 1993):

$$Q = a\sqrt{\frac{2gh}{1 + K_e + K_b + K_p L}} \quad (8)$$

Where: Q = flow through the pipe, m^3/s;

a = cross-sectional area of pipe, m^2;

g = acceleration due to gravity, m/s^2;

h = water height above centerline of pipe opening, m;

K_e = entrance loss coefficient;

K_b = bend coefficient;

K_p = head loss coefficient = $\frac{1244522n^2}{d_i^{4/3}}$;

n = Manning's roughness coefficient;

d_i = inner diameter of pipe, mm;

L = length of pipe, m.

Actual discharge from the pond is the lesser of the calculated weir flow rate, the orifice flow rate, or the pipe flow rate, each calculated at the appropriate openings. Therefore, whichever opening (riser top, side orifice, pipe) will allow the least flow to pass will control the flow through the outlet structure. If the water height is such that flow can occur through the riser top and the side orifice opening, then these flows are combined to calculate a total limiting flow for the inlets to the pipe and are then compared to flow through the pipe. Flow, sediment, and nutrients leaving the pond through the riser are discharged to a user-specified receiving water element. Because the receiving water element does not have to be adjacent to the pond, the model can simulate flow via buried stormwater conveyance structures.

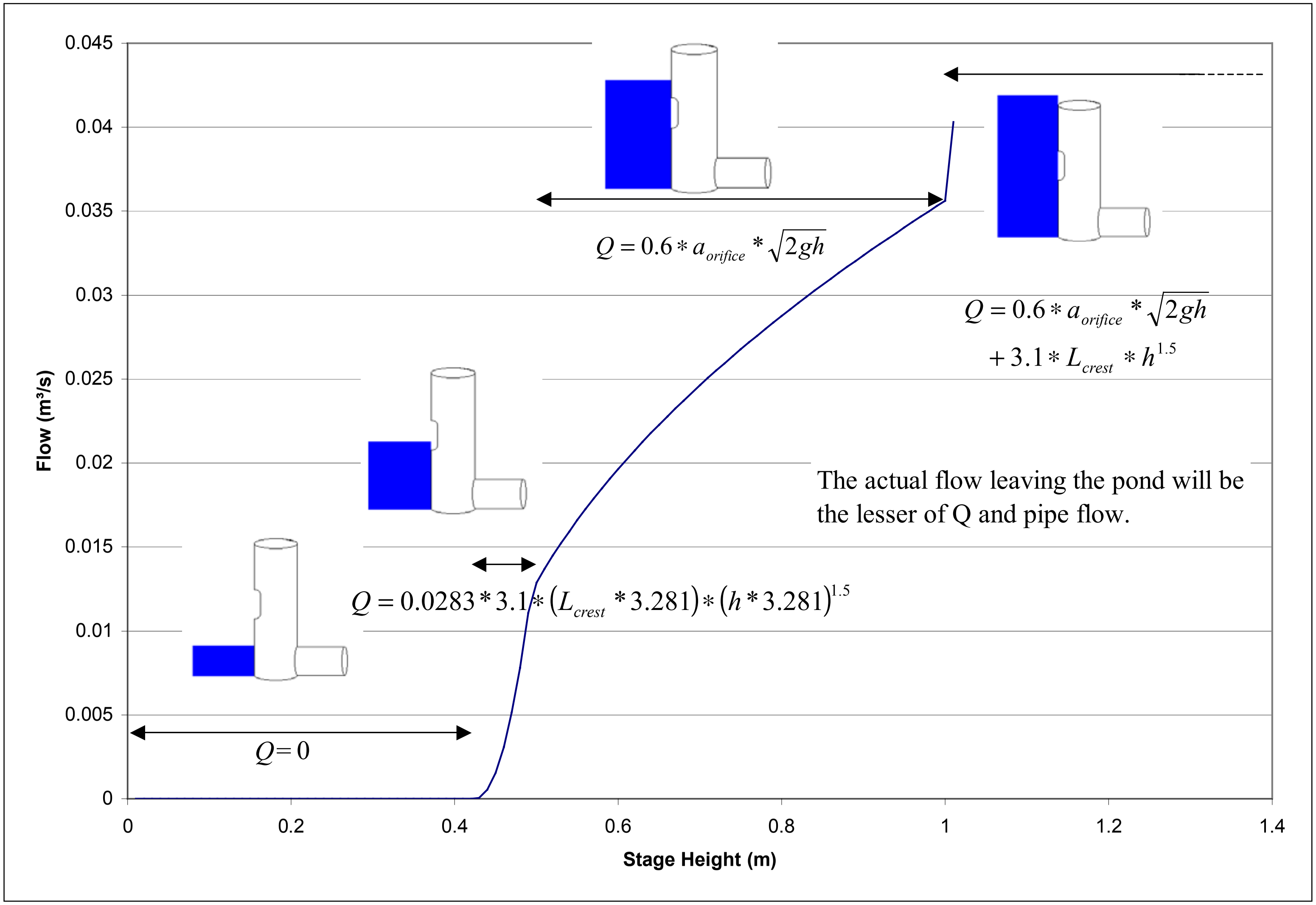

Figure 2. Stage-Discharge Relationship for Example Structure. The dimensions are: pipe orifice diameter = 0.5 m; pipe length=10 m, side opening orifice diameter= 0.15 m, side opening centerline height= 0.5 m, riser top orifice diameter= 0.45 m, and riser top height= 1 m.

If this standard principal spillway does not adequately represent the spillway for a BMP, the program can simulate a different type of riser. For instance, if there is simply a grating at the bottom of a pond, the user could specify zero diameter for the side orifice and zero height for the riser top and a riser diameter that would approximate the opening area for the grating. There are checks in the model to ensure that such approximations will not cause errors in the execution of the program. Flow over the emergency spillway is simulated as shallow overland flow over the width of the cell. The user specifies the height of the emergency spillway, corresponding to the depth of the pond when full.

Flow over the emergency spillway is represented by the existing overland flow equations in ANSWERS-2000, which are based on the continuity equation. The emergency spillway is treated as a regular cell and particular geometries of the embankment are not considered. Flow that leaves a pond via the emergency spillway flows to the adjacent non-pond cell with a lower elevation as normally determined by the program.

The primary difference between wet and dry ponds from a simulation perspective is that the wet pond has a permanent pool level that is designed to remain full between storm events. Simulation of the effects of a dry pond or infiltration trench BMP continue until the structure is drained via infiltration or the outlet structure. This may take several days. For wet ponds, flows from the pond spillways, infiltration, and evaporation drain the pond back to the permanent pool level after inflow ceases. After reaching the permanent pool level, simulation of the wet pond ceases until the next storm event. The pool is assumed to remain full between storm events as designed. Because ANSWERS-2000 does not simulate perennial streams, this assumption allows simulation of wet ponds that have flow from perennial streams. This baseflow cannot represented by the current version of ANSWERS-2000, and without this assumption the pond could completely drain between storm events, resulting in an inaccurate calculation of the detention capacity of the pond at the next storm event.

Ponded infiltration within the pond is simulated using the Green-Ampt infiltration equation (Green and Ampt, 1911), which is also used in ANSWERS-2000 to simulate infiltration in pervious areas during storms. If the entire calculated infiltration capacity cannot be satisfied, only the available water will infiltrate. Because this equation can be used for ponded and non-ponded conditions (Bouraoui, 1994), it can be used for wet and dry ponds. Evaporation from the pond surface is simulated as free water surface evaporation. The free water surface area is assumed constant and does not vary with depth, which follows the assumption that the pond has vertical sidewalls. The annual free water surface evaporation is input by the user for the watershed. Subroutine EVAPFW, preexisting in the code, is used to determine the daily evaporation by month, based on the input annual free water surface evaporation and monthly solar radiation, with the equation:

$$DFWEV = \frac{FACT * AFWEV}{YEARDAYS} \tag{9}$$

Where: DFWEV = daily evaporation, m/day;
FACT = factor to adjust evaporation based on the solar radiation for the month;
AFWEV = mean annual free water evaporation, m/year;
YEARDAYS = number of days in the year = 365 or 366.

The FACT variable changes according to the ratio of the average total solar radiation for the month divided by the average total solar radiation for the year. The default values of FACT vary by month and are, starting with January: 0.05, 0.065, 0.082, 0.099, 0.110, 0.115, 0.112, 0.104, 0.089, 0.071, 0.055, and 0.046. These are hardcoded into the program and were obtained by the original programmer from analysis of Table III.1 in *Handbook on the Principles of Hydrology* (Gordon, 1970) for 35 degrees north latitude.

Sedimentation within the pond is a function of the settling velocity of each sediment particle size class and the pond overflow rate, and is computed according to the "overflow rate" theory (Novotny and Olem, 1994). The equation is:

$$OR = \frac{Q}{A_s} \tag{10}$$

Where: OR = overflow rate, m/day;
Q = inflow in the basin, m^3/day;
A_s = surface area of the basin, m^2.

If OR is less than the particle settling velocity, the particle may be removed from the flowing water. This method assumes that the surface area of the basin does not vary during a storm event (Schwab *et al.*, 1993). This is consistent with the assumptions of vertical pond walls. The equation from Novotny *et al.* was designed for a weir situation, in which the flow rate into the basin is an accurate quantification of the flow rate across the surface of the pond. In the program, the flow rate across the pond surface would be most frequently limited by the flow exiting through the outlet structure; therefore Q was changed to be the rate of outflow from the pond. In addition, this equation was modified (Byne, 2000) so that the fraction of sediment that does deposit could be determined as follows:

$$RE = FV * \frac{A_s}{Q} \qquad (11)$$

$$DP = RE * SI \qquad (12)$$

Where: RE = removal efficiency, as decimal;
FV = fall velocity of particle, m/s;
Q = flow rate out of basin, m^3/s;
DP = deposited sediment, kg/s;
SI = sediment inflow, kg/s.

Sediment-bound nutrients in ANSWERS-2000 are bound according to the particle size class distribution of the sediment. Therefore, the sediment-bound nutrients deposit in the pond with the same removal efficiency as the sediment particle size classes to which they are bound. Dissolved nutrients pass through the pond following the continuity equation as used by the existing dissolved nutrient subroutines in ANSWERS-2000. No nutrient transformations are considered within the pond. The equations used to calculate the outflow of dissolved nutrients from the pond are:

$$OUTSN_{weir} = \frac{(AISN + STOSN) * WLOST}{H2ODEPTH + LOST + WLOST + INFIL} \qquad (13)$$

$$OUTSN_{pipe} = \frac{(AISN + STOSN) * LOST}{H2ODEPTH + LOST + WLOST + INFIL} \qquad (14)$$

$$INFSN = \frac{(AISN + STOSN) * INFIL}{H2ODEPTH + LOST + WLOST + INFIL} \qquad (15)$$

Where: $OUTSN_{weir}$ = outflow of dissolved nutrient over emergency spillway, kg/s;

$OUTSN_{pipe}$ = outflow of dissolved nutrient through riser, kg/s;

INFSN = loss of dissolved nutrient due to infiltration, kg/s;

AISN = inflow of dissolved nutrient to pond, kg/s;

STOSN = dissolved nutrient in storage in the pond, kg/s;

WLOST = water lost over the embankment, m^3;

LOST = water lost through the pipe, m^3;

INFIL = water lost to infiltration, m^3;

H2ODEPTH = total water remaining in the pond, m^3.

The AISN and STOSN variables represent the initial concentration of nutrients in the pond. This is then multiplied by the ratio of the discharge volume to the total water volume in the pond during the time increment to determine the amount of nutrient that is lost through each potential exit route. The ending nutrient storage in an element is the difference between the inflow and outflows of the element, as described in equation 16.

$$STOSN_2 = STOSN_1 + AISN - OUTSN - INFSN \qquad (16)$$

Where: $STOSN_2$ = storage at end of time increment, kg/s;

$STOSN_1$ = storage at beginning of time increment, kg/s;

AISN = inflow of dissolved nutrient to pond, kg/s;

OUTSN = outflow of dissolved nutrient from pond (through both the embankment ($OUTSN_{weir}$) and the riser ($OUTSN_{pipe}$)), kg/s;

INFSN = loss of dissolved nutrient due to infiltration, kg/s.

The volume of an infiltration trench is computed in the following manner:

$$V = L * W * D * P \qquad (17)$$

Where: V = volume of trench, m^3;

L = length of trench, m;

W = width of trench, m;

D = depth of trench, m;

P = porosity of coarse aggregate fill, as a decimal.

This gives the total pore space available to hold water in the trench. Water entering the infiltration trench can exit in one of two ways: over the top of the trench or via infiltration. All sediment that enters the trench is deposited. The volume of sediment deposited is determined at each time increment by the following equation:

$$NEWSED = \frac{SE * DT}{SG * 1000} \qquad (18)$$

Where: NEWSED = volume of deposited sediment during the time increment, m^3;

SE = sediment entering the trench per particle size class, kg/s;

DT = time increment, s;

SG = density of the sediment in the particle size class, g/cm^3.

The NEWSED variable is calculated for every particle size class and summed to give the total volume of deposited sediment for the time increment. This total volume is then subtracted from the total volume of the trench to compute the known declining capacity of a trench due to filling with sediment and resulting decrease in treatment capacity. Infiltration trenches are treated as nutrient sinks; i.e., nutrients that come into a trench do not leave, except by infiltration. As groundwater flow is not simulated by ANSWERS-2000, no further calculations are made on the nutrients. However, the leached nitrate is added to the total volume of leached nitrate for the watershed. Once the infiltration trench is full of water on a given day, all water that comes onto the element is treated as though there is no trench present – i.e., the water flows over the element as it would if there was no trench on the element. Infiltration, however, is an ongoing process, so space made by infiltrating water can be filled by incoming water. Infiltration is calculated with the Green-Ampt equation, as used in the rest of the program. Infiltration can occur on all sides and the bottom of the infiltration trench. The necessary modifications to accomplish this were in the definition of three conversion factors: CU, CU1, and CU2. The original equations in the ANSWERS-2000 code were:

$$CU = \frac{DX^2}{3600000} \tag{19}$$

$$CU1 = \frac{DX^2}{1000} \tag{20}$$

$$CU2 = \frac{DT}{DX^2 * 500} \tag{21}$$

Where: CU = conversion factor to convert mm/hr to m^3/s;

CU1 = conversion factor to convert mm to m^3;

CU2 = conversion factor for twice m^3;

DX = cell width, m;

DT = time increment, s.

These equations (19 through 21) were not applicable for infiltration trenches because DX^2 (the area of a cell) does not represent the infiltration area for infiltration trenches. After modification, these equations are, for infiltration trenches only:

$$CU = \frac{(L*W + 2*D*L + 2*D*W)^2}{3600000} \tag{22}$$

$$CU1 = \frac{(L*W + 2*D*L + 2*D*W)^2}{1000} \tag{23}$$

$$CU2 = \frac{DT}{(L*W + 2*D*L + 2*D*W)^2 * 500} \tag{24}$$

Where: L = length of infiltration trench, m;

W = width of infiltration trench, m;

D = depth of infiltration trench, m.

Bouraoui (1994) derived the specific form of the Green-Ampt equation used in ANSWERS-2000.

A flow chart of the BMPS subroutine is included in Figure 3.

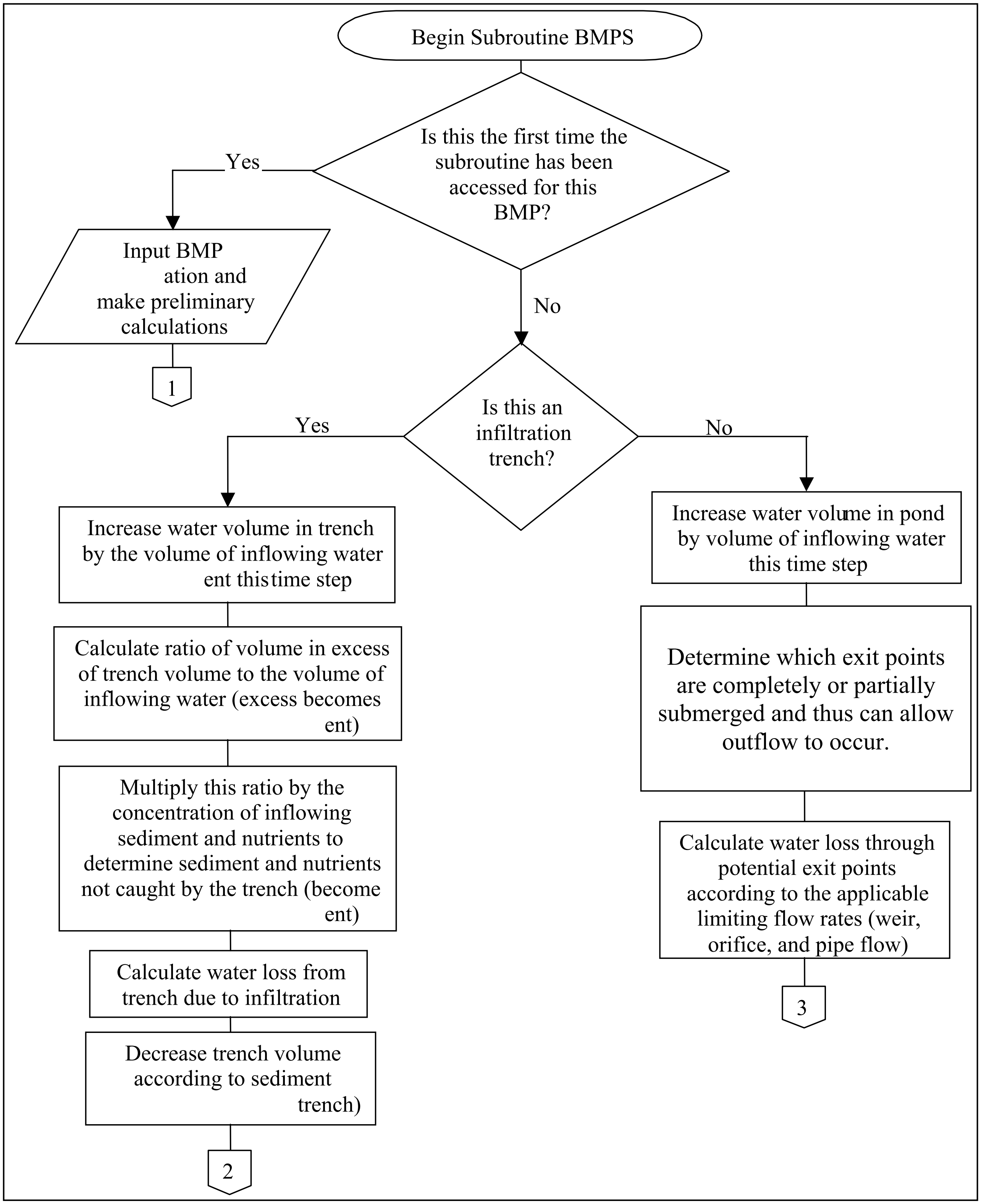

Figure 3. Flow Chart of BMPS Subroutine.

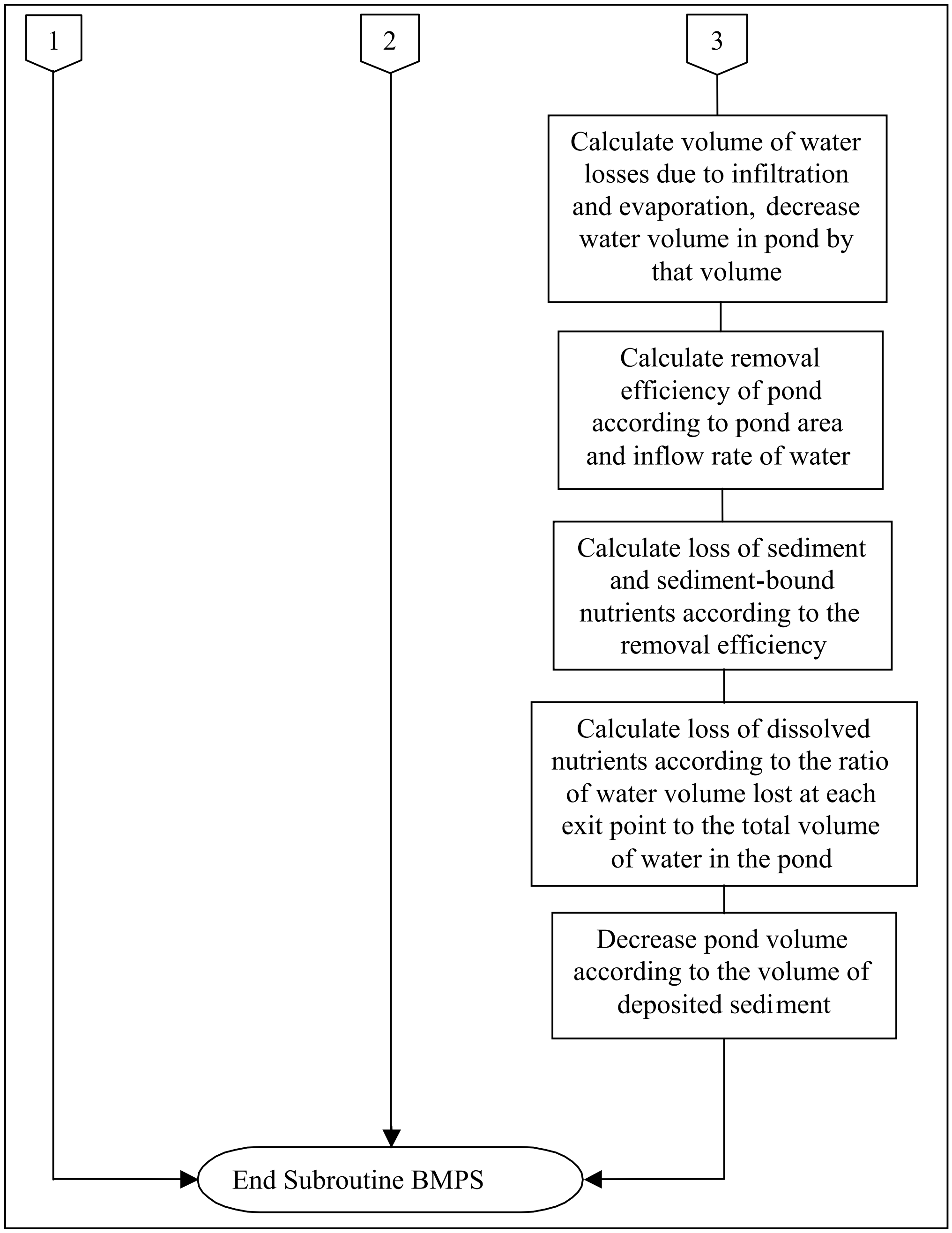

Figure 3. (continued) Flow Chart of BMPS Subroutine.

3.2.1 Assumptions and Limitations for the BMPS Subroutine

Several assumptions were made for the BMPS subroutine, most of which have been previously mentioned. They are listed here in their entirety for ease of reference. First, it is assumed that a BMP can be represented with a specified surface area and vertical walls; thus, the surface area of the pond does not vary during a storm event. It is assumed that the slope of the land in a cell containing a BMP is such that all flow from that cell will be directed to the BMP. Dissolved nutrients are assumed to be completely mixed within the BMP and trapped sediment and sediment-bound nutrients are not resuspended. It is assumed that the wet pond will remain at the permanent pool level, as designed, between storm events.

There are also four limitations to the use of the subroutine, necessitated by the manner in which the subroutine was designed. The riser outlet structure is only permitted to have one side opening and one top opening. A wet pond is required to maintain a permanent pool level at the top of the riser opening and thus cannot have a side orifice. The geometry of the overflow embankment is not considered, making the model unfit to simulate BMPs for which the overflow embankment geometries have a large effect on flow leaving the BMP. Nutrient transformations within the pond are not considered, which may create a problem for ponds with long detention times.

3.3 URBANIZED Subroutine

The urban subroutine, URBANIZED, simulates hydrology and pollutant fate on impervious cells and consists of six main parts. The first two parts are for the soil and the land use parameter inputs. When the main program encounters impervious and nonerodible surfaces, it reads the set of parameters in the URBANIZED subroutine instead of the crop and soil parameters used with pervious land use cells. Although roads and houses and other impervious surfaces are not actually crops or soils, they are represented as dummy crops and soils and assigned crop and soil parameters that allow simulation of impervious and nonerodible conditions. This is necessary because ANSWERS-2000 groups and processes individual cells according to their crop and soil types.

The next section in the URBANIZED subroutine calculates the flow path for impervious and nonerodible cells that have curbs and/or stormwater drains. The flow path for impervious and nonerodible cells is altered where there is a curb or drain present. If a curb is present, the model directs runoff to an adjacent impervious/nonerodible cell (or cells) downslope of the current impervious cell. Flow along roads is simulated with Manning's equation as channelized flow with a user-specified channel width.

Users can specify the locations of stormwater inlets on any cell in the watershed using the QUESTIONS interface. If the stormwater inlet leads to a sewer that discharges to a sewage treatment plant, the stormwater inlet is treated as a sink as ANSWERS-2000 does not simulate sewage treatment. If the stormwater inlet discharge is directed to a cell within the watershed, the outflow from the cell is immediately added to the inflow of the receiving cell during the next time step of the model. The program does not attempt to represent complex sewer systems, nor to represent the hydraulics of flow through the sewer pipes. Cities with complex and extensive stormwater sewer systems should not be simulated using ANSWERS-2000.

The last two sections calculate sediment detachment, transport, and deposition on impervious and nonerodible cells. The sediment portion of the URBANIZED subroutine is a modification of the existing ANSWERS-2000 sediment model. The main difference between the pervious and impervious sediment transport models is the way sediment detachment is calculated. For pervious surfaces, ANSWERS-2000 calculates the detachment capacity for a cell using a soil erodibility factor and differences in shear stress (Byne, 2000):

$$DCAP = K_{radj} * (TAUEFF - TAUCADJ) * (NORILLS * RILLWID * DX) \quad (25)$$

Where:
- DCAP = detachment capacity, kg/s;
- K_{radj} = baseline rill erodibility adjusted for effects, s/m;
- TAUEFF = effective shear stress;
- TAUCADJ = adjusted critical shear stress;
- NORILLS = number of rills;
- RILLWID = width of rills;
- DX = width of a cell, m.

Equation 26 is inappropriate for use with nonerodible cells because the baseline rill erodibility and the effective shear stress are rooted in calculations that have no meaning for nonerodible cells. Therefore, the assumption was made that the limiting factor on sediment detachment and transport from a nonerodible cell (such as a road, rooftop, or sidewalk) would be the mass of soil previously deposited in the cell (either by atmospheric deposition or deposition from the inflow from other elements). The detachment on an erodible cell cannot exceed this previously deposited sediment. A new array, SEL2, was created to keep track of the sediment in each particle size class deposited on a non-erodible element. It is assumed that this sediment is readily detachable and thus detachment is the lesser of the amount available for detachment and the sediment transport capacity. Transport capacity is calculated using Yalin's equation (Dillaha and Beasley, 1983), the same equation used to calculate transport capacity for pervious erodible cells in the main program.

A flow chart of the URBANIZED subroutine is included in Figure 4.

3.3.1 Assumptions and Limitations for the URBANIZED Subroutine

Several assumptions were made in the design of the URBANIZED subroutine. They are listed here for ease of reference. First, the transit time from a stormwater inlet in the watershed to the stormwater inlet's outlet cell is negligible. The sediment on a nonerodible cell is considered to be readily detachable, and the limiting factor on sediment detachment from a nonerodible cell is the mass of this readily detachable sediment that has already been deposited on the cell.

The URBANIZED subroutine has two primary limitations. First, as a result of the assumption made about stormwater drain flow, extensive stormwater drain networks cannot be represented. And second, due to the flow direction calculations pre-existing in ANSWERS-2000, curbed roads cannot cross stream networks. The pre-existing calculations require stream networks to be continuous, which prohibits curbs from rerouting flow from a stream network.

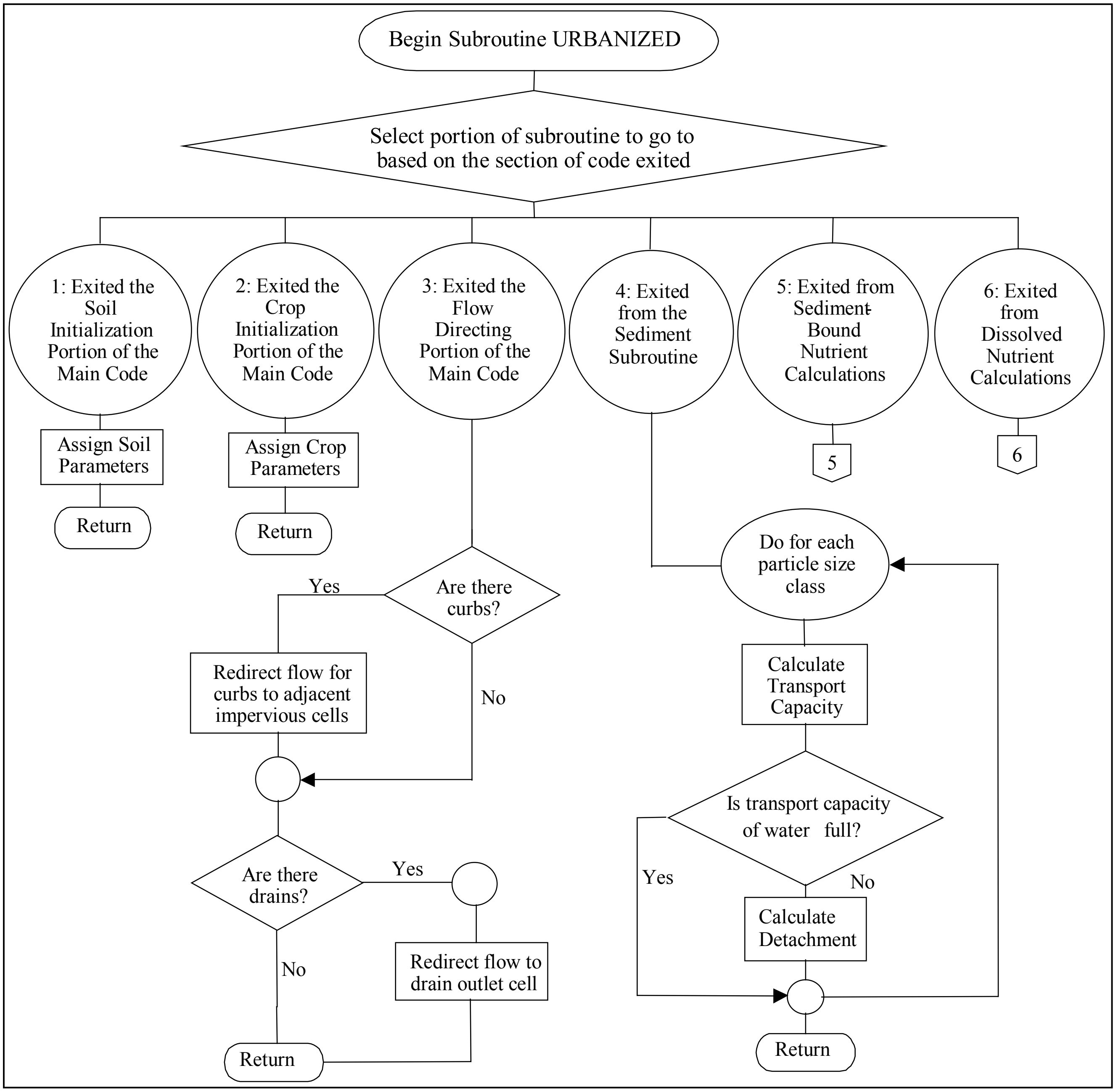

Figure 4. Flow Chart of the URBANIZED Subroutine.

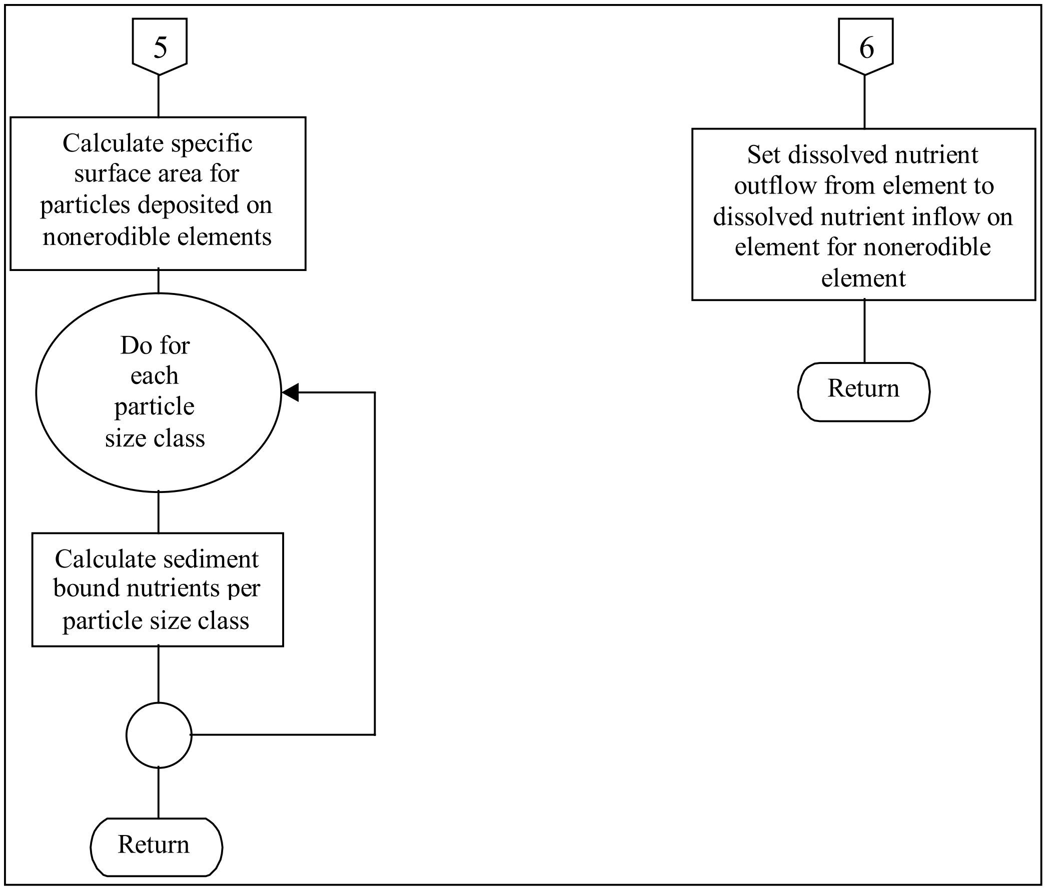

Figure 4. (continued) Flow Chart of the URBANIZED Subroutine.

3.4 Atmospheric Deposition

Two subroutines were developed to simulate atmospheric deposition of sediment and nutrients. Subroutines ATMDEPOSIT and WETDEP calculate dry and wet atmospheric deposition of sediment and nutrients, respectively. Both routines are called only on rainfall days. As with the other new additions to ANSWERS-2000, simulation of atmospheric deposition is optional. Entering zeros for the atmospheric deposition input values prevents simulation of atmospheric deposition.

As ATMDEPOSIT is only called on a rainfall day, the first task is to determine the number of days since the last rainfall event. Since atmospheric deposition rates are allowed to vary by season, the model determines the days since the last precipitation event and multiples this value by the deposition rate for a specific season and land use combination to get dry deposition at the start of the precipitation event. This is the same approach used in SWMM (Halverson *et al.*, 1982). The pollutants are then added to the existing sediment and sediment-bound nutrient pools on the element. This is calculated once per rainfall event.

The second subroutine, WETDEP, calculates the wet atmospheric deposition of nutrients and sediment. These values are input in mg/L of rainfall. This subroutine is called every precipitation event; however, it only needs the season in which the current day falls to choose the correct deposition value from the input, as wet deposition is not cumulative between precipitation events. The deposited sediment and nutrients are added to the suspended solids and dissolved nutrients flowing over the element surface. This is calculated every time step by multiplying the deposition concentrations for each contaminant by the volume of rainfall occurring during the time step.

To use subroutine ATMDEPOSIT, the user needs to input deposition rates in kg/ha-year for sediment and sediment-bound ammonia, nitrate, and ortho-phosphorus. These rates are specified in the crop declaration section of ANSWERS. Details on the format and placement of the values are included in the user's manual (Zeckoski, 2002) (Appendix C).

To use subroutine WETDEP, seasonal values for wet deposition concentrations of sediment, nitrate, ammonia, and ortho-phosphorus must be estimated and entered in the crop description section of QUESTIONS. These values can vary seasonally and between land uses. Flow charts of the dry and wet atmospheric deposition subroutines are included in Figure 5.

3.4.1 Assumptions and Limitations for the Atmospheric Deposition Subroutines

There are two assumptions for the atmospheric deposition subroutines. First, it is assumed that an average seasonal value is representative of the daily dry deposition. Second, the deposition parameters are assumed to be constant within a season and for a particular land use. The limitation to the use of the atmospheric deposition subroutines is that actual atmospheric deposition parameters are difficult to obtain and entering incorrect values can significantly affect model results (section 5.2).

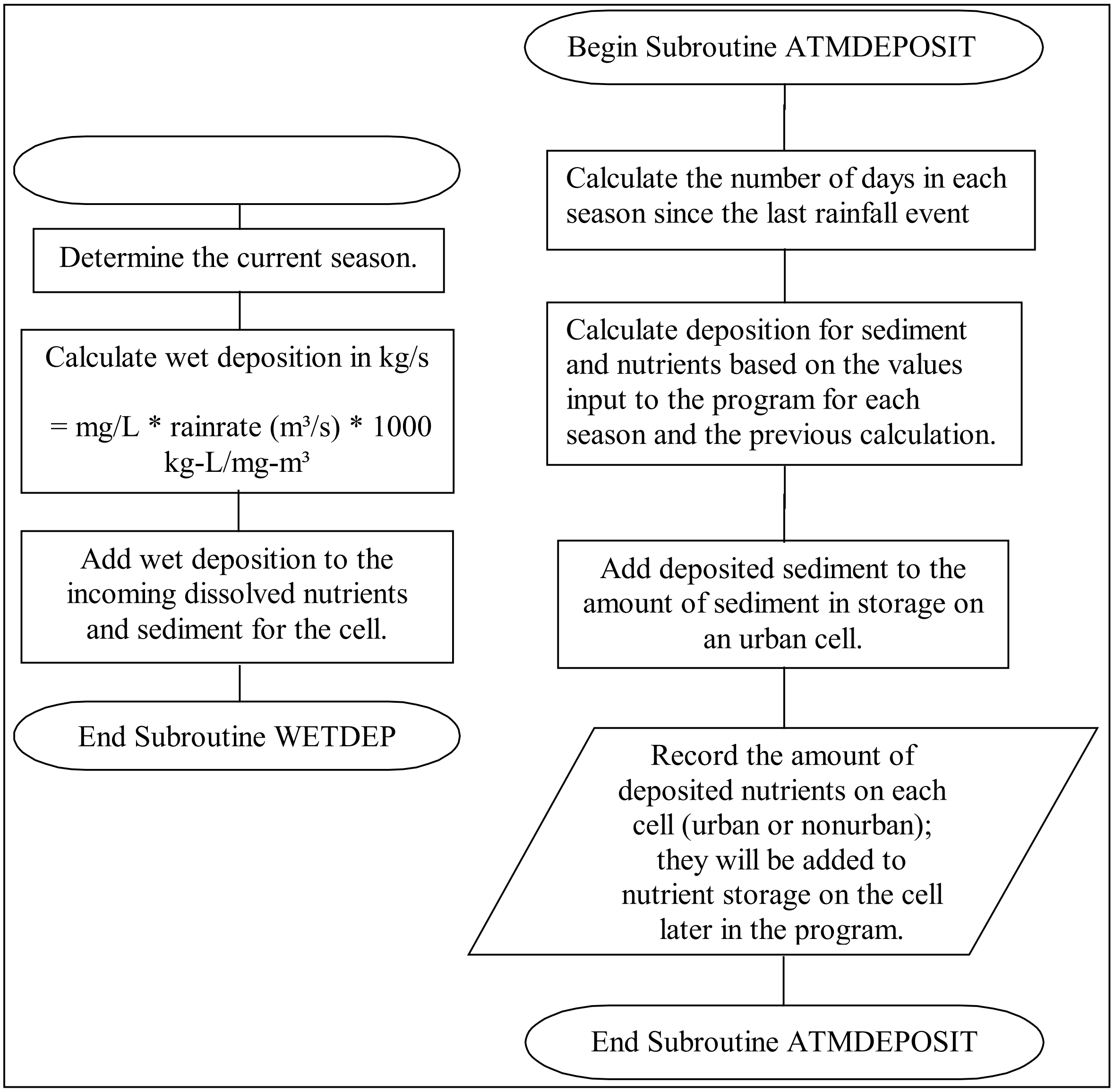

Figure 5. Flow Charts of the Atmospheric Deposition Subroutines.

Chapter 4. Model Evaluation

4.1 Introduction

The model was evaluated on two watersheds located in Blacksburg, Virginia. A subwatershed of the Stroubles Creek watershed was used to evaluate the urbanized subroutine. Evaluation of the model hydrology was performed for this watershed for the entire year of 1999, because hydrologic monitoring data were available for this time period. However, evaluation of the sediment and nutrient losses was done only for 29 individual storm dates for which water quality monitoring data were available. A second watershed, a parking lot located on the Virginia Tech campus that drains to a dry pond, was used to evaluate the BMP pond subroutine. Evaluation of both the hydrology and water quality portions of the model was performed on this watershed for the available monitoring dates, 15 storm events between August and November of 1995.

4.2 QVA Watershed

4.2.1 QVA Watershed Characterization

A subwatershed in the Stroubles Creek watershed on the Virginia Tech campus in Blacksburg, VA was chosen for evaluation of the urbanization component of ANSWERS-2000. This subwatershed is contained entirely within the town of Blacksburg and is centered along Southgate Drive. It is referred to in this text as the QVA Watershed, named for the monitoring station at its outlet. A diagram of the subwatershed and its urbanized components is shown in Figure 6. The subwatershed was monitored from 1997-1999 (Lovern, 2000). Water quality and runoff data were collected at several points within the subwatershed. Monitoring data from one point, QVA, were used in calibrating and evaluating the proposed model. The QVA watershed is 144.5 ha in area and is located immediately upstream of an existing wet pond. It was divided into 15m x 15m cells for simulation. The watershed cover includes a mixture of pasture, residential, and commercial areas, with impervious surfaces covering 17.8% of the area.

Runoff and water quality data, precipitation records, and ArcView landuse files for this analysis were collected by and obtained from Lovern (2000). The required soils shapefile was obtained from the SSURGO database (http://www.ftw.nrcs.usda.gov/ssur_data.html); digital elevation data from the Radford

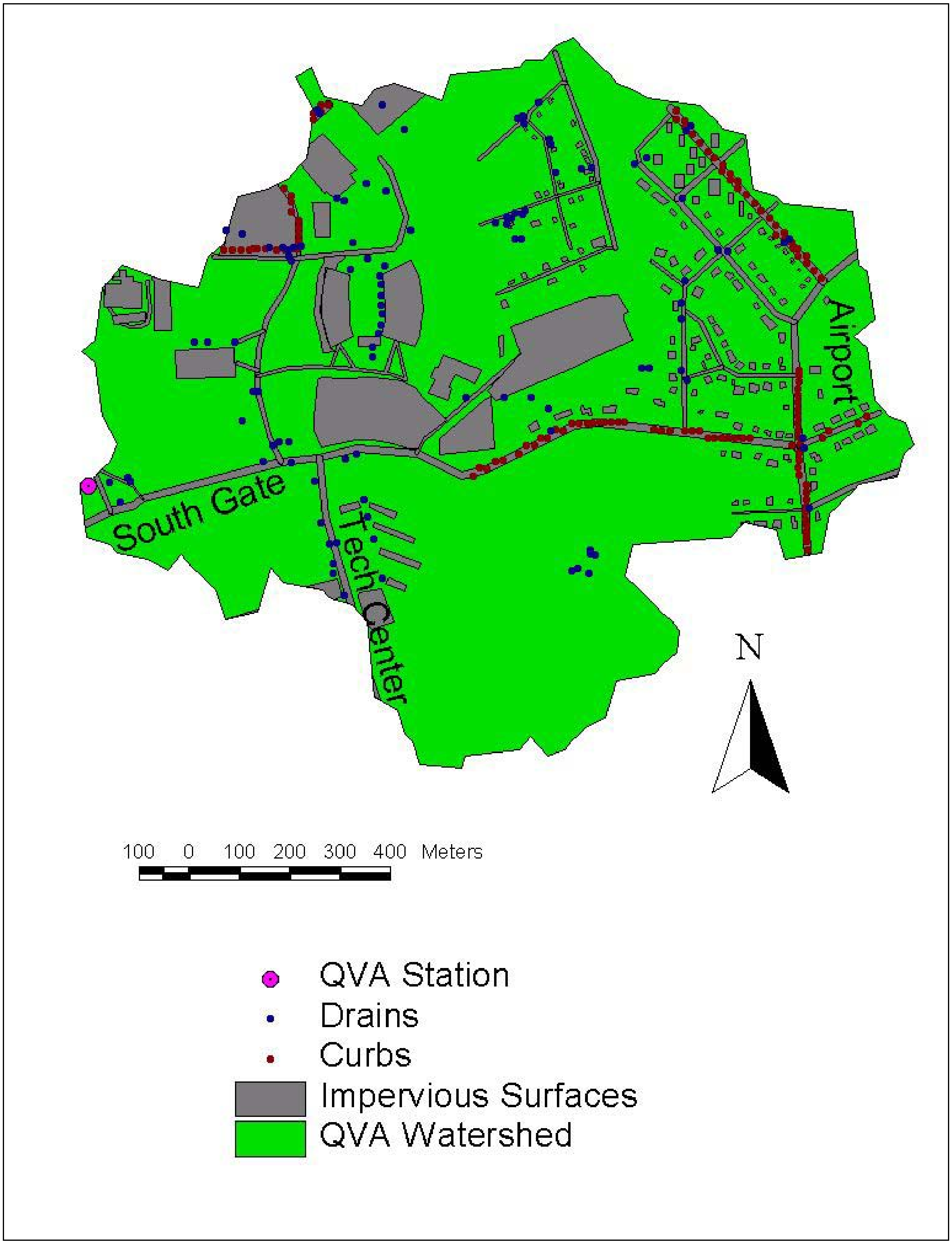

Figure 6. Curbs, drains, and impervious surfaces in the QVA Watershed in 1999.

University Geography Department website (www.radford.edu/~geoserve/main_page.html); and stormwater drain maps from the Town of Blacksburg Planning and Engineering Department. Figures 7 and 8 detail the different ArcView files collected and/or created for the QVA watershed.

The required breakpoint weather file for the QVA watershed was generated from the daily rainfall data collected by Lovern (2000) using a weather converter program described in Appendix B. The runoff data collected from the watershed monitoring station were analyzed to determine the total amount of runoff attributable to the storms recorded by the weather station. Appendix D contains a sample file from the monitoring logger and equations for conversion of the data from the logger format to the units used by ANSWERS-2000. Appendix E contains the derived runoff record.

4.2.2 QVA Evaluation Results

ANSWERS-2000 is not intended to be calibrated, since it is intended for use primarily on ungaged watersheds (Byne, 2000; Bouraoui,1994). However, the accuracy of the model will be increased if parameters are calibrated to site-specific conditions. In this study, the model was initially not calibrated and model parameters were the default parameters recommended by the QUESTIONS model interface for the pervious land uses. The parameters for the impervious land uses were based upon the visually observed characteristics of impervious surfaces.

Uncalibrated input files were used to simulate runoff and pollutant loss during the 1999 calendar year for the QVA watershed. All identified stormwater inlets; all impervious areas including buildings, roads, and parking lots; and a combination of pasture, turf, and sparse forest in the watershed were simulated. The cow pastures in the watershed were represented as pastures; pervious land in high-density areas was characterized as poor turf; pervious land in residential areas was represented as sparse forest (based on visual inspection of an aerial photograph of the region); and buildings and roads were represented as impervious surfaces. A fertilizer input file was created for the turf in the watershed using values obtained from Lovern (2000). With these input files, the annual predicted runoff for 1999 was 7.4% above the actual measured annual runoff for the QVA watershed (Table 2). The annual predicted sediment loss was

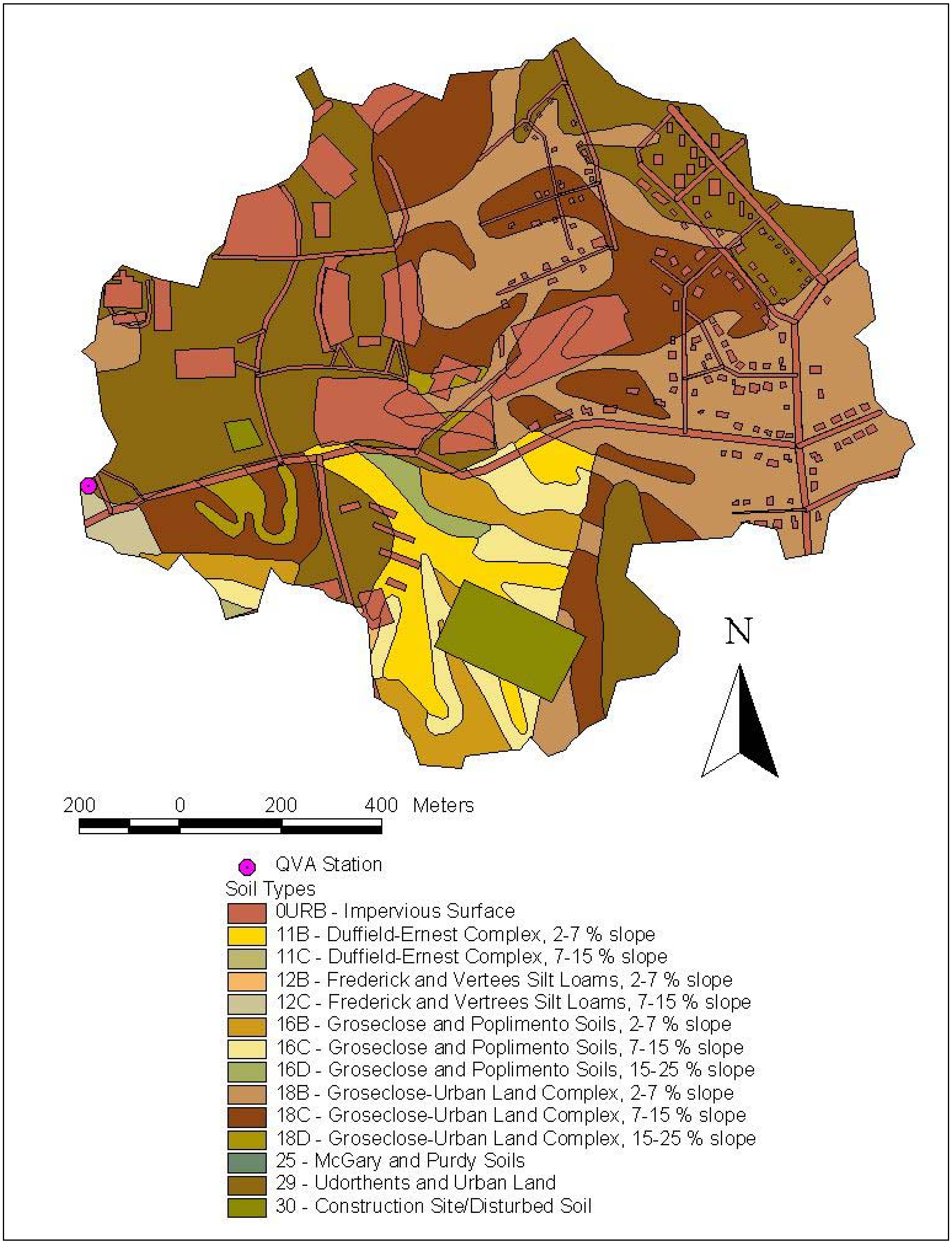

Figure 7. Soils map for the QVA watershed, including the impervious surfaces.

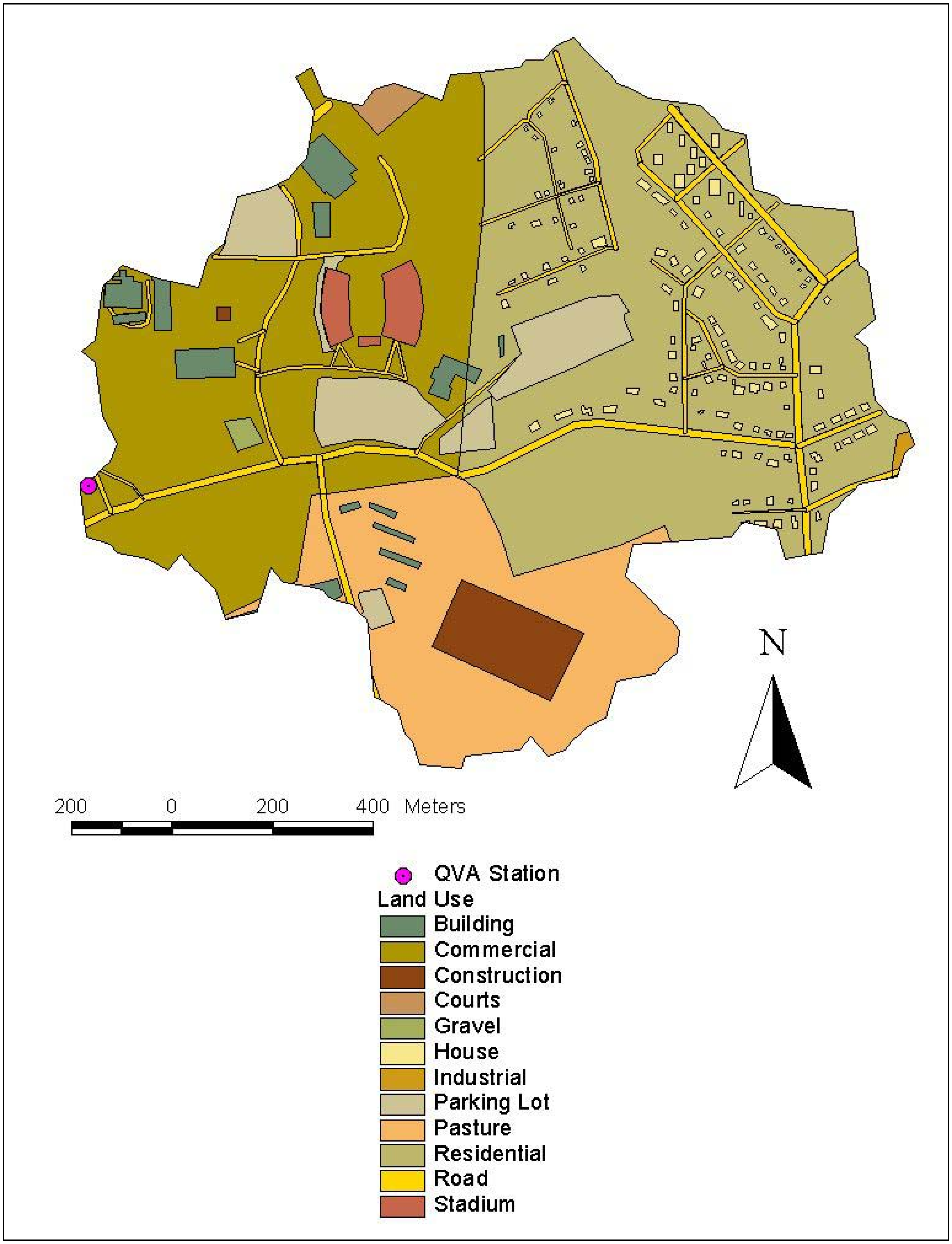

Figure 8. Landuse in the QVA watershed, including impervious surfaces, in 1999.

91.2% less than the measured sediment loss. Comparison of all output parameters can be found in Table 2.

Table 2. Comparison of Measured and Predicted Losses for the QVA Watershed in 1999 without Calibration.

	Runoff[1] (mm)	**Sediment[2] (kg/ha)**	**NO_3[2] (kg)**	**NH_4[2] (kg)**	**PO_4[2] (kg)**	**TKN[2] (kg)**
Measured	63.3	8071.8	27.2	1.14	0.50	23.5
Predicted	68.0	706.5	6.9	1.1	2.1	202.1
% Error	+7.4	-91.2	-74.6	-3.5	+320	+760

[1]Runoff comparisons were made for the entire year of 1999.
[2]Sediment and nutrient comparisons were made only for the available monitored storm dates of 1999.

Due to the poor performance of the uncalibrated sediment model on the QVA watershed, calibration was performed to attempt to increase the accuracy of the model predictions. The final results were produced by decreasing the interrill vegetative cover for the crop types, decreasing the sand content of soils, and increasing the atmospheric deposition rates for sediment on the impervious/nonerodible areas. The input variables mentioned were chosen for modification based on the sensitivity analysis conducted by Byne (2000). The modification of these variables was done to the extent considered practical. While greater changes would have further increased sediment loss, it was not considered practical to greatly alter the soil properties for the watershed as most of the soils were clearly defined; the sand content of soils was only decreased for the two soils with unknown parameters – the soil group listed as udorthents/urban land in the soil survey, and the soil in the construction area. These soil types comprised 27% of the soils in the watersheds. Atmospheric deposition rates were increased to a value higher than that reported in more heavily urbanized areas, and further adjustment was deemed impractical. The specific input files (answers.inp, weather.inp, fertilizer.inp) determined through calibration to best represent the different land uses are listed in Appendix E.

In addition to these parameters, the initial concentrations of nutrients in the soils were decreased greatly. In particular, the error in the prediction of total Kjeldahl nitrogen appeared to be primarily a result of faulty input of the initial concentration of nitrogen in the soil. With this calibration, the runoff predicted was 22.21% higher than the measured runoff. This was due to the adjustments made to the soil textures, which altered the infiltration capacity of the affected soils. The simulated sediment loss was underpredicted by 45.72%. After calibration, the runoff and ammonia losses increased, a result of the changes in the sand content of soil and the manipulation of nitrogen required to bring the TKN and nitrate values into a more reasonable range, respectively. These increased errors were considered acceptable in light of the decrease in error of the other output parameters. The results are shown in Table 3. The monitored values were reported as concentrations and for comparison were multiplied by the measured runoff to obtain the measured values listed in the tables. The storm-by-storm comparisons of runoff, sediment, and nutrients are shown in Figures 13 through 18.

Table 3. Comparison of Measured and Predicted Losses for the QVA Watershed in 1999 with Calibration.

	Runoff[1] (mm)	**Sediment[2] (kg/ha)**	**NO_3[2] (kg)**	**NH_4[2] (kg)**	**PO_4[2] (kg)**	**TKN[2] (kg)**
Measured	63.3	8071.8	27.2	1.14	0.50	23.5
Predicted	77.3	4381.5	34.6	1.23	0.63	25.2
% Error	+22.1	-45.7	+27.2	+7.9	+26.0	+7.2

[1]Runoff comparisons were made for the entire year of 1999.
[2]Sediment and nutrient comparisons were made only for the available monitored storm dates of 1999.

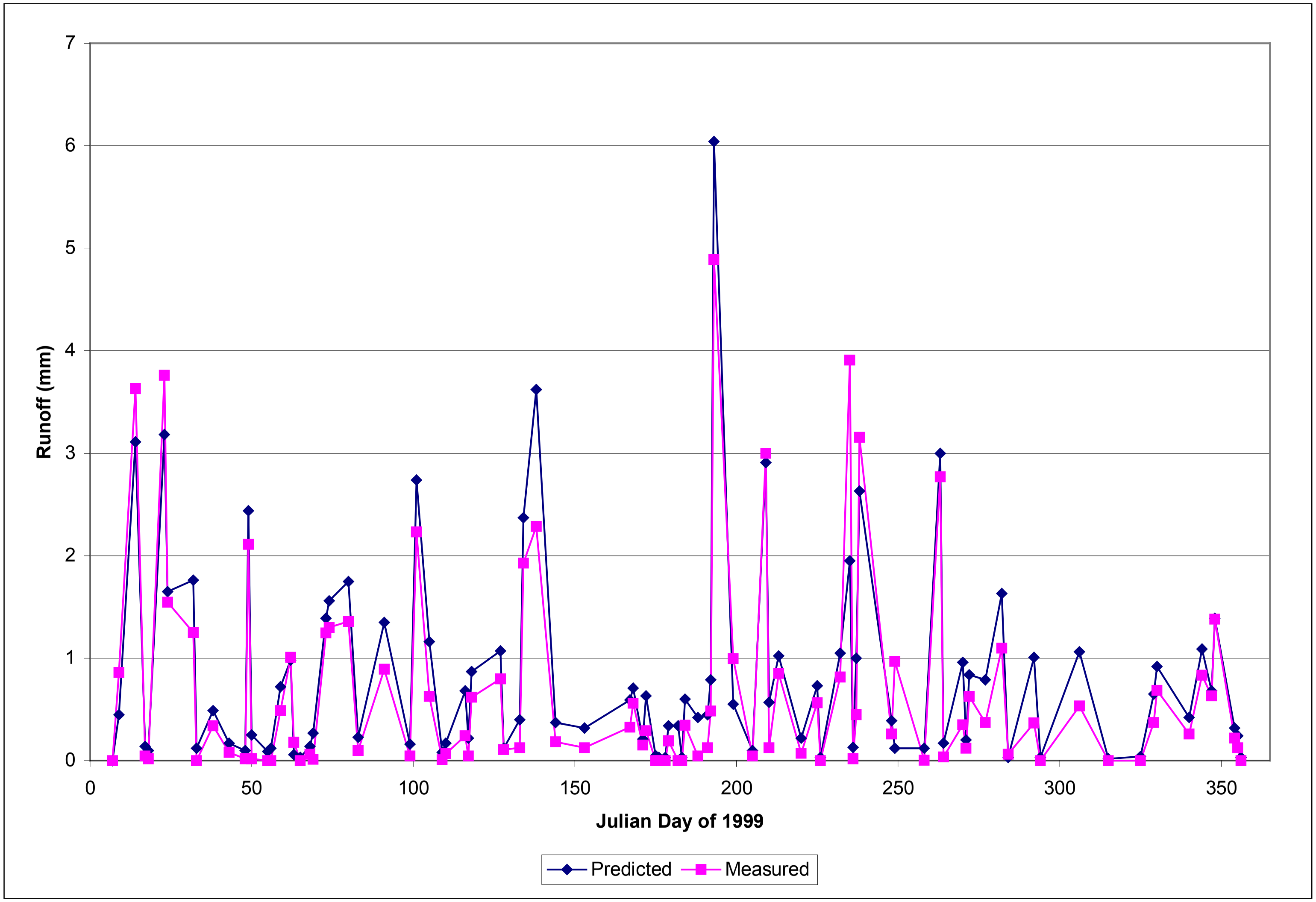

Figure 9. Predicted and Measured Runoff from the QVA Watershed in 1999 after calibration.

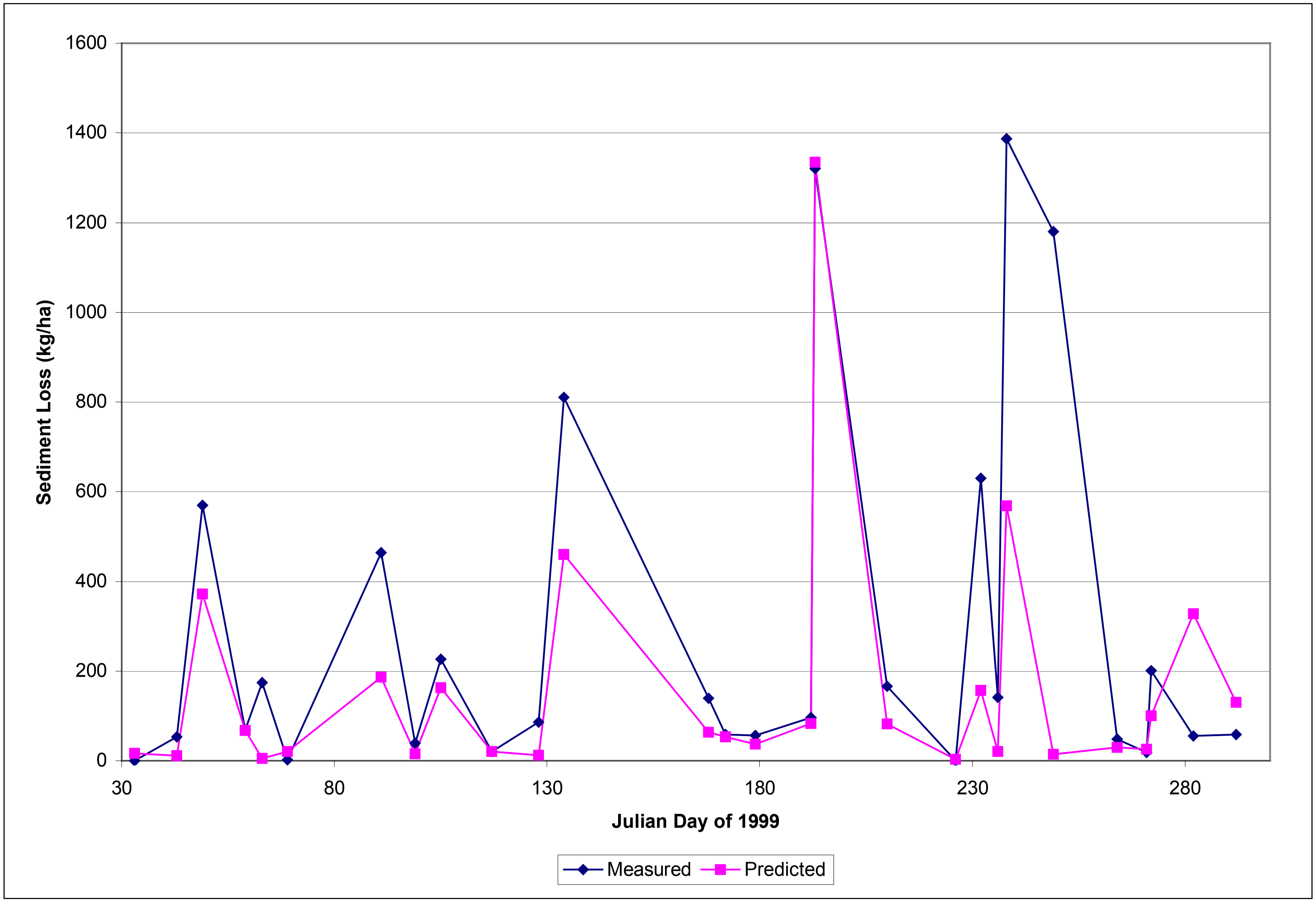

Figure 10. Predicted and Measured Sediment Loss from the QVA Watershed in 1999.

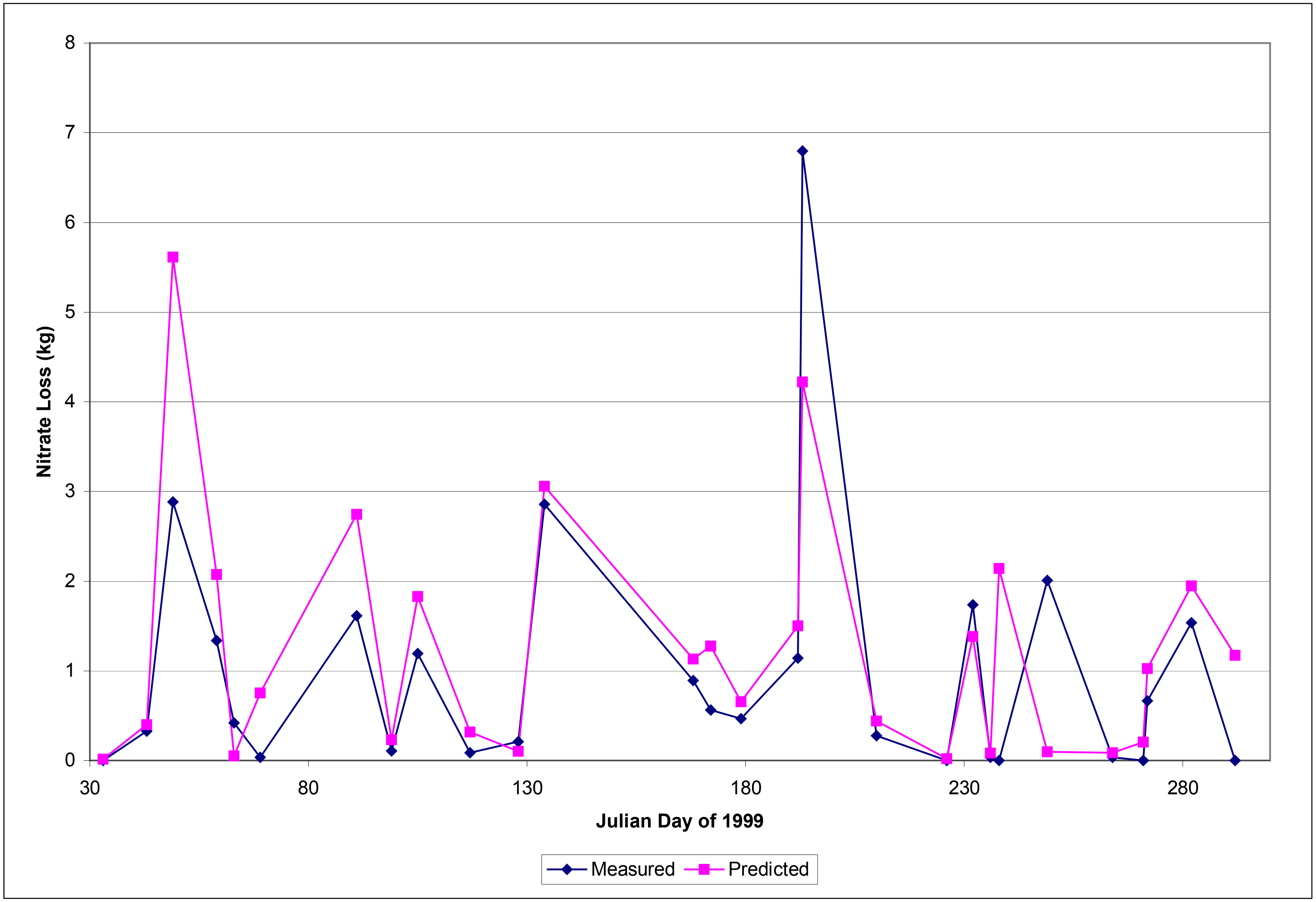

Figure 11. Predicted and Measured Nitrate Loss from the QVA Watershed in 1999.

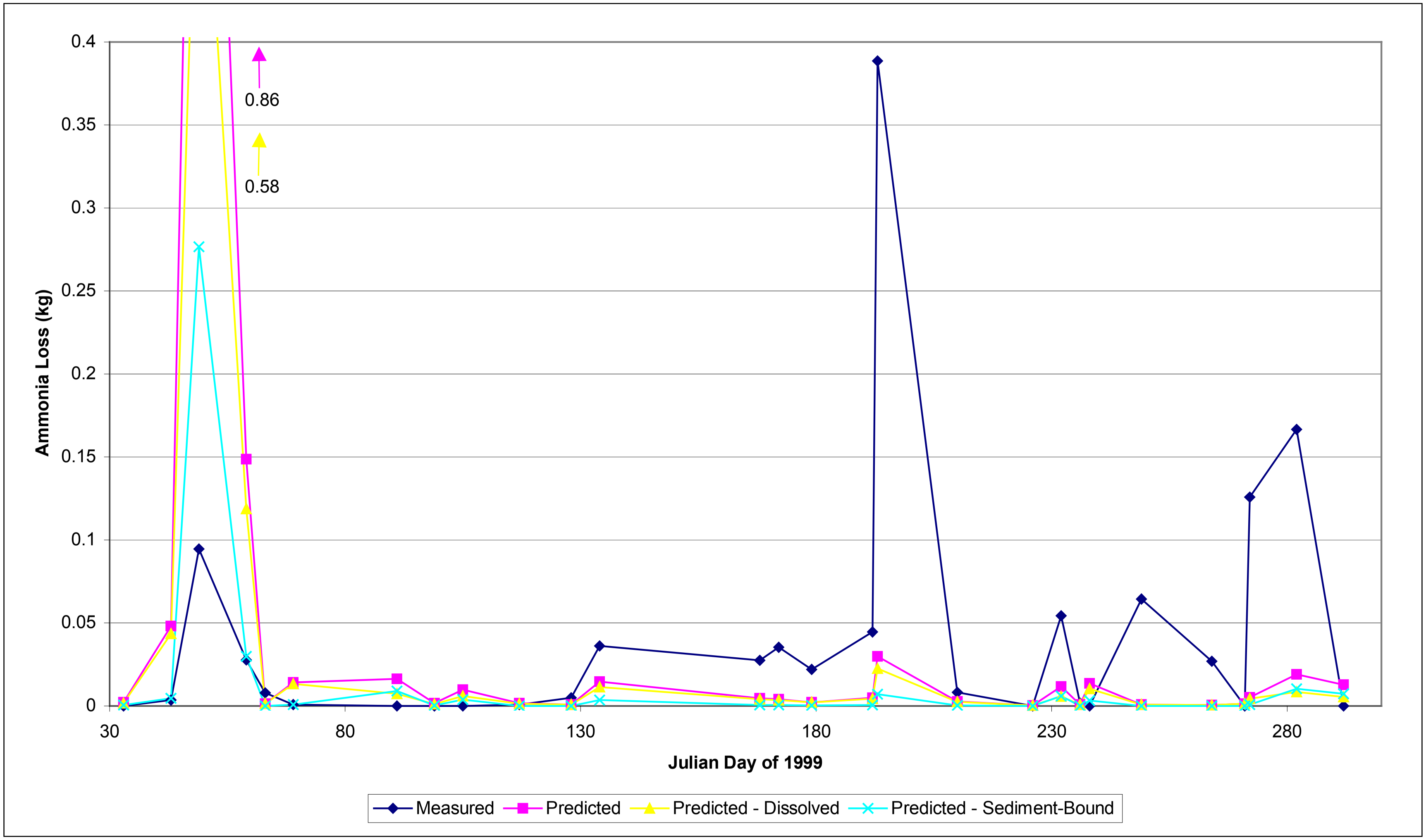

Figure 12. Predicted and Measured Ammonia Loss in the QVA Watershed for 1999.

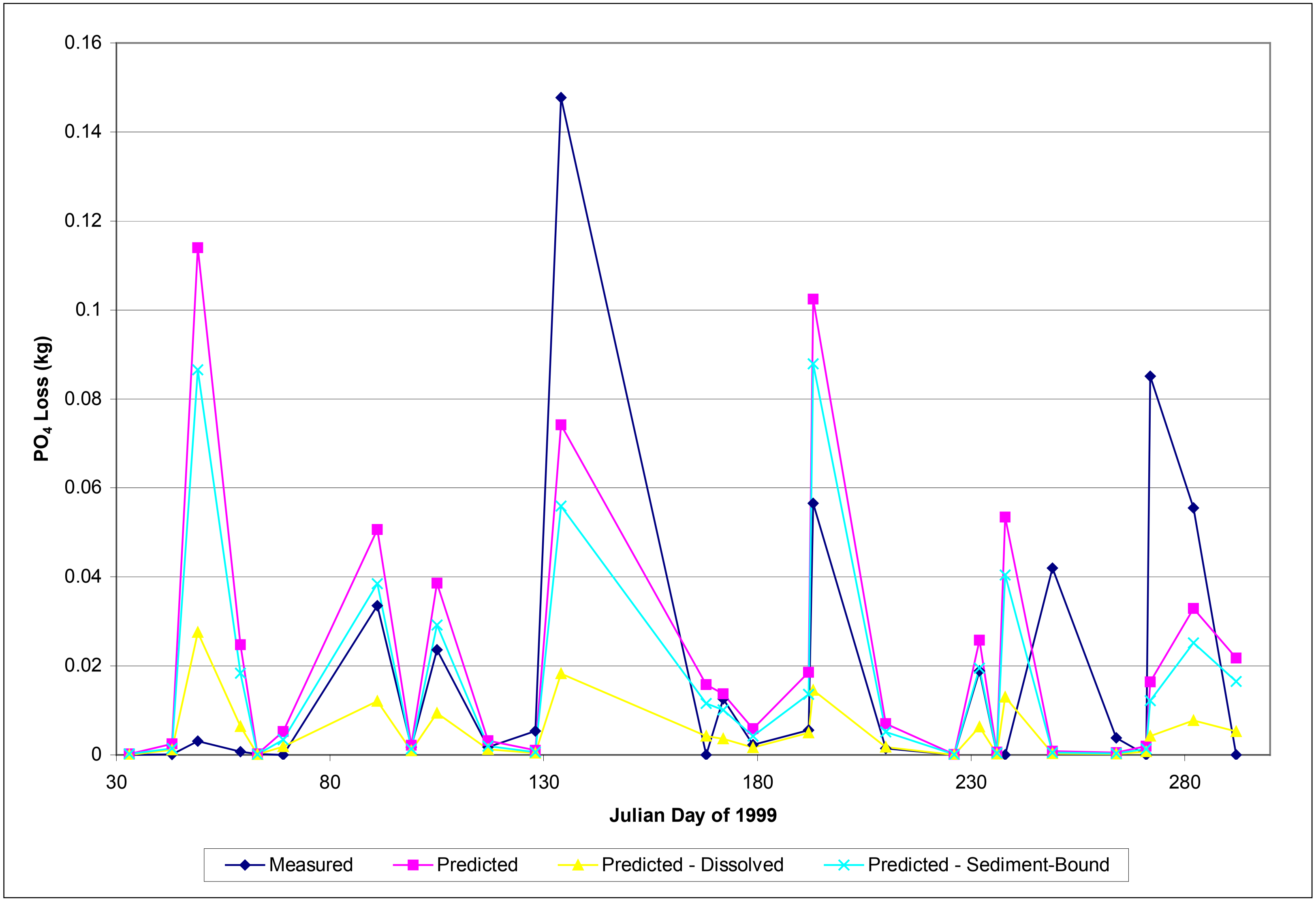

Figure 13. Predicted and Observed PO_4 Loss from the QVA Watershed in 1999.

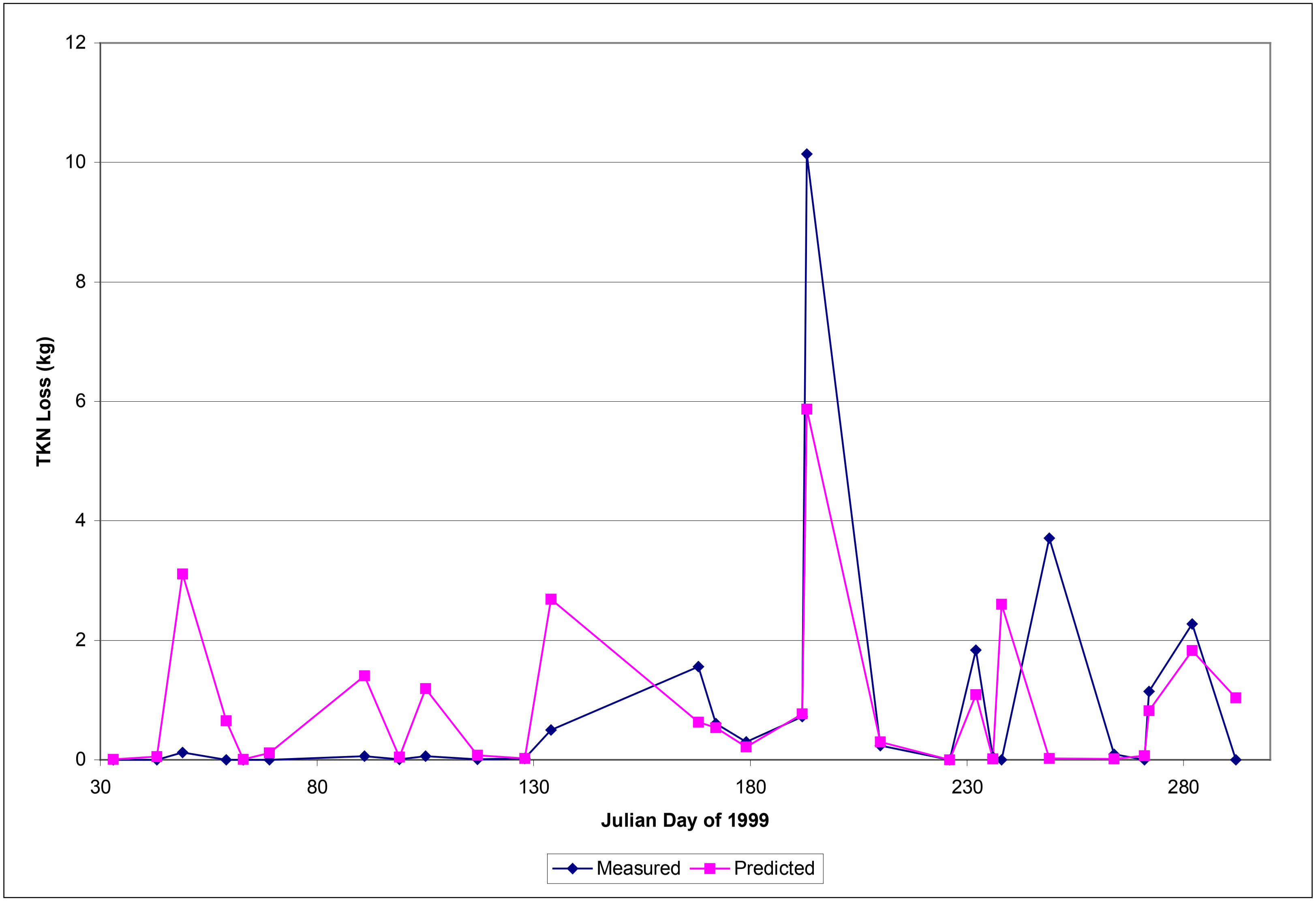

Figure 14. Predicted and Measured Total Kjeldahl Nitrogen Loss from the QVA Watershed in 1999.

4.2.3 QVA Analysis of Error

There were several potential sources of error in the QVA simulation. First, there were construction activities occurring within the QVA watershed at the time the monitoring data were collected (Lovern, 2000). The model was calibrated for sediment loss from these areas, but the exact soil and cover conditions for the construction areas at the time of data collection were unknown. The actual soil nutrient levels for the entire watershed and fertilizer nutrient applications for the majority of the watershed were not measured nor recorded in 1999 and were estimated for the model simulation. These estimations were most likely different from the actual situation in 1999, contributing to the errors in the nutrient response of the model.

Another source of error in the QVA simulation could have been a result of errors in the measured data. The nutrient concentrations were reported as totals, not divided between sediment-bound and dissolved phases. Therefore it was impossible to tell if the ANSWERS-2000 model was accurately simulating either one of the phases. The raw water quality data provided for the QVA watershed was not well documented and was difficult to analyze, resulting in possible misinterpretations of the measured results. The monitored data reported by Lovern (2000) included days with multiple storms, with pollutant loss concentrations for each storm that were frequently orders of magnitude in difference. This could not be represented by ANSWERS-2000. ANSWERS-2000 does not distinguish between the output from different storms on a single day. The daily runoff and pollutant losses that the model reports cannot be separated into values for each storm event. The combination of these sources of error contributed to the errors noticed in the model predictions.

4.2.4 QVA Discussion

There are several proposed guidelines for determining the success of a model evaluation. No standard has been set, but Heatwole *et al.* (1991) suggest that a calibrated model is acceptable if its predicted values are within a factor of two of the observed values. This guideline was followed by the two most recent modifiers of ANSWERS-2000, Faycal Bouraoui (1994) and F. Wes Byne (2000), and will be followed in this study. According to this guideline, the urbanization component of ANSWERS-2000 that predicts runoff, sediment, and nutrients is acceptable.

The simulated runoff from the urbanized watershed (QVA) matched the measured data well: the uncalibrated annual predicted runoff was 7.4% above the annual measured runoff. The uncalibrated sediment prediction for 1999 was 91.2% below the actual measured value. Calibration was performed to increase the accuracy of the sediment and nutrient predictions. The runoff prediction error increased to 22.2% above the measured value. However, the sediment error was reduced to 45.7% below the measured value, and all the nutrient predictions were overpredicted within 30% of measured values, meaning that all prediction errors fell within the necessary factor of two after calibration. The reduced errors were primarily the result of calibrating model input parameters that were not measured nor reported during the simulation period (atmospheric deposition and characterization of disturbed soils). Therefore, although these values seem to better represent the watershed for this model, it is not known if the values are actually a truer representation of the watershed, because they were not measured at the time of data collection.

4.3 Commuter Lot B Watershed

4.3.1 Commuter Lot B Watershed Characterization

The second watershed, Commuter Lot B on the Virginia Tech campus, was used to evaluate the BMP pond subroutine. The parking lot is 8.78 ha in area and was divided into 10m x 10m cells for simulation. It is covered with 73% impervious surfaces. The remaining pervious area is covered in grass or ornamental flowerbeds. Curbs bound the impervious area. The runoff from the lot drains to an extended detention dry pond. All input to the dry pond comes from the parking lot and thus there is an isolated system with inputs clearly defined (Latham, 1996). Figure 15 is a topographic map of the parking lot.

The dry pond is designed to detain the first 1.27 cm of runoff from the parking lot for 40 to 50 hours (Hodges, 1997). This requires a pond with a volume of 1115 cubic meters. The riser outlet is 1.22 m high, with a 1.58 square meter opening at the top. Two concrete pipes drain the riser outlet structure, each with a diameter of 0.91 meters. At the base of the riser structure is a 7.62 cm diameter riser inlet, designed to release the required volume in the designed detention time of 40-50 hours (Latham, 1996; Hodges, 1997).

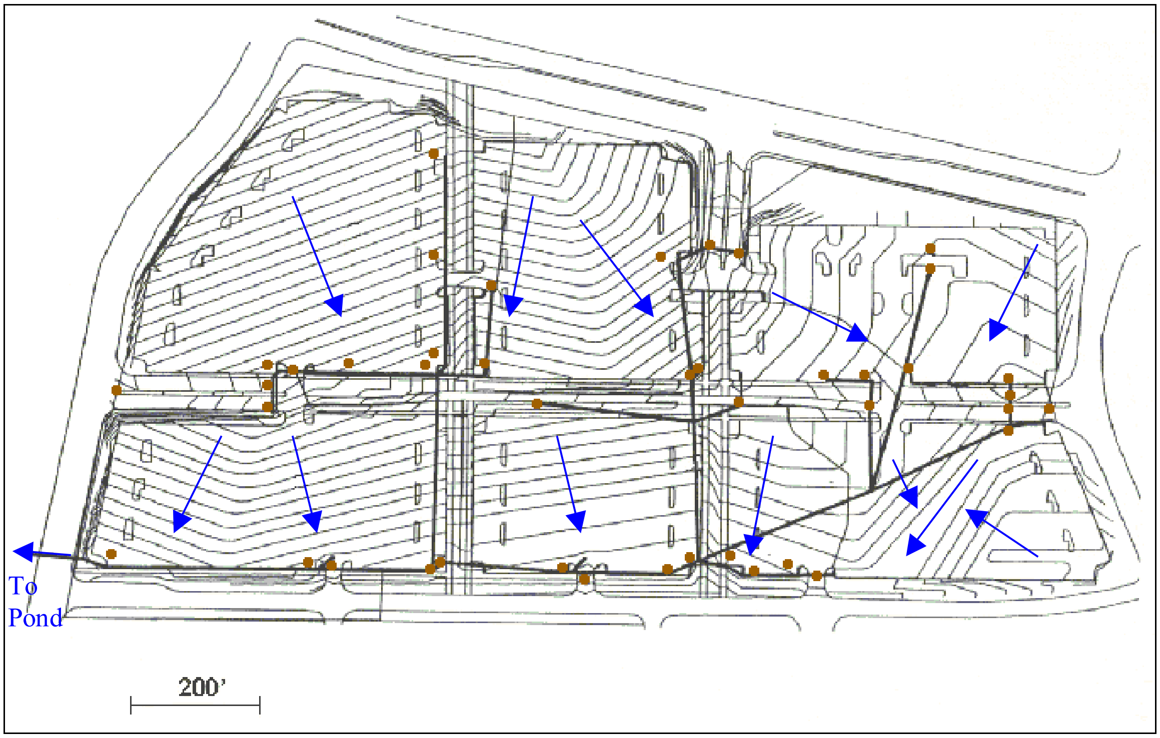

Figure 15. Topographic Map of Commuter Lot B. The dark lines indicate the layout of the stormwater drainage system. Blue arrows indicate flow directions and brown dots indicate stormwater drain inlets. Contour interval = 2 feet. Taken from Latham (1996).

The required breakpoint weather file for the Commuter Lot B watershed for 1995 was created as a combination of data collected by the NOAA station in Blacksburg, VA and data collected by Hodges (1997) at the parking lot site. Hodges reported only 16 storms in 1995; the data lacked detail about the storm events preceding the time period and about several of the storm events that occurred between the ones she reported. Thus, the NOAA station data were used to fill in the gaps between Hodges' recorded data. This was necessary to determine the appropriate initial moisture content and water depth of the dry pond for each storm event. Hodges' precipitation data were used on the days they were available.

4.3.2 Commuter Lot B Evaluation Results.

Commuter Lot B was simulated from August 1, 1995 to February 29, 1996 (this period of time was chosen based on the available weather data and the dates that the monitored data were collected). In the commuter lot, the asphalt-covered areas were simulated as impervious land and the pervious areas were simulated as sparse grass. The entire asphalt area was surround by curbs and the drains were placed according to the maps created by Latham (1996) and Hodges (1997). Atmospheric deposition parameters were the only ones used for calibration of this watershed for conditions at the pond inlet; due to the large percent of impervious area (73%), crop and soil parameters of the surrounding grassed area would have little effect on model output. The atmospheric deposition of nutrients was altered until the nutrient and sediment output from the model at the pond inlet reached an acceptable degree of error (within a factor of two of the observed data); results reported were not calibrated for runoff. Once the model was calibrated to the conditions at the pond inlet, those input files were used to model the conditions at the pond outlet. When calibrating for the conditions at the pond outlet, only the pond dimensions were calibrated. The diameter of the side orifice opening was reduced to account for the clogging of this opening noticed in observation of the pond. The area was increased slightly (with a corresponding decrease in depth). Because the pond is not square, it was possible to alter the area slightly to better represent the pond as a square pond with vertical walls. The runoff for the storms available for comparison was under-predicted by 11.5% at the pond outlet. A comparison of the measured and predicted runoff at the pond outlet can be found in Figure 16. The sediment loss for the storms available was over-predicted by 60.4% at the pond outlet. The runoff for the parking lot at the inlet to the pond was under-predicted by 8.8%. Sediment loss from this watershed was over-predicted by 14.4 %. Results from each of these runs can be found in Table 4.

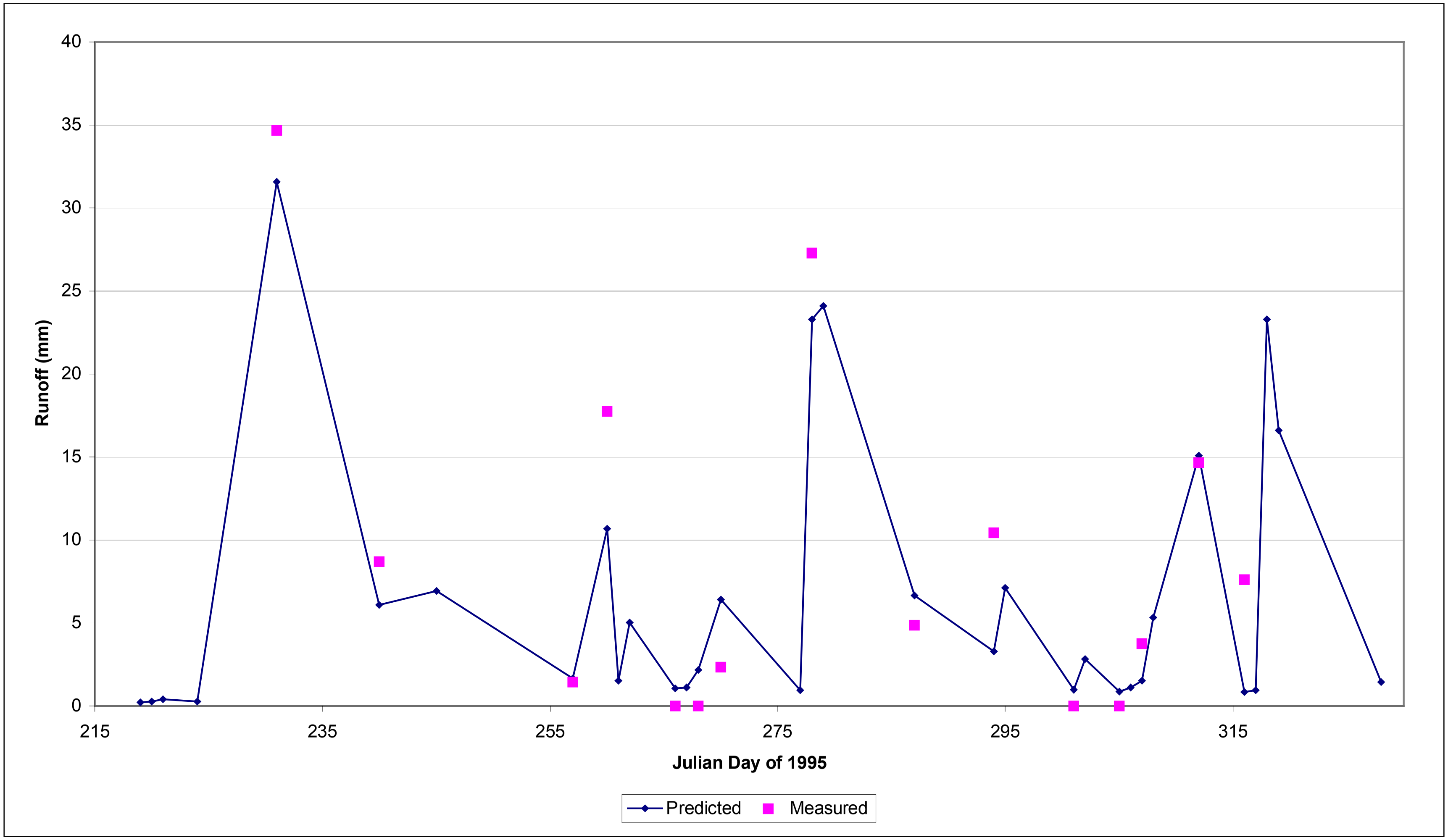

Figure 16. Predicted and Measured Runoff for Commuter Lot B with a Dry Pond at the Outlet in 1995

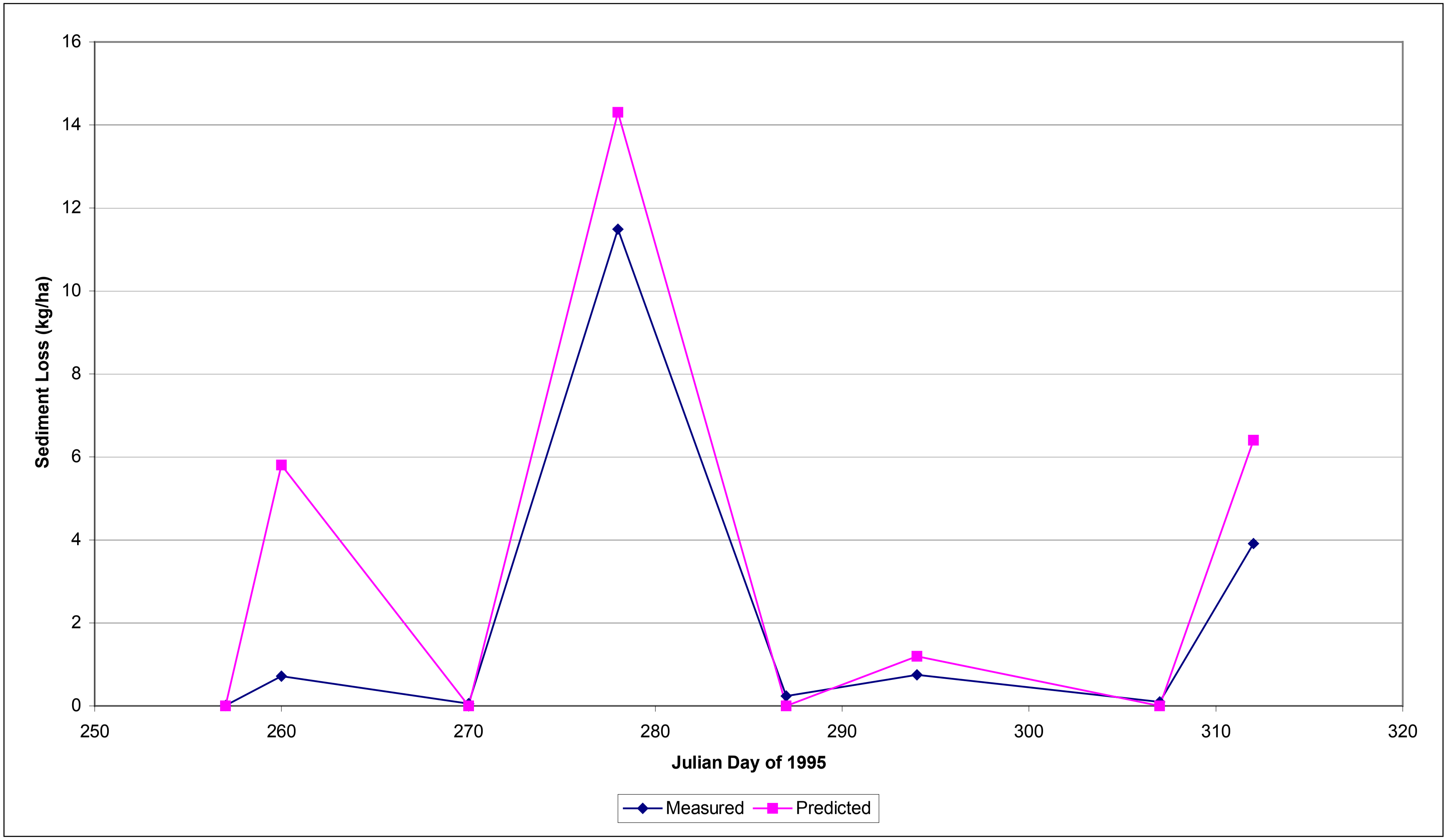

Figure 17. Predicted and Measured Sediment Loss for Commuter Lot B with a Dry Pond at the Outlet in 1995.

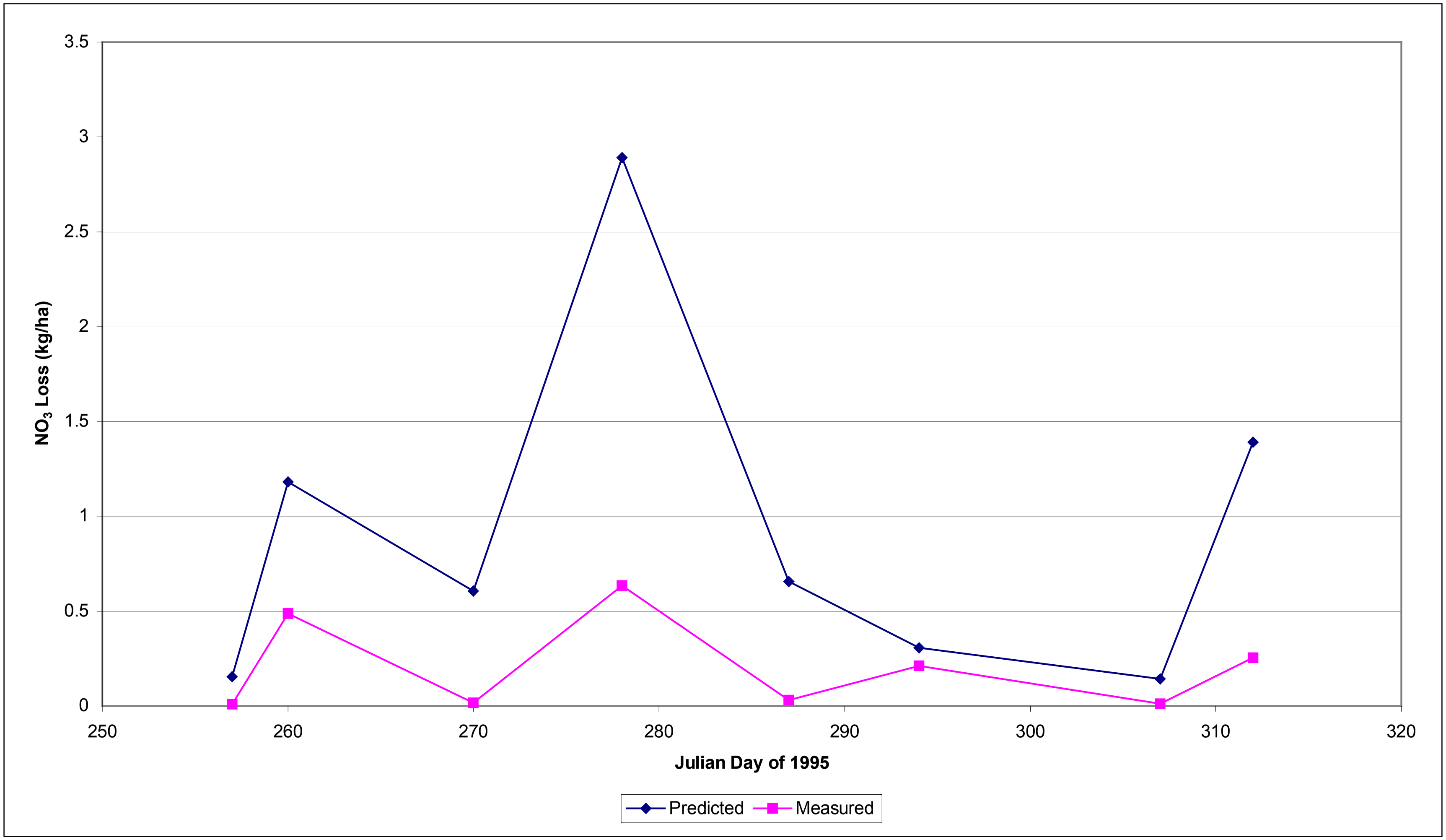

Figure 18. Predicted and Measured Nitrate Loss from Commuter Lot B with a Dry Pond at the Outlet in 1995.

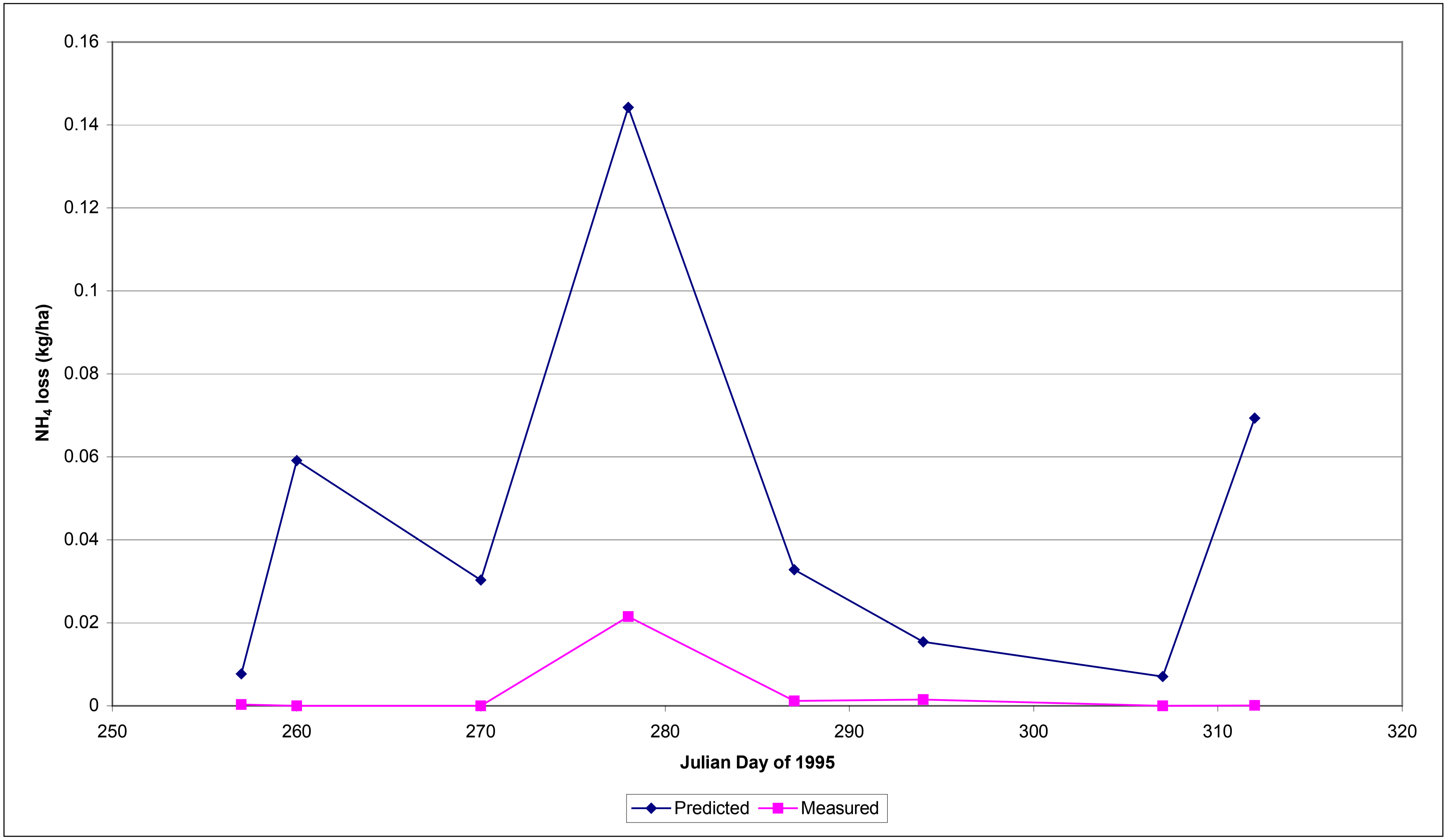

Figure 19. Predicted and Measured Ammonia Loss for Commuter Lot B with a Dry Pond at the Outlet in 1995.

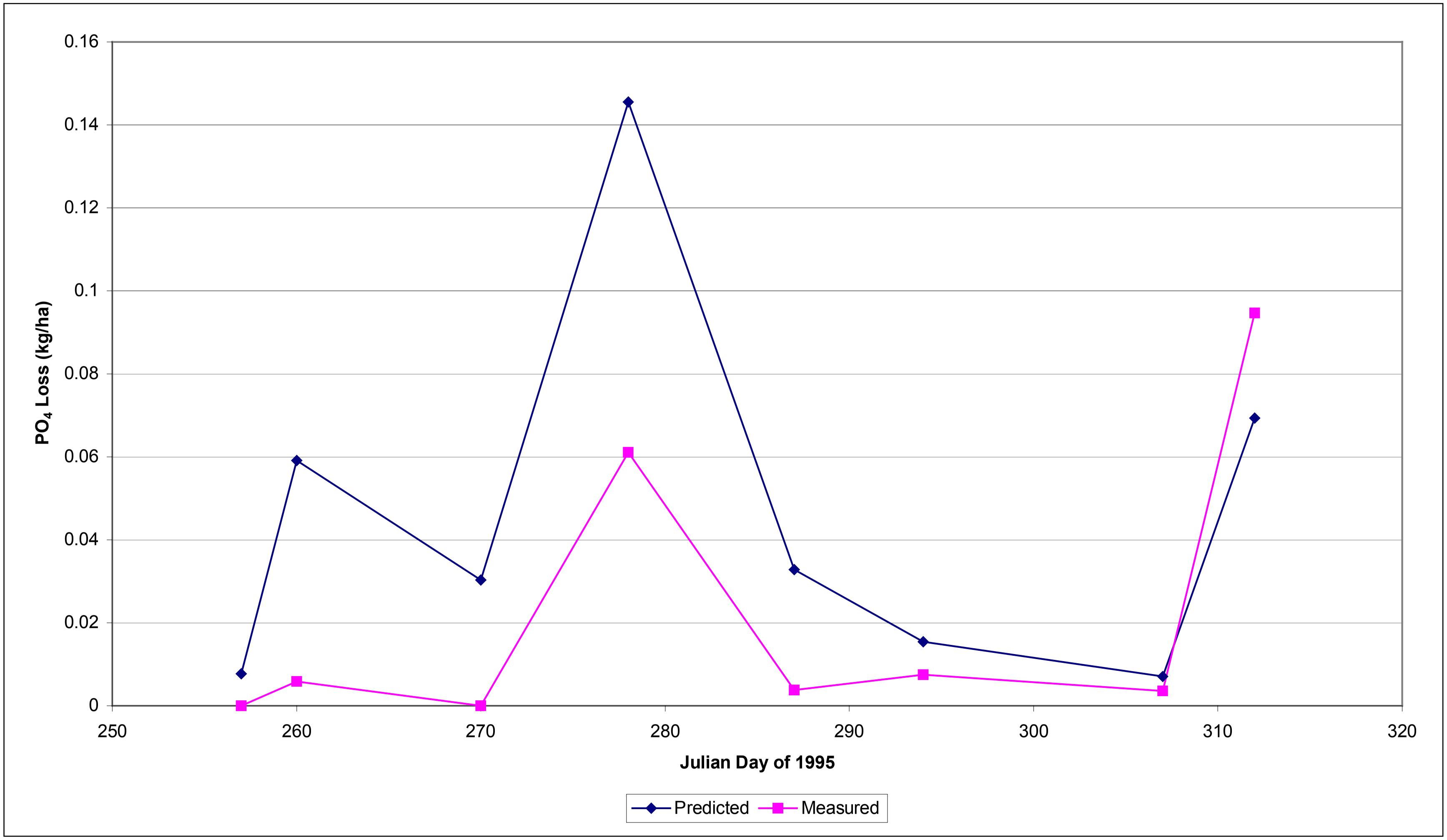

Figure 20. Predicted and Measured PO_4 Loss for Commuter Lot B with a Dry Pond at the Outlet in 1995.

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Table 4. Runoff and Pollutant Loss from Commuter Lot B and Percent Reduction in Runoff and Pollutants in Dry Pond after Calibration.

		Runoff (mm)	Sediment (kg/ha)	NO_3 (kg)	Total NH_4 (kg)	Total PO_4 (kg)	Total TKN (kg)
Lot B pond effluent	Predicted	111.4	27.7	7.3	0.4	0.4	0.0007
	Measured	125.9	17.3	1.7	0.02	0.2	8.1
	% Error	-11.5	+60.1	+329	-1900	+100	-100
Lot B pond influent	Predicted	147.1	68.3	13.8	0.7	0.7	0.003
	Measured	161.3	59.7	14.7	0.8	0.7	27.0
	% Error	-8.8	+14.4	-6.1	+12.5	0	-100
Percent reduction by pond	Predicted	24.3	59.4	47.1	42.9	42.9	76.7
	Measured	22.0	71.0	88.4	97.5	71.4	70.0

4.3.3 Commuter Lot B Analysis of Error

As was mentioned previously, this revised model is not intended for use on highly impervious watersheds, those with 30% or greater impervious cover. Cars and people deposit a variety of pollutants at varying rates that were not measured and this deposition was difficult to quantify for the Commuter Lot B simulations. While this contribution might be minor in a watershed with a low percentage of impervious areas, in a watershed such as Commuter Lot B, this contribution is the primary source of pollutants and errors are inevitable.

The errors in nutrient loss from the outlet of the dry pond associated with Commuter Lot B seem to be a result of a problem in the modeling of nutrients in the pond. In particular, the dissolved nutrients appear not to be well-mixed, or perhaps there are sources and sinks for nutrients not accounted for in the model. The monitoring stations were positioned to avoid a known problem with backwater effects, but during large storms there still may have been backwater effects that the model cannot simulate.

Another possible source of error in the predictions of nutrient losses from the dry pond at the foot of Commuter Lot B could reside in the way the nutrients were represented during calibration. The measured values from Hodges (1997) were reported only as totals – no distinction was made between dissolved and sediment-bound nutrients. As a result, the calibration performed for the scenario at the inlet to the pond may have placed too great a weight on the dissolved nutrient contributions and not enough weight on the sediment-bound contributions to the total nutrient loss from the watershed at the inlet to the dry pond. In other words, the nutrient concentrations could be predicted with an acceptable rate of error at the inlet to the pond if the sum of sediment-bound and dissolved nutrients equaled the total measured nutrient loss, while the actual distribution of nutrients between sediment-bound and dissolved forms was not accurately quantified.

The removal of sediment-bound and dissolved nutrients differs within the dry pond, as the removal rate for each form of nutrient is dependent on different pond parameters. Therefore, if the distribution of nutrients between sediment-bound and dissolved phases was not accurately represented at the inlet to the pond, the removal rate of nutrients from the pond could have been misrepresented. In particular for the Commuter Lot B calibration, the simulated sediment and sediment-bound nutrient removal rates were much higher than the dissolved nutrient removal rates (59.4 and 76.7% for sediment and sediment-bound nutrient (TKN) versus an average 44.3% for dissolved nutrients). Therefore, assigning too much weight to the dissolved nutrients would have resulted in predicted removal rates for total nutrients within the pond much less than the actual removal rates.

A final source of error in the Commuter Lot B could have been a result of errors in the measured data. As already mentioned, the nutrient concentrations were reported as totals, not divided between sediment-bound and dissolved phases. This resulted in possible errors in the pond subroutines in particular, as mentioned previously. The monitored data reported by Hodges (1997) included days with multiple storms, with pollutant loss concentrations for each storm that were frequently very different. As mentioned in section 4.4, this could not be represented by ANSWERS-2000. None of the raw data were available for the Commuter Lot B evaluation, which made it impossible to evaluate the analysis that produced the measured data for this watershed. Data were not collected from the majority of the storm events during the time period considered for Commuter Lot B, which meant that there was not a broad database for comparison with the model output for the time period. Results might have produced better total predictions had all the storm events been considered.

4.3.4 Commuter Lot B Discussion

The runoff from Commuter Lot B was predicted within the acceptable error range (see section 4.5) at the inlet and outlet of the dry pond. Errors in runoff were –8.05% for the inlet to the pond and –11.5% at the outlet of the pond for the storms considered. This evaluation could only be performed on the limited number of storms for which data were collected by Hodges (1997). The sediment and nutrient losses (with the exception of TKN) at the inlet to the pond were predicted acceptably, with errors between –12.6% and +12.5%. At the pond outlet, the sediment loss was overpredicted by 60% (considered acceptable according to the criteria set), but total nutrient loss was poorly predicted, with all errors greater than 100% in magnitude. The error appears to reside in the prediction of dissolved nutrient loss from the pond. The sediment-bound nutrient loss was near zero for all storm events, and therefore did not contribute to the high nutrient loss predictions from the pond. However, this might indicate that the portion of nutrient contribution to the watershed given to the sediment-bound nutrients was too low. This would cause the model to overpredict the total nutrient losses from the pond. Alternatively, these results may indicate that the assumption that the dissolved nutrients are well-mixed in the pond is not valid.

As with the QVA watershed, the model accuracy at the inlet to the dry pond below Commuter Lot B was improved through calibration of parameters not recorded for the time period, principally atmospheric deposition. The contributions from people and their cars are random in nature and were not measured. The parameters used to generate the reported results could be an accurate representation of the parking lot, but it is possible that they are not. Future users will need to be able to represent the contributions from cars and people in order to use this model.

A limitation of ANSWERS-2000 simulations for highly urbanized areas is that the model does not simulate complex stormwater routing through drains to the degree necessary to represent such watersheds. This may result in errors in the runoff hydrograph and thus some errors in pollutant washoff predictions. Depending on the watershed characteristics, these errors may or may not greatly affect total predictions at the watershed outlet. Evaluation of the ANSWERS-2000 model on a watershed in which the deposition rates were better quantified would demonstrate more clearly the predictive capabilities of the model.

Of greater concern for the parking lot simulation was the comparison of removal rates for the measured and calculated events, recorded in Table 4. These removal rates demonstrate the predicted and actual efficiencies of the dry pond. The runoff reduction rates were nearly identical, only differing by 2.3%. The predicted removal rate for sediment was 11.6% lower than the actual removal rate. The model did well in predicting these reductions due to the presence of a dry pond. It was less successful in predicting the removal rates for the nutrients. The predicted removal rates for nitrate, ammonia, and PO_4 were 41.3, 54.6, and 28.5% lower than the actual removal rates, respectively. The TKN removal rate was predicted within 6.7% of the actual rate, although the mass of TKN was significantly under-predicted at the inlet and outlet of the pond. Overall, the model did well in simulating the reduction in sediment loss due to the presence of a dry pond. The error in nutrient losses was most likely due to the inaccurate prediction of dissolved nutrient losses (these losses constituted all of the NO_3 losses and most of the NH_4 and PO_4 losses). This implies that the dissolved nutrients were not accurately represented in the dry pond, or that the inputs to the dry pond were not accurately quantified. Although the inputs to the dry pond from the parking lot were calibrated, the pond might also have received inputs from the surrounding golf course or other vegetated areas that were not accounted for.

Chapter 5. Sensitivity Analysis

5.1 Introduction

A sensitivity analysis was performed on the new model to determine the sensitivity of the model to the new variables. An understanding of the sensitivity of the model to the new parameters will aid future users and/or modifiers of the program to determine which input parameters are most critical for accurate representation of a watershed. The information obtained from this analysis was used in evaluation of the model to determine which input variables should be changed to achieve a desired change in model output. In addition, to demonstrate the effectiveness of using a distributed parameter model, the sensitivity analysis was used to determine model response to spatial changes within the watershed, such as changing impervious cover and variation in placement of a pond BMP.

A relative sensitivity parameter was used to determine the sensitivity of the model to the various parameters, as described by Byne (2000):

$$S_r = \left(\frac{O - O_b}{P - P_b} \right) * \left(\frac{P_b}{O_b} \right) \tag{26}$$

Where:
- S_r = relative sensitivity;
- O = output for scenario tested;
- O_b = output for the baseline scenario;
- P = value of the input parameter being tested;
- P_b = value of the baseline input parameter.

An S_r value with a magnitude near one for a given parameter indicates high sensitivity of the model to that parameter. An S_r value with a magnitude closer to zero indicates low sensitivity to that parameter. A negative S_r value indicates a parameter to which the model response has an inverse relation. A positive S_r value indicates a parameter to which the model response has a direct relation (Byne, 2000).

Input parameters for the new BMP and atmospheric deposition subroutines were varied -25%, -10%, +10%, and +25% from the base value used in the evaluation simulation to judge the sensitivity of the model's predicted sediment and nutrient losses to each parameter.

The sensitivity of the model to the dimensions of BMPs was tested on the dry pond from the parking lot watershed. The QVA watershed was simulated with and without curbs to demonstrate the sensitivity of the model to curbs. For the atmospheric deposition analysis, the nutrient and sediment outputs from the watershed were considered. For the imperviousness analyses, the main items of concern were the runoff and sediment losses. For the BMP and curbs analyses, the runoff, sediment, and nutrient losses from the watershed were considered. Details on the parameters used for the analysis and the results thereof can be found in Appendix F.

The model was run on the QVA watershed for two years at 0%, 4.2%, 16.2%, and 17.8% imperviousness to test the sensitivity of the model to the new impervious and nonerodible routines. Differences in the sediment loss and runoff from the test watershed under each scenario were considered. For the sake of simplicity, fertilizer applications were not used during the sensitivity analysis of impervious and nonerodible routines. The 0% imperviousness represents a completely agricultural watershed, with no roads or buildings. The 4.2% imperviousness represents the watershed with all the roads represented, but no other impervious surfaces represented. The 16.2% imperviousness represents the watershed with its roads, parking lots, and commercial buildings. The 17.8% imperviousness represents the watershed with everything represented in the 16.2% imperviousness category plus all the houses within the watershed. The sensitivity of the model to atmospheric deposition parameters was tested on the QVA watershed with the impervious area at 17.8%.

A wet pond BMP was positioned at the headwaters, tailwaters, and middle of the QVA watershed with 17.8% imperviousness to test the model sensitivity to the spatial placement of ponds within the watershed. The ponds were designed to detain the first 1.8 cm of a runoff event from the intended drainage area and to discharge the design volume in 48 hours.

5.2 Sensitivity Analysis Results

5.2.1 Analysis of Atmospheric Deposition Parameters

The atmospheric deposition parameters influenced the nutrient and sediment loss from the watershed, as can be seen from the Tables F1 and F2 in Appendix F. All the sediment and nutrient deposition parameters (dry and wet) affected sediment and nutrient yields in the expected manner (with higher deposition, there were higher watershed yields). The output parameters that showed the most sensitivity to variations in atmospheric deposition input parameters were nitrate, dissolved and sediment-bound ammonia, and dissolved phosphate (Table 5). Sediment, sediment-bound phosphate, and sediment-bound total Kjeldahl nitrogen had relative sensitivities of zero, 0.10, and 0.019, respectively, and thus were not sensitive to the changes in atmospheric deposition input parameters. These parameters were insensitive because the pervious areas were already contributing large amounts of sediment and sediment-bound nutrients to the output from the watershed and the small addition of these pollutants due to atmospheric deposition did not affect the output. The potential users of this model should be careful in their description of wet atmospheric deposition at all times in order to not produce erroneous output from the model; the description of dry atmospheric deposition parameters will become more important as the contributing erodible area decreases, as when large parking lots are present in a watershed.

Table 5. Model Sensitivity to Variation in Atmospheric Deposition Parameters.

	Output Parameter Relative Sensitivity			
Variation in Atmospheric Deposition Parameters	**Nitrate**	**Dissolved Ammonia**	**Sediment-Bound Ammonia**	**Dissolved Phosphate**
+25%[1]	0.97	0.99	1.0	0.80
+10%	0.94	1.03	1.0	0.80
-10%	0.88	1.03	1.0	0.80
-25%	0.94	0.99	1.0	0.80

[1] **The percentages refer to change in wet deposition input parameters for the dissolved species (sediment, TKN, ammonia, ortho-phosphorus) and change in dry deposition input parameters for the sediment-bound species (nitrate, ammonia, ortho-phosphorus, TSS).**

5.2.2 Analysis of BMP Parameters

The variation in pond BMP parameters influenced runoff and nutrient and sediment yields from the parking lot. The complete analysis can be found in Appendix F. The model was least sensitive to changes in pipe parameters, most likely because in the case tested the pipe was not limiting flow. The parameters the model was most sensitive to can be found in Tables 6 and 7. None of the parameters had relative sensitivities above 0.1 for runoff; therefore, runoff does not seem to be sensitive to changes in the pond BMP parameters. This was expected, as the outlet of the pond was located so low as to totally drain the pond if given enough time. Therefore, the majority of the water would be lost through the outlet, with a small amount exiting via infiltration or evaporation, as the permanent detention capacity of the pond was low.

The parameters that had the greatest effect on sediment loss were pond area and side orifice diameter. This was expected, as the pond area is directly proportional to the removal efficiency of the pond (equation 12). As the pond area increased, more sediment was deposited in the pond, and as it decreased, less sediment was deposited in the pond. As the side orifice diameter increased, thus increasing the rate of flow out of the pond, the sediment loss from the pond increased (this is also related to equation 12). Although there are other possible controls for the outflow from the pond, in this case the side orifice diameter had the most direct control on the rate of flow from the pond and thus most affected the sediment loss from the pond.

Changes in sediment-bound nutrient losses were barely noticeable due to the nature of the watershed used for testing. A parking lot does not have soil with nutrients, and therefore does not have a ready source of sediment-bound nutrients. With the exception of one instance with riser height, none of the relative sensitivities were above 0.1 for sediment bound nutrients, and therefore in this case the sediment bound nutrient output from the model was not sensitive to input parameters. However, the small sensitivities showed the same trend as the sediment relative sensitivities, as would be expected as the sediment bound nutrients must necessarily deposit with the sediment in a pond.

Four parameters caused similar relative sensitivities for the model prediction of dissolved nutrients: pond area, side orifice height, side orifice diameter, and riser height. The magnitude of nutrient loss, as with the sediment-bound nutrient losses, was low due to the nature of the watershed. The relative sensitivities were not all positive or all negative for any given pond parameter, likely due to the small differences reported between different scenarios. The parameters to which the model was most sensitive for dissolved nutrients all affected the rate of flow out of the pond. The increasing pond area and side orifice height increased the permanent retention storage of the pond (and thus tended to decrease the dissolved nutrient loss from the pond). The increasing side orifice diameter increased the flow rate from the pond, thus decreasing the amount of water available to infiltrate and tending to increase the nutrient loss from the pond. The increasing riser height had a lesser effect on the flow rate from the pond, causing the dissolved nutrient losses to tend to decrease. The increase in dissolved nutrient loss for the riser height + 25% scenario is likely due to the increasing head driving flow through the side orifice opening. The dissolved nutrients are lost in proportion to the water losses through the spillways and through infiltration, so anything that would increase or decrease the detention time of water in the pond will affect the way in which the dissolved nutrients exit the pond. As expected, the dissolved nutrient loss sensitivities were roughly equivalent between the among dissolved species (Table 7).

Table 6. Relative Sensitivity of Sediment Losses.

Parameter		Sediment Loss Relative Sensitivity
Pond Area	-25%	-0.24
	-10%	-0.25
	+10%	-0.23
	+25%	-0.24
Side Orifice Diameter	-25%	0.32
	-10%	0.22
	+10%	0.21
	+25%	0.18

It is possible to specify dimensions for a pond BMP that will never allow water to exit other than by infiltration or evaporation. Setting the overflow, riser, and orifice heights higher than the pond can be expected to fill will cause this situation. If this occurs, a user might not see the same sensitivity that was reported here. If the user specifies dimensions of a pond such that water leaves through each of the possible exit points, the model will show greater sensitivity to the BMP parameters.

Table 7. Relative Sensitivity of Dissolved Nutrient Losses.

Parameter		Relative Sensitivity		
		NO_3	Dissolved NH_4	Dissolved PO_4
Pond Area	-25%	-0.01	-0.01	0.00
	-10%	0.26	0.25	0.27
	+10%	-0.48	-0.48	-0.49
	+25%	-0.11	-0.11	-0.11
Side Orifice Height	-25%	0.08	0.08	0.08
	-10%	0.31	0.31	0.31
	+10%	-0.45	-0.45	-0.46
	+25%	-0.17	-0.17	0.18
Side Orifice Diameter	-25%	0.03	0.03	0.03
	-10%	-0.12	-0.12	-0.12
	+10%	0.90	0.90	0.90
	+25%	-0.12	-0.11	-0.12
Riser Height	-25%	0.06	0.06	0.06
	-10%	-0.24	-0.24	-0.24
	+10%	-0.37	-0.37	-0.37
	+25%	0.41	0.41	0.41

5.2.3 Analysis of Impervious and Nonerodible Subroutines

The results of the analysis of the impervious and nonerodible routines are presented in Table 8. In this analysis, a relative sensitivity parameter was not applicable, as the percent impervious cover affected multiple input categories and thus could not be treated as a single input parameter for equation 26. As expected, an increase in impervious area (and thus a decrease in potential infiltration) increased runoff dramatically. As the directly connected impervious area increased, more runoff left the watershed through drains that discharged to areas outside the watershed.

Table 8. Results of the Sensitivity Analysis for Impervious Cover of the QVA Watershed.

Impervious Cover	Runoff (mm)	Runoff (percent of precipitation)	Runoff to Outside of Watershed (through drains) (mm)	Sediment (kg/ha)
0%	14.34	0.79	0.0	382.5
4.2%	34.58	1.9	0.25	719.9
16.2%	160.11	9.3	8.68	5887.1
17.8%	170.06	10.0	11.24	6590.8

The total rainfall for the two year period of simulation was 1819.26 mm. With no impervious cover, 0.79% of the rainfall became runoff. With increasing impervious areas, that figure rose to 1.9%, 9.3%, and 10.0% (corresponding to 4.2%, 16.2%, and 17.8% impervious areas, respectively). The increase in impervious area also increased sediment loss (Figures 21 and 22), as a result of increased runoff rates from the urban areas. These figures detail the total sediment loss for an equivalent period of time for the QVA watershed with no urban surfaces, just roads, just roads and buildings, and roads and all buildings. The darker areas in these figures represent areas with higher sediment loss. As can be seen from these figures, the sediment loss is greatest at the edges of the impervious surfaces, where the runoff rate is higher and the water is less sediment laden (and thus able to transport more sediment). The water coming off impervious surfaces is less sediment laden because the nonerodible nature of the surfaces limits the sediment in transport on those cells to atmospheric deposition and sediment detachment that occurred on cells prior to the time the runoff reached the impervious areas.

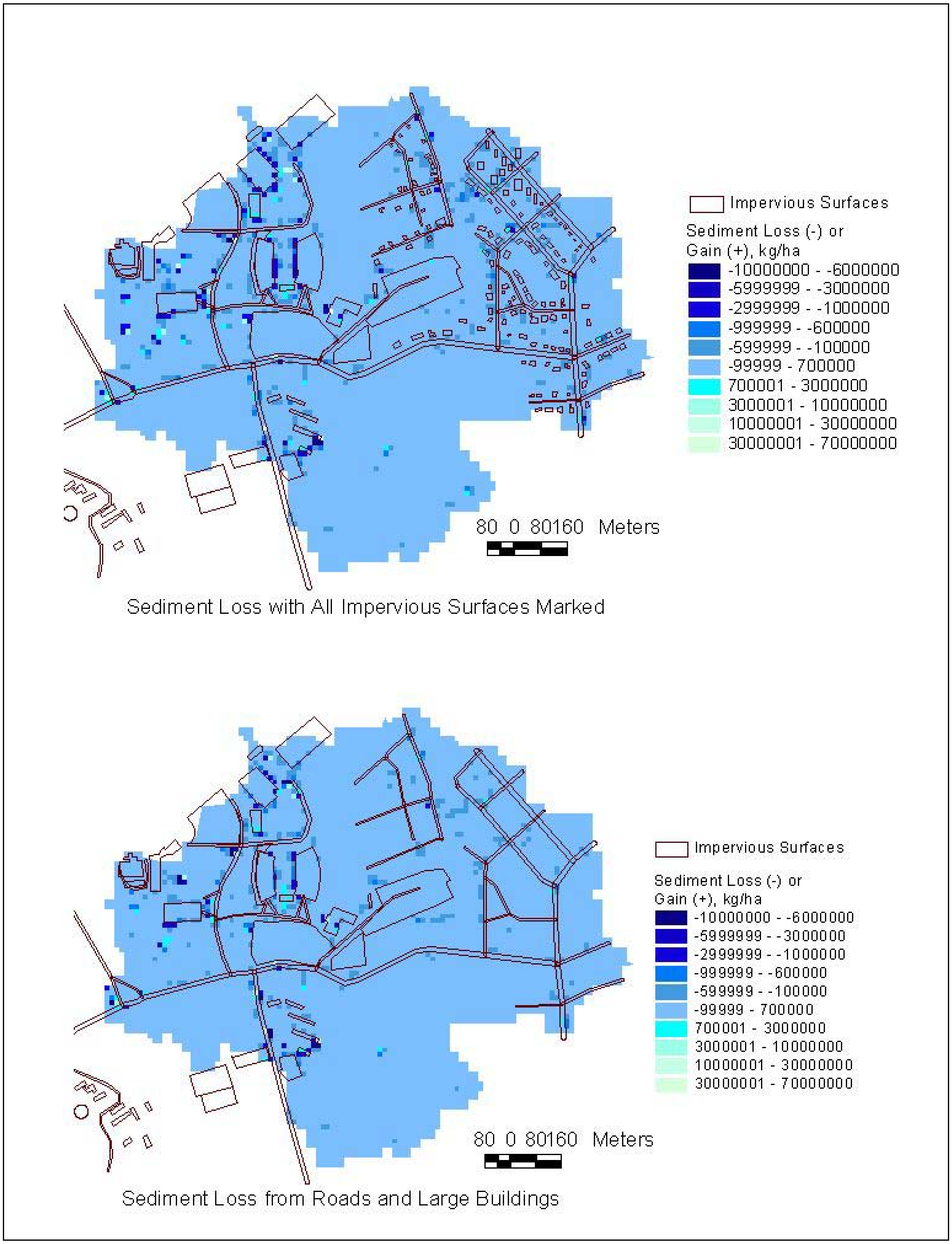

Figure 21. Annual Sediment Loss from Completely Urbanized QVA Watershed (top) and QVA Watershed without Residential Buildings (bottom).

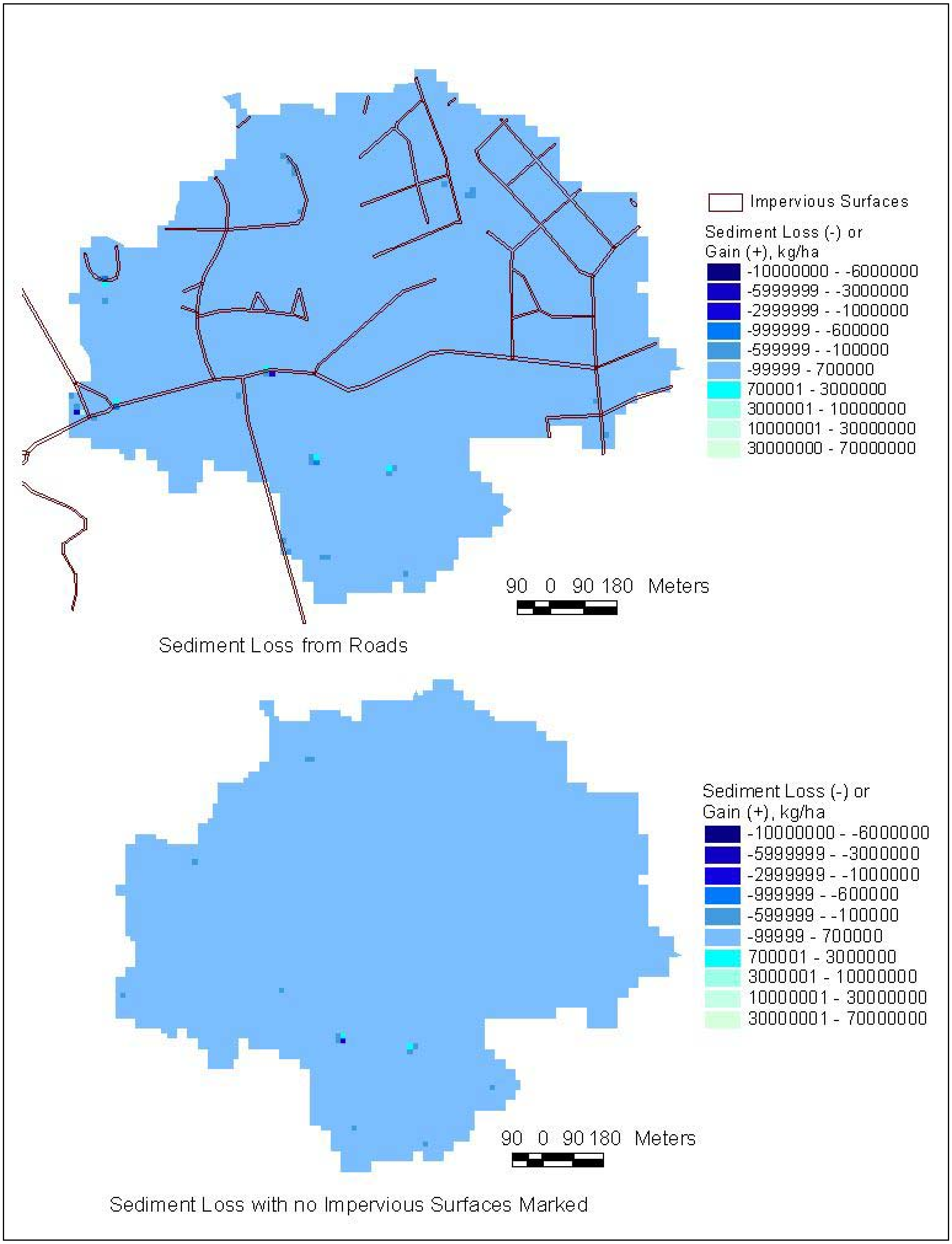

Figure 22. Annual Sediment Loss from QVA Watershed with only Roads Marked (top) and with no Impervious Surfaces (bottom).

5.2.4 Analysis of Placement of Wet Pond BMP

The placement of the three ponds for this analysis can be found in Figure 23. As with the impervious surface analysis, this analysis did not have a clearly defined input parameter to be used in equation 26, and thus no relative sensitivity parameter is presented here. Each successively larger drainage area in Figure 23 contains the smaller drainage area plus the colored portion according to the legend. For example, the Middle drainage area in the figure contains the entire area for the Headwaters drainage area, plus the area in orange. The 'Near Outlet' drainage area contains the entire Middle drainage area as described in the previous sentence, plus the area in green. The QVA Watershed area contains the entire figure, but it is hidden by the other three drainage areas. The dimensions of the ponds used at each position in the watershed are listed in Table 9.

Table 9. Dimensions of Pond BMPs used in BMP Sensitivity Analysis.

Scenario	Pond Length (m)	Pond Width (m)	Pipe n	Pipe Diameter (m)	Pipe Length (m)	Riser Height (m)	Riser Diameter (m)	Embankment Height	Drainage Area (ha)
Headwaters	15.71	31.42	0.02	0.05	11.3	1.2	0.05	2.0	15.95
Middle	42.28	84.56	0.02	0.14	11.3	1.2	0.139	2.0	31.10
Outlet	53.21	106.42	0.02	0.50	11.3	1.2	0.125	2.2	141.14

The results of the analysis of the variation in placement of the BMP in the watershed can be found in Table 10. This analysis was run for 192 days in 1999. The weather data used contained only storms with runoff that ended in one day. This was done to ensure that the runoff from the ponds in the headwaters and middle of the watershed had adequate time to reach the watershed outlet before the end of simulation for the storm day. The watershed size is 144.5 ha.

Table 10. Sensitivity Analysis Results for Variation in Placement of Wet Pond BMP within the QVA Watershed.

Scenario	Runoff (mm)	Sediment (kg/ha)	NO_3 (kg)	Diss. NH_4 (kg)	Sed. NH_4 (kg)	Diss. PO_4 (kg)	Sed. PO_4 (kg)	Sed. TKN (kg)
No pond (baseline)	10.06	89.6	34.7	7.2	1.1	3.6	0.6	72.9
Pond at headwaters of watershed	9.83	88.7	33.1	7.1	0.9	3.6	0.6	70.8
Pond in middle of watershed	8.41	78.2	28.2	6.4	0.9	3.1	0.2	16.9
Pond near the watershed outlet	6.33	42.6	20.8	4.4	0	2.3	0	2.0

The placement of the wet pond BMP within the watershed affected the runoff and pollutant losses (Table 10). The required pond surface area increased with ponds placed farther down the watershed to maintain capacity to treat the runoff in 48 hours as designed. The increase in pond size, necessitated by the increased portion of watershed runoff being treated, caused the removal of pollutants by the ponds to increase, as the removal of sediment (and thus sediment-bound nutrients) is directly related to the area of the pond (as demonstrated in equation 12). As a result, the sediment and sediment-bound nutrients had the most pronounced reaction to the positioning of the BMP in the watershed, with more nutrients being removed as the pond was positioned farther downstream.

The dissolved nutrient losses (nitrate, ammonia, phosphate) were less responsive to the placement of the BMP. This was because the dissolved nutrients were considered well-mixed within the ponds. The slight changes in runoff for the BMPs located in the headwaters and the middle of the watershed were not significant enough to result in a large change in dissolved nutrient loss. The reduction in runoff was only 15%, and the dissolved nutrient loss at the outlet was reduced between 10 and 20% for each pollutant. The greatest contrast was for the watershed with no pond versus the watershed with a pond near the outlet. The reduction of runoff was 37% when the pond near the outlet was added, and the corresponding nutrient losses at the outlet were between 36 and 40% for each pollutant. There were greater reductions in runoff and nutrient loss as the pond was positioned progressively downstream because more flow, and thus more dissolved

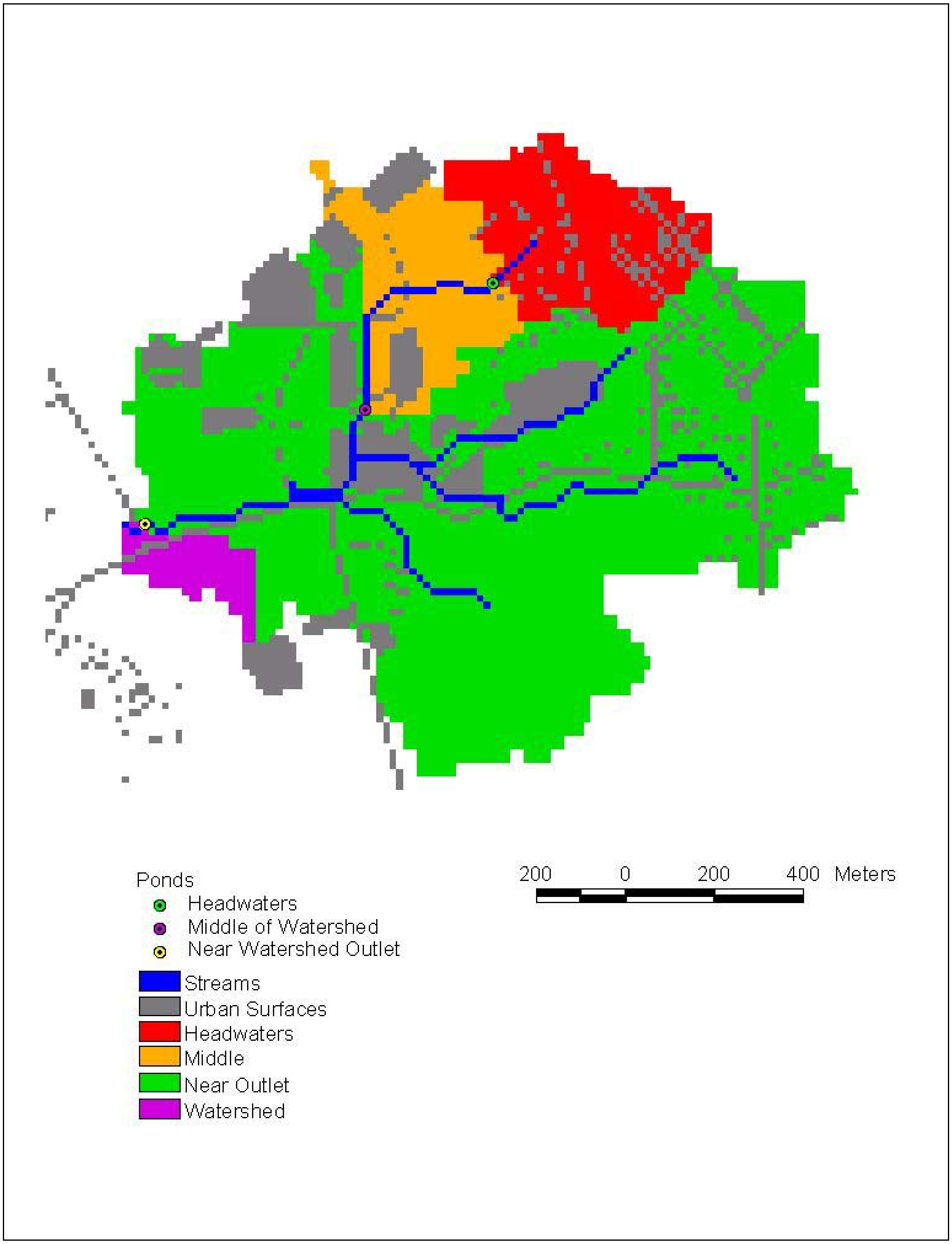

Figure 23. Drainage Areas for BMP Placement Analysis. Each successively larger area (headwaters, middle, near outlet, QVA watershed) contains the areas above it.

nutrients, infiltrated within the ponds. More flow infiltrated as a result of the increased area for infiltration that the downstream ponds had. This analysis shows how the revised ANSWERS-2000 model can be used to aid in effective placement of best management practices within a watershed.

5.2.5 Analysis of Drain and Curb Placement

The results of the curb analyses are presented in Table 11.

Table 11. Results of the Curb Sensitivity Analysis

Scenario	RUNOFF (MM)	SEDIMENT (KG/HA)	NO_3 (KG)	DIS-NH_4[1] (KG)	SED-NH_4[1] (KG)	DIS-PO_4[1] (KG)	SED-PO_4[1] (KG)	SED-TKN[1] (KG)
No Curbs	37.52	1310.8	22.7	0.8	3.1	1.3	2.1	358.2
With Curbs	32.79	1082.6	38.2	2.2	1.8	1.2	1.3	270.9

[1]DIS refers to dissolved nutrients and SED to sediment-bound nutrients

The runoff, sediment loss, and sediment-bound nutrient losses were less for the watershed when curbs were present. The dissolved nutrient losses were less for the watershed when curbs were not present. The reason for this is the redirection of flow due to curbs. One effect of this redirection was that the curbs routed flow to drain cells that flowed outside the watershed (and thus did not contribute to runoff and pollutant loss at the watershed outlet). This is evident from looking at the losses from the watershed area that do not contribute to the runoff and pollutant losses at the watershed outlet, as reported by the model (Table 12). These losses are primarily composed of the flow from stormwater inlets that are within the watershed and have outlets outside of the watershed.

Table 12. Losses from the QVA Watershed that do not Contribute to Runoff and Pollutant Losses at the Watershed Outlet: With and Without Curbs.

	RUNOFF (MM)	SEDIMENT (KG/HA)	NO_3 (KG)	DIS-NH_4[1] (KG)	SED-NH_4[1] (KG)	DIS-PO_4[1] (KG)	SED-PO_4[1] (KG)	SED-TKN[1] (KG)
No Curbs	1.92	701.8	0	0	0	0	0	0.5
With Curbs	5.84	2059.1	1.6	0	0	0	0	3.6

[1]DIS refers to dissolved nutrients and SED to sediment-bound nutrients

Another effect of the redirection of flow due to curbs is to keep runoff and corresponding pollutant loads running along impervious surfaces. This prevents the runoff from entering vegetated areas and thus reduces the filtering effect the vegetation could have on such runoff.

Runoff traveling along impervious surfaces cannot infiltrate and this may affect the total runoff from the watershed.

Large portions of the runoff, sediment, and sediment-bound TKN for the curbed scenario were lost outside the watershed and thus did not contribute to the output at the watershed outlet. This explains the difference at the watershed outlet in runoff, sediment, and sediment-bound TKN loss between the two scenarios. Nitrate and dissolved ammonia appear to be most responsive to the filtering effect of vegetation, as their losses were lower for the watershed when curbs were not present. Dissolved phosphate varied little between the two scenarios. Sediment-bound ammonia, sediment-bound phosphate, and sediment-bound TKN losses were higher from the scenario without curbs. This was likely due to the fact that more sediment made it to the watershed outlet in this scenario, as did its accompanying nutrients.

The user should be careful to specify correct placement of drains and curbs within the watershed. A misplaced curb or drain in the input files for a key part of the watershed could significantly alter the hydrology and pollutant loss at the watershed outlet by routing the flow outside the watershed if stormwater sewers discharge outside the delineated watershed boundary. In addition, beneficial effects of vegetative filtering could be ignored by the model if the user inappropriately specifies curbs that channel the flow along the road instead of allowing it to enter the surrounding vegetated areas.

5.3 Discussion

The response of the model to the atmospheric deposition parameters was as expected. Increases in the atmospheric deposition parameters caused increases in the loss of the corresponding pollutants at the watershed outlet.

During the sensitivity analysis for the pond BMP placement, an important discovery was made for future users of ANSWERS-2000. This discovery was made after extremely high scour was predicted from an unprotected receiving element for the dry pond. The discharge from the pond spillway may cause scouring to occur in unprotected receiving elements. The water coming out of the pond is flowing rapidly and is relatively clear (due to having just passed through a detention pond). The water is flowing more rapidly than it would in a natural channel because it is being channeled through a pipe with smaller diameter than the natural channel.

This factor, in addition to reduced sediment load, would increase the potential for scour at the pond outlet. Concrete and riprap-lined channels are typically used in actual conditions and reduce the scour of the land at the outlet to such a pond. It is therefore important to represent whatever protective measures are in place when using ANSWERS-2000 to simulate a watershed with a pond.

The user can specify channel stabilization in one of three ways. The first way is applicable if the outlet is protected by a concrete slab beneath the pipe opening. In this case, the user may specify that the receiving element is an impervious and nonerodible element, thus eliminating the possibility for simulation of erosion on the element. The second way is applicable if the pond outlet is located in a channel cell (as defined by ANSWERS-2000). If so, one can set the percent erodibility of the channel in the input file and should specify an erodibility appropriate for the outlet conditions. The third way is applicable if the first two methods will not work due to the particular characteristics of a watershed. The user must create a land use and soil type specific for the receiving element and define the soil and crop parameters to adequately represent the conditions at the pipe outlet.

Changes in the impervious and nonerodible land use cover for the QVA watershed showed an effect on all the output parameters of the model. Runoff increased, as did sediment and nutrient losses. The accuracy of the degree of response cannot be tested (due to the lack of monitoring records as the QVA watershed was urbanized). However, the response shows the importance of detailing impervious and nonerodible areas for the ANSWERS-2000 model.

As expected, the positioning of the wet pond at different points within the watershed made a noticeable difference in the runoff and pollutant losses at the outlet. At the headwaters, the wet pond was not as effective at attenuating the overall watershed runoff as it was in the central portion of the watershed, which in turn was not as effective as the pond near the outlet of the watershed. As mentioned previously, this was due to the larger area of the ponds further downstream, which allowed for increased infiltration. The ponds further downstream had a larger area because of the increased contributing area as they were placed further downstream, allowing for treatment of a larger portion of the runoff from the watershed. The sediment-bound nutrient losses were most affected by the positioning of the wet pond within the watershed, also partially a result of the necessary increase in pond area as the pond was positioned further downstream. In addition, the pond in the headwaters of the watershed only treated the small portion of the watershed runoff that flowed into it. As the ponds were placed further down the watershed and the contributing area for each pond increased, a larger portion of the total pollutant losses from the watershed area had the opportunity to be trapped in the pond, resulting in the demonstrated greater effect of downstream ponds on water quality at the watershed outlet.

The capacity of the model to redirect flow according to user-specified curb and drain placement allows the simulation of areas in which all the runoff in a watershed may not go to the outlet due to the presence of man-made structures. The sensitivity analysis shows the effect that this redirecting of flow can have on the losses at the watershed outlet.

5.4 Summary

A sensitivity analysis of the subroutines added to the ANSWERS-2000 model was conducted. The model was found to be sensitive to the placement of urbanized (i.e., impervious and nonerodible) areas, curbed roads, and to the placement of best management practices within a watershed, although due to lack of any monitored data to evaluate the sensitivity, the degree of sensitivity to these conditions may or may not be appropriate. The new BMPS subroutine parameters were analyzed, and the pond area and side orifice height were found to be the parameters to which the model was most sensitive. The parameters for the atmospheric deposition subroutines were analyzed, and the dissolved nutrient output from the model was found to be most sensitive to variations in these parameters. This analysis was used in calibrating the model, and will be helpful to future users of the ANSWERS-2000 model.

Chapter 6. Model Application

In a practical application of the model, ANSWERS-2000 was applied to the Battlefield Green watershed in Hanover County, Virginia, to demonstrate how a watershed planner might use the model. The watershed is 3376.7 ha in size, and the development involved converting 16% of the existing agricultural land to impervious areas (roads and houses). The watershed layouts for pre- and post-development are shown in Figures 24 and 25, respectively. Runoff was not monitored for the watershed and thus it was not possible to assess the model accuracy for pre- and post-development conditions. The model was run for pre- and post-development conditions, three years each. The precipitation records were generated with the weather generator program, CLIGEN, used by the input generator program (QUESTIONS) for ANSWERS-2000. The results of these runs can be found in Table 13.

As seen in Table 13, urbanization increased runoff for the watershed by a factor of 25 over the three-year period. It increased sediment loadings by a factor of 31 and pollutant loadings between factors of 31 and 55 for individual nutrients over the three-year period. This information would prove useful for the planners of this watershed in considering what types of flood and erosion control need to be incorporated into the development plan.

Table 13. Comparison of Yields for Pre- and Post-Development Battlefield Green Watershed.

		RAIN (MM)	RUNOFF (MM)	SEDIMENT (KG/HA)	NO_3 (KG)	DIS-NH_4 (KG)	SED-NH_4 (KG)	DIS-PO_4 (KG)	SED-PO_4 (KG)	SED-TKN (KG)
Pre-Development	Year 1	864.86	3	67.7	36.2	13.5	3.8	11.1	3.8	333.8
	Year 2	820.06	1.26	26.4	11.3	3.9	2.2	4.4	3.4	291.5
	Year 3	839.97	3.58	56.3	25	10.7	2.5	10.2	3.1	268.0
	Total	2524.89	7.84	150.4	72.5	28.1	8.5	25.7	10.3	893.3
Post-Development	Year 1	864.86	66.2	1493.3	1242.2	557.4	102	340.3	83.7	8183.3
	Year 2	820.06	60.21	1522.4	699.7	457.8	137.7	311.4	127.3	11149.7
	Year 3	839.97	72.68	1664.9	925.7	532.1	138	362.9	113.1	9452.8
	Total	2524.89	199.09	4680.6	2867.6	1547.3	377.7	1014.6	324.1	28785.8

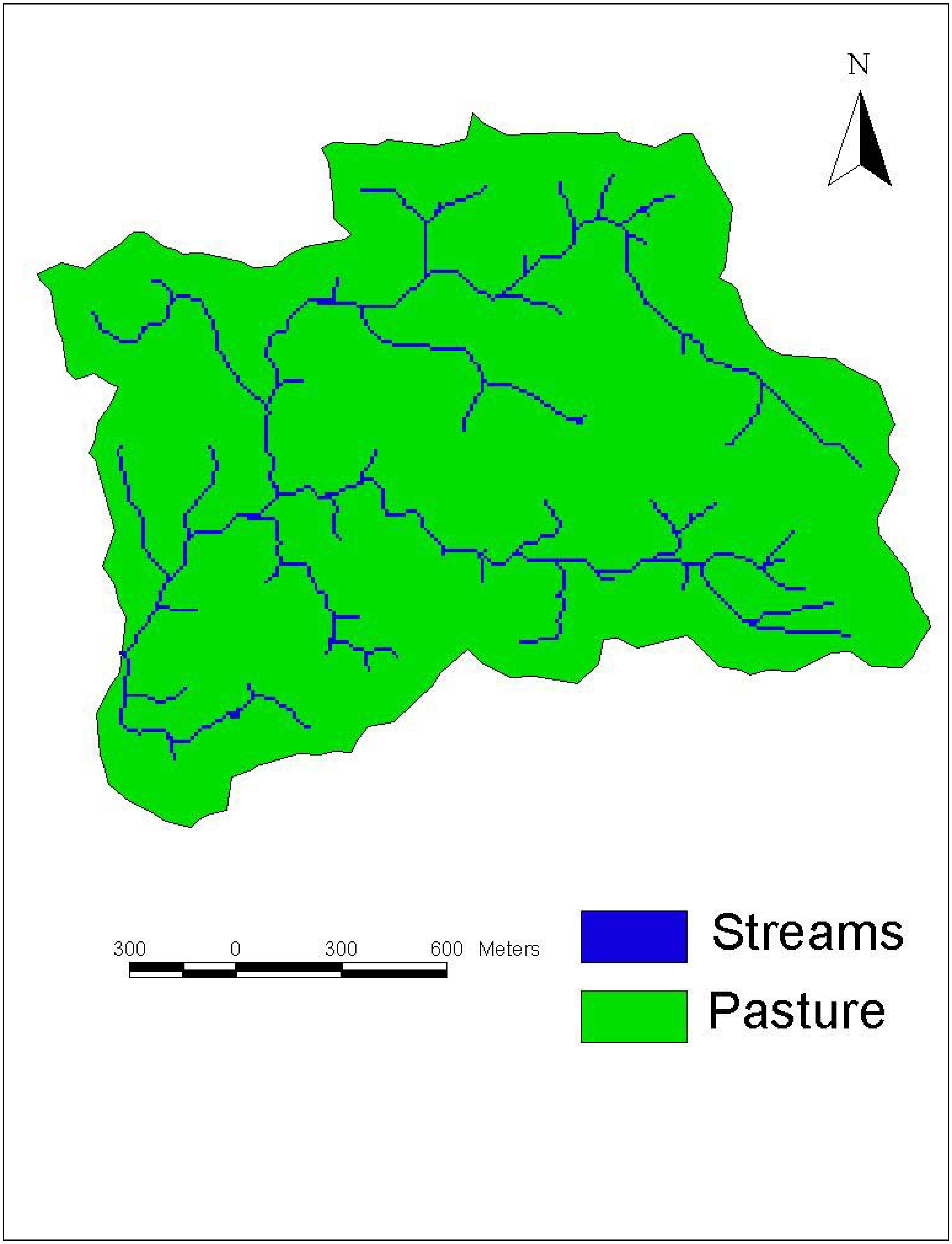

Figure 24. Battlefield Green - Pre-Development.

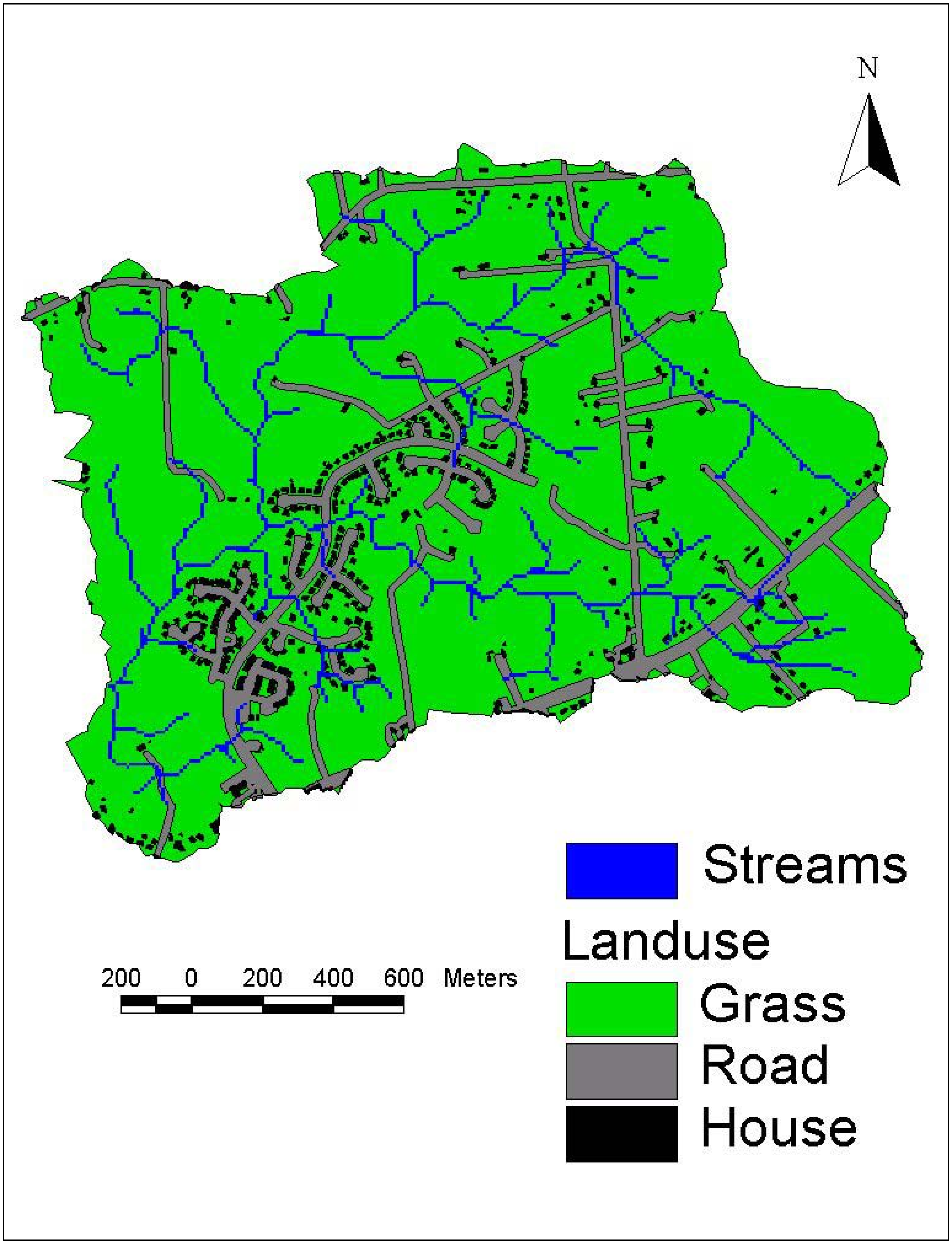

Figure 25. Battlefield Green - Post-Development.

After conducting this analysis, the strategic placement of a wet pond BMP was investigated. A pond was placed at three locations in the watershed to determine the best placement of the BMP. The best placement was determined as the site that provided the greatest reduction in loads to the watershed outlet. Each location was chosen based on the large percentage of urbanized land within its drainage area. Watershed planners would position ponds based on this information and additionally on the availability of the land for construction, costs of construction for this area, and standards that must be met - none of which was known in this case. The drainage area of the first point (Figure 26), located on the main stream right above the outlet, was 288.35 ha and was 16.1% impervious. The drainage area of the second point, located at the mouth of a tributary to the main stream, was 20.66 ha and was 28.2% impervious. The drainage area of the third point, located at another mouth of a tributary to the main stream farther upstream than the second point, was 86.69 ha and was 19.9% impervious. The drainage areas for points 2 and 3 do not overlap each other, but do overlap the drainage area for point 1. The drainage areas for all three points overlap the total watershed area. The results of the analysis can be found in Table 14.

Table 14. Runoff and Pollutant Losses at the Battlefield Green Watershed Outlet for the Different BMP Placements for a One Month Simulation.

	RAIN (MM)	RUNOFF (MM)	SEDIMENT (KG/HA)	NO_3 (KG)	DIS-NH_4 (KG)	SED-NH_4 (KG)	DIS-PO_4 (KG)	SED-PO_4 (KG)	SED-TKN (KG)
Point 1	21.45	2.20	15.4	123.5	5.6	1.0	0.7	0.2	12.7
Point 2	21.45	2.85	61.2	228.9	10.7	2.8	1.3	0.5	63.6
Point 3	21.45	2.70	51.5	188.4	8.6	2.2	1.1	0.4	46.1
Pre-Development	21.45	0.33	4.4	0	0	0	0	0	0
Post-Development/No Pond	21.45	2.85	61.2	228.7	10.7	2.8	1.3	0.5	63.6

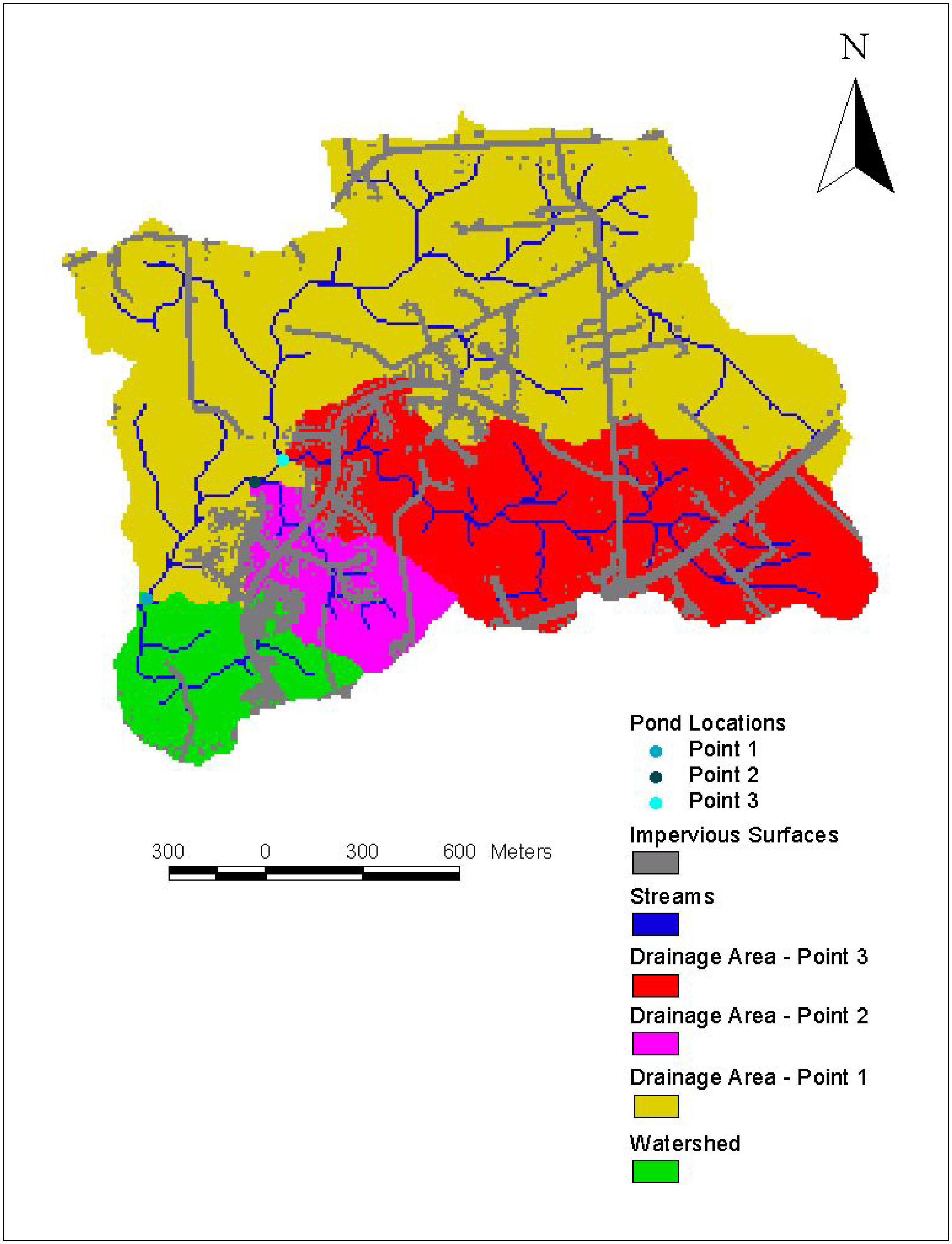

Figure 26. Locations of Wet Ponds for Battlefield Green Model Application.

None of the BMP placements reduced the loads to the pre-development state. However, the pond located near the watershed outlet (Point 1) did the best at attenuating the higher flows and loadings at the outlet. Point 2, which caught runoff from only 21 ha of the 3377 ha watershed, had no effect on the runoff at the outlet of the watershed, so placement of a pond at this location would not help meet water quality standards. The third point did reduce flows and pollutant loadings at the outlet to the watershed, though not to the same extent as the downstream location. However, the pond for the third location would be much smaller than the pond required for the first location. This might be a consideration if there is a limited amount of land available for the construction of a BMP, or if the construction cost is a limiting factor in the decision of where to create the pond BMP. Watershed planners could use the ANSWERS-2000 model to select the best locations for ponds to meet water quality goals. In addition to the simple analysis presented here, watershed planners could consider the water quality effects of placing several smaller-sized pond BMPs upstream in the watershed versus placing one large pond BMP at the watershed outlet.

Chapter 7. Summary and Conclusions

The primary objective of this research was to develop a model to simulate runoff and pollutant losses in watersheds with a combination of agricultural and urban areas (this includes simulation of the effects of impervious and nonerodible land uses on hydrology) and to simulate urban best management practices. A second objective was to evaluate this model for water quality planning use. The developed model simulated hydrology and pollutant losses for the test watersheds within a factor of two of their measured values, with generally less than 20% error. This portion of the model will be useful with an acceptable error rate for water quality planning purposes according to the standards set by Heatwole *et al.* (1991). A model was successfully developed that simulated the hydrology and sediment loss from a dry pond. Nutrient losses were poorly predicted for the dry pond used in evaluation. The distributed parameter model showed sensitivity to the placement of an urban best management practice within the watershed, showing that it is effective in representing spatial variability of pond placement. The model is capable of showing some relative effects of BMP placement and sizing, but should not be used as a predictor of pollutant losses from BMPs until further testing of the simulated nutrient processes in BMPs can be conducted. In addition to these primary components, utilities for the ANSWERS-2000 program were developed to facilitate model use (Appendix B).

The modified ANSWERS-2000 model will be useful to planners seeking to represent watersheds with mixtures of urbanized and agricultural practices. It has also been shown to be useful for planners considering how best to develop an area that is currently agricultural, completing the third objective, the demonstration of an application of the model. As the original model was developed for agricultural watersheds, ANSWERS-2000 should be used with great caution in areas with greater than 30% imperviousness. The modified version of ANSWERS-2000 adequately represents mixed land use watersheds, but should still be used with caution in highly developed areas with complex stormwater conveyance systems. Several models, as mentioned previously, exist for urban areas and are quite capable of modeling highly urbanized areas. They are better equipped to handle storm drains and flow routing in sewers than ANSWERS-2000. Whereas most urban runoff models are concerned with adequate capacity for the storm drains, the revision of the ANSWERS-2000 model is focused on the quality of runoff leaving the urban area, and is intended for use by planners trying to increase the quality of runoff from their watersheds.

The evaluation of the modified ANSWERS-2000 model conducted as part of this research was limited due to the lack of information on the watersheds used for model evaluation. Based on the limited evaluation that was conducted, the conclusions from this research are:

- The modified ANSWERS-2000 model is acceptable in prediction of flow and pollutant loss in urbanizing areas;
- The model is not acceptable for prediction of pollutant losses from a dry pond BMP;
- The model is responsive to urbanization effects on a watershed, specifically changes in impervious area; and
- The model is responsive to the placement of urban BMPs within a watershed.

Chapter 8. Recommendations for Future Research

In order to improve the simulation capability of the ANSWERS-2000 model, and to aid future graduate students who will be conducting research in the general area of watershed modeling, the following research topics are recommended:

- Add the ability in ANSWERS-2000 to simulate baseflow in streams. This would be useful in simulating some wet pond BMPs that have continuous inflow from perennial streams.
- Further evaluation should be performed of the new BMP subroutine. In particular, evaluation should be performed on watersheds with monitored wet ponds and infiltration trenches.
- Incorporate snowfall and snowmelt processes into the ANSWERS-2000 model to increase the accuracy of the program during winter months.
- Monitoring projects should be conducted to quantify the average atmospheric deposition and solar radiation information for several test watersheds that could be used for evaluation of future models, as those parameters are hard or impossible to acquire in detail for most areas. In addition, the test watersheds should have detailed water quality monitoring projects conducted and have the watershed characteristics well-documented for use in evaluation of future models. In particular, watersheds containing universities are popular research sites for graduate students and their parameters should be better defined.
- Research should be conducted to better quantify the deposition of pollutants directly from cars and people in impervious areas such as parking lots.
- ANSWERS-2000 should be modified so that simulation of runoff occurs until the hydrograph approaches zero. As currently written, the program simulates runoff for the duration of the precipitation event. Currently the user must specify a period of zero rainfall in the weather file after the actual storm event to force the program to continue to simulate runoff. However, the length of this period is up to the user and he or she may or may not select a length that will encompass the entire runoff duration.
- The runoff appears to be greatly underpredicted for the pre-development model application condition. Further research into the default parameters provided by

Questions should be conducted to determine if the cover or soil parameters are causing an overprediction of infiltration.

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Appendix A

Variable Glossary

Variable Glossary

A	= area (m^2)
A	= cross-sectional area of pipe (m^2)
AFWEV	= mean annual free-water surface evaporation (m/day)
AISN	= inflow of soluble nutrient due to infiltration (kg/s)
$a_{orifice}$	= orifice area for flow calculations (m^2)
A_s	= surface area of the basin (m^2)
C	= USLE C factor
clay	= percent clay in the soil
CU	= conversion factor to convert mm/hr to m^3/s
CU1	= conversion factor to convert mm to m^3
CU2	= conversion factor to convert twice m^3
D	= detachment (kg/min)
D	= depth of trench (m)
DCAP	= detachment capacity (kg/s)
DFWEV	= daily free-water surface evaporation (m/day)
d_i	= inner diameter of pipe (mm)
DP	= deposited sediment (kg/s)
DT	= time increment (s)
DX	= width of a cell (m)
FACT	= factor to adjust evaporation based on the solar radiation for the month
FV	= fall velocity of sediment particle (m/s)
g	= acceleration due to gravity (m/s^2)
h	= height of water above weir (m)
H2ODEPTH	= total water remaining in the bmp (m^3)
INFIL	= water lost from a bmp via infiltration (m^3)
INFSN	= loss of soluble nutrient due to infiltration (kg/s)
K	= USLE K factor
K_b	= bend coefficient
K_e	= entrance loss coefficient
K_{ib}	= baseline erodibility, unitless

K_p	= headloss coefficient = $(1244522n^2)/(d_i^{4/3})$
K_{radj}	= baseline rill erodibility adjusted for effects, s/m
L	= length of pipe (m)
L	= length of trench (m)
L_{crest}	= length of weir crest (m)
LOST	= water lost through the pipe of a pond (m^3)
NEWSED	= volume of deposited sediment (m^3)
Q	= flow rate per unit width (m^2/min)
Q	= flow rate (m^3/s)
Q	= inflow to basin (m^3/day)
n	= Manning's n
NORILLS	= number of rills
OR	= overflow rate (m/day)
$OUTSN_{weir}$	= outflow of dissolved nutrient over emergency spillway, kg/s
$OUTSN_{pipe}$	= outflow of soluble nutrient through riser (kg/s)
P	= porosity of coarse aggregate fill in trench as decimal
R	= rainfall intensity during the time interval (mm/min)
RILLWID	= width of rills (m)
SE	= sediment entering trench per particle size class (kg/s)
SG	= density of sediment per particle size class (g/cm^3)
SI	= sediment inflow (kg/s)
SL	= slope steepness
STOSN	= soluble nutrient in storage in the pond (kg/s)
T	= time (hr)
TAUCADJ	= adjusted critical shear stress
TAUEFF	= effective shear stress
T_F	= transport capacity (kg/min-m)
V	= volume of trench (m^3)
vfs	= percent very fine sand
W	= width of trench (m)
WLOST	= water lost over the embankment (m^3)

YEARDAY	= number of days in a year (days/year) = 365 or 366
x	= fraction impervious area

Appendix B

ANSWERS Utilities

B.1 Weather Programs

Two programs were written to convert the weather data from NOAA format to the format readable by ANSWERS-2000. Both of these programs can be readily modified for use with alternate data, as detailed in the user's manual (Zeckoski, 2002). The user's manual is included as Appendix C in this thesis.

The first weather converter program was written to process hourly weather data. This program first requires user input of the average monthly radiation. If daily radiation is known, the program should be modified to accept it (daily radiation was not known in this case). Then the program reads in the date and time; the time is converted from military time to hours and minutes and later used to calculate rainfall rates. Then precipitation and temperature are read in. The temperatures for a day are averaged by summing the temperatures available and dividing by the number of available temperature readings. The precipitation is given as an amount of rainfall since the last entry. This data is converted to a rainfall rate by dividing the precipitation by the time since the last entry. This is then entered into the output file (weather.inp) for each time increment.

The second weather program was written to handle NOAA daily weather data. The approximated hyetographs from the first program were inspected to try and get an idea of what a 'typical' hyetograph looked like for given total precipitation values at this station. The divisions and hyetograph types determined for the Dulles station (the first weather station analyzed, although the watershed turned out to be unsatisfactory for simulation by ANSWERS-2000) can be found in Table B1.

Table B1. Information for the Weather Converter program.

Amount of Rainfall (inches)	Rainfall Duration (min.)	Hyetograph Type
rainfall>3.0	210	Beginning peak, then die off
1.0<rainfall≤3.0	240	Beginning peak, then die off
0.7<rainfall≤1.0	500	fluctuating peaks
0.5<rainfall≤0.7	100	large initial peak, then nothing
0.3<rainfall≤0.5	375	Beginning peak, then die off
0.07<rainfall≤0.3	300	low, then peak at the end
0.02<rainfall≤0.07	150	flat
Rainfall≤0.02	25	flat

This table is for the Dulles Station only; these values should not be used for other stations. Individual inspections of the rainfall histories of each station should be analyzed. When generating weather data for the Stroubles Creek watershed, the table above was found to be unsatisfactory. The program produced several storm events with excessively large intensities. Therefore, the amount of the beginning peak case was reduced from 75% to 50%. This reduced the erroneously high runoff in the output file.

The daily weather program used the information in the table above to determine the increments of time between breakpoints (number of breakpoints was also estimated off the hyetographs). For the beginning peak case, it was assumed that approximately 75% of the rainfall occurred in the first time interval (based on observation of hyetographs). The fluctuating peaks were approximated using a random number generator. The large initial peak was approximated using the same method as the beginning peak case, but was restricted so that only the peak existed. The peak at the end of the hyetograph for the 'low, then peak at the end' type was approximated at about 50% of the total rainfall. The flat hyetograph was simulated by dividing the rainfall volume evenly over the duration of the storm.

Flow charts for both weather programs can be found in Figure B 1 and Figure B 2.

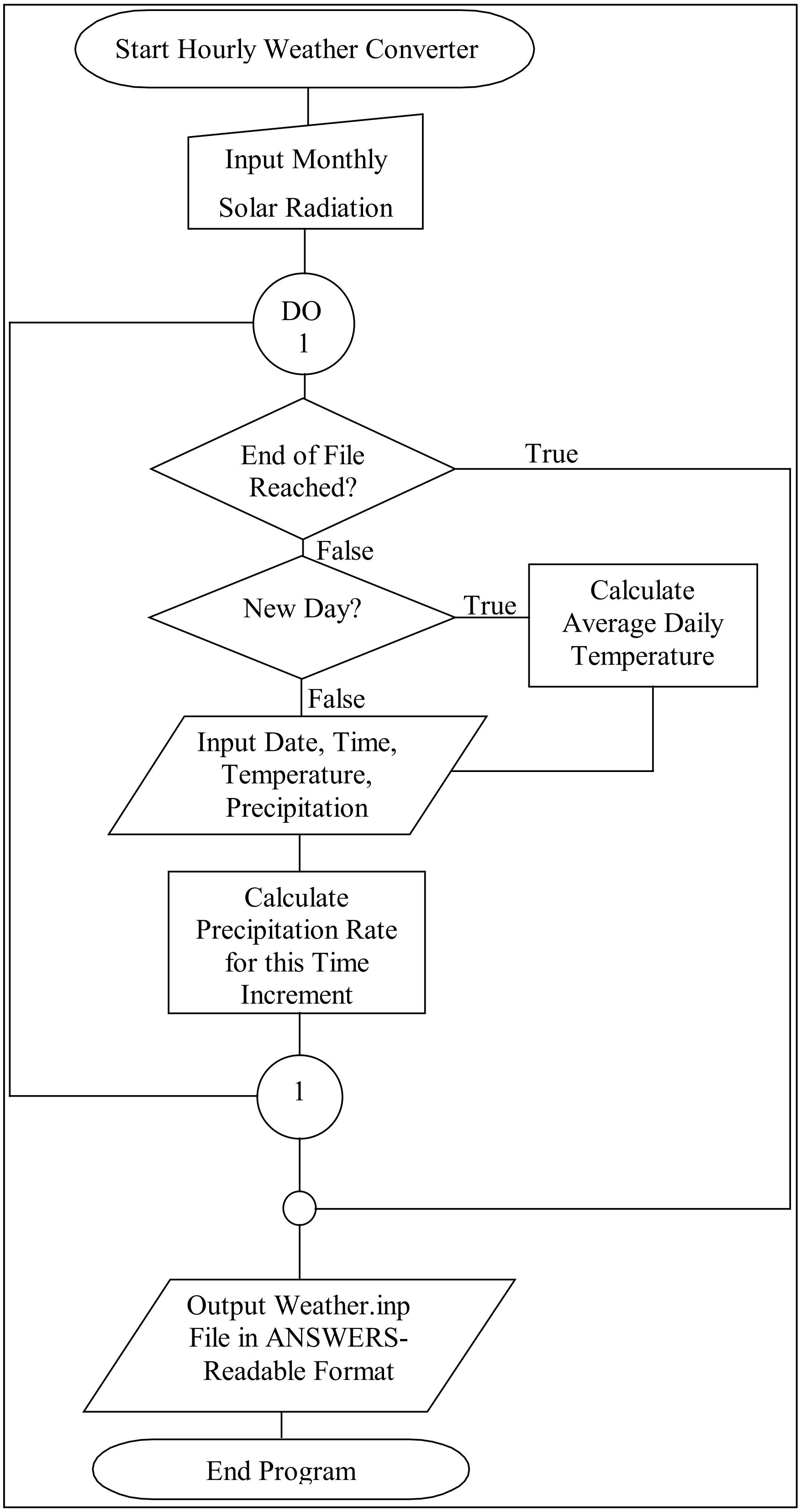

Figure B 1. Flow Chart Hourly Weather Converter Program.

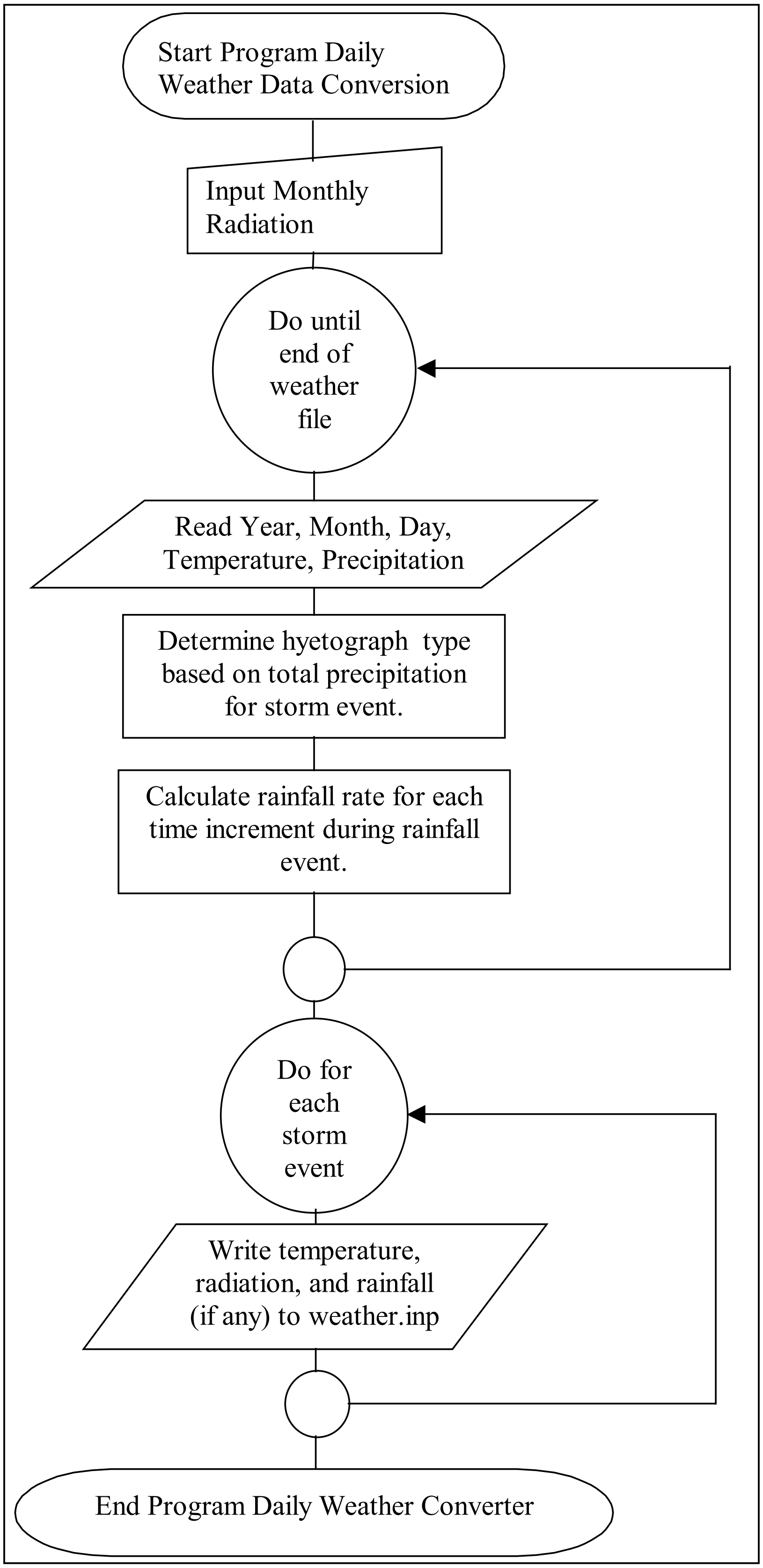

Figure B 2. Flow Chart for Daily Weather Converter.

B.2 QUESTIONS Modifications

The modifications to the Visual Basic user interface program, QUESTIONS, consisted of modifications to the landuse and input forms, as well as the addition of an atmospheric deposition form, a drain form, and a bmp form. Forms are roughly equivalent to subroutines in FORTRAN, or objects in object-oriented programming.

The landuse form was altered for the impervious/nonerodible practices. A new form was created, modeled after the original landuse form. It provides recommended crop parameter values for roads, houses, and sidewalks; it also has an 'other' category which is completely blank. The user may modify any of these parameters. This landuse form and the original form both had a button added to connect to the atmospheric deposition form. The new landuse form can be bypassed by instructing the program not to simulate impervious/nonerodible areas when prompted.

The atmospheric deposition form consists of a table for the user to fill in with deposition rates for each pollutant for each season. Default values are provided, based on the atmospheric deposition rates reported in the Occoquan watershed in northern Virginia in 1987. There is a button to zero the values if the user does not wish to simulate atmospheric deposition.

The drain form consists of a map of the watershed (including locations of roads and drains as input by the user in ArcView) and a table. The user can select cells on the map and input them to the table, along with an outlet cell if desired. Clicking on 'drains' on the main form will bring up a page asking if the user wishes to simulate drains, to which the user can answer 'no' and the form will be bypassed.

The BMP form consists of a map and three tables. There is one table for each BMP it is possible to simulate: dry ponds, wet ponds, and infiltration trenches. The map includes BMPs as input by the user into ArcView, as well as roads and watershed boundaries for reference in picking outlet cells. The user specifies the dimensions of the BMP for each cell and the outlet cell for principal spillways. The user may add and delete BMPs as desired. Clicking on 'BMPS' on the main form will bring up a page asking if the user wishes to simulate BMPs, to which the user can answer 'no' and the form will be bypassed.

The final input generation form was modified to check if the user desired to simulate impervious/nonerodible surfaces, drains, and/or BMPs. If the user desires to simulate impervious/nonerodible surfaces, a separate output statement is written for the impervious/nonerodible 'crop' and 'soil' types. If the user desires to simulate drains, the required separate drain input file is created. If the user desires to simulate BMPs, the required separate BMP input file is created.

B.3 Irrigation Submodel

An irrigation submodel (subroutine IRRIGATE) was developed to simulate irrigation. The submodel treats irrigation as rainfall on a particular land use (crop type). Users of this submodel should tailor the irrigation input file with this fact in mind. The irrigation subroutine consists of two parts: the first part determines whether any land uses are irrigated on the current day and initiates irrigation if needed. The second determines if irrigation should continue during the time increment based on user-specified conditions.

The user must specify the start day and end day of the irrigation cycle. The user can specify different rates and intervals of irrigation throughout the year by creating different irrigation cycles with beginning and end dates spaced throughout the year. Irrigation occurs according to land use type. The user can choose from three different irrigation methods. The first method initiates irrigation on a set schedule – every user-specified number of days, rain or shine. The second method initiates irrigation a user-specified number of days after the last rainfall or irrigation event, regardless of the size of the last rainfall event. The third method initiates irrigation when the soil moisture deficit reaches a user-defined level. The user also specifies the duration of irrigation events and the irrigation application rate.

The second part of the subroutine decides whether irrigation should occur during the time increment. This decision is based on the input the user specifies in the first part of the subroutine. First, the current date is compared to the start and end days specified by the user to see if the current date is in the irrigation cycle. Next, for the first two types of irrigation, the program checks to see if the appropriate time has passed since the last irrigation. For the last type of irrigation, the program checks to see if the soil moisture deficit is below the user-specified amount. When the soil moisture deficit decreases to the user-specified amount for the this type of irrigation, water application will cease.

Once all the checks have been performed, control returns to the main program, where the appropriate irrigation amount is applied. The irrigation amount is added to the rainfall for that time interval. If rainfall does not occur on the irrigation day or if the rainfall for that day has ceased, the program is run with the irrigation water acting as rainfall on the irrigated land uses. If only a portion of a particular land use category is irrigated and the user only wants to apply irrigation to a portion of a land use category, then the land use classification should be split into two land use categories, one irrigated and one not irrigated. A flow chart for the irrigation subroutine is show in Figure B 3.

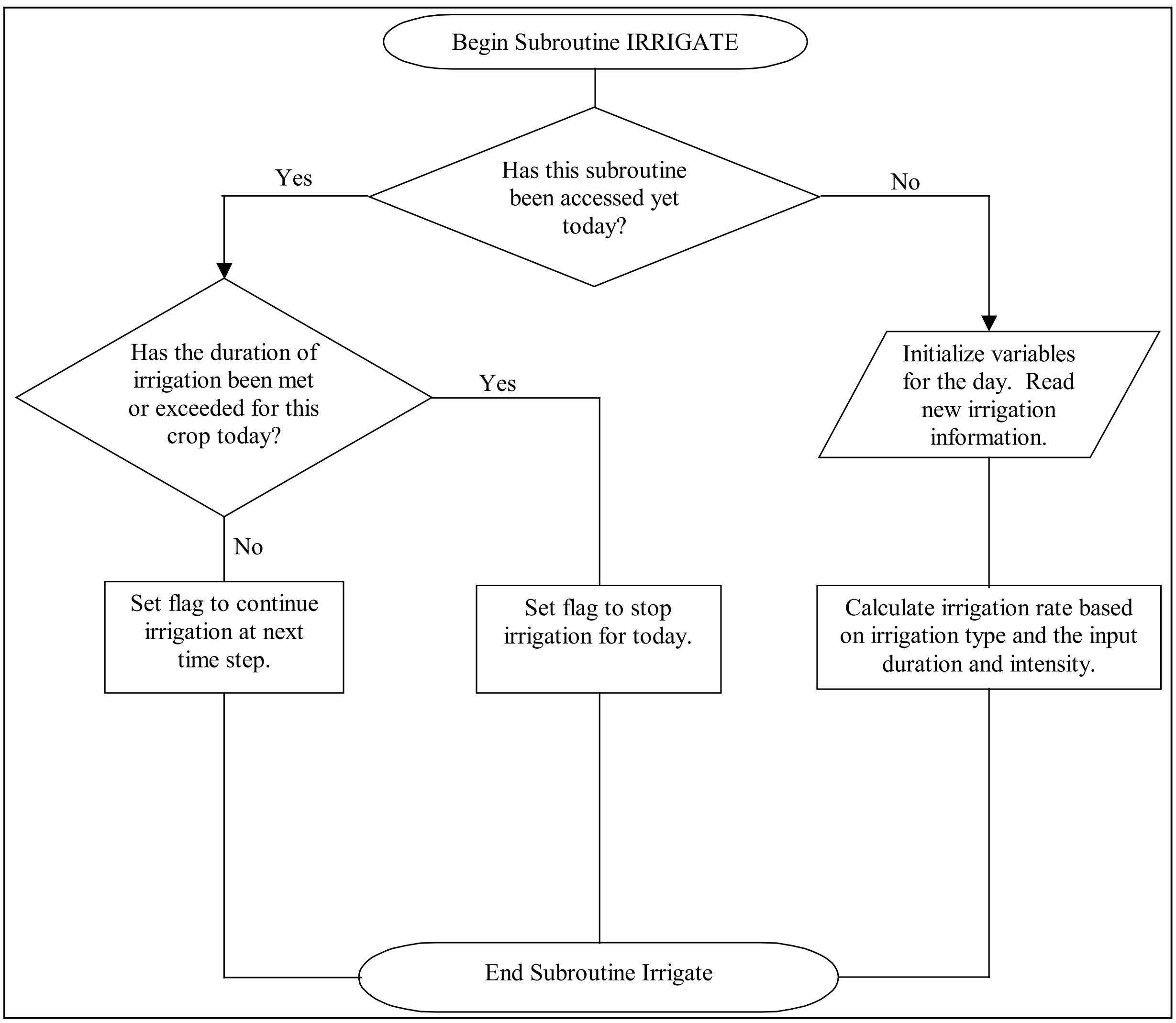

Figure B 3. Flow Chart for IRRIGATE Subroutine.

B.3.1 Assumptions and Limitations of the IRRIGATE Subroutine

The assumptions of the IRRIGATE subroutine are:

- Irrigation can be represented as rainfall on an element.
- Irrigating water is distributed evenly over all the cells in an irrigated land use (crop type).

The limitations of the IRRIGATE subroutine are:

- Decreased impact energy of irrigation water cannot be simulated.
- Some irrigation methods, such as flood irrigation, can be approximated but are poorly represented as rainfall.

Appendix C

User's Guide

User's Guide

For

ANSWERS-2000

Urbanization Additions

Rebecca Zeckoski

March 21, 2002

Introduction

This user guide is intended for the person who would like to take advantage of the urbanization additions to ANSWERS-2000 that were made by Rebecca Zeckoski in 2002. These additions include a best management practice subroutine, an atmospheric deposition subroutine, and an irrigation subroutine. The first part of this guide is intended for programmers – those who would like to know how things are done in ANSWERS-2000 or future modifiers of the code. This section contains information on the sediment routing as well for those users. In addition to this document, such users should refer to Zeckoski's M.S. thesis (listed in the references), the extensive comments made in the program code itself, and the input guide for QUESTIONS (distributed with the QUESTIONS program). The second and third parts of the code (input files) are intended for the casual user who does not care to know anything about the code and only needs some guidance on input file generation for the program. It should be noted here that such input file generation could be greatly facilitated by using the Visual Basic interface program, QUESTIONS, and following the instructions provided with that program.

Modifications to the Program (differences from ANSWERS-2000)

Urban Best Management Practices

A new subroutine was developed to simulate Urban BMPs. This subroutine considers 3 types of BMPs: dry ponds (type 1), wet ponds (type 2), and infiltration trenches (type 3). Infiltration basins can be considered as well, best represented as a dry pond with no pipe outflow.

Each type of pond can have one outlet structure and one emergency spillway. The user specifies dimensions for the outlet structure, as well as the destination for the outlet structure discharge. If channel cells within the watershed discharge to the pond, the user must specify a channel cell to receive the pond discharge. If the pond does not receive runoff from channel cells, the destination for the outlet structure discharge may be any cell specified by the user. See Figure 27 for an explanation. These cells should typically be 10 to 15 m on a side for an urbanized application of ANSWERS-2000, but are specified by the user and therefore could possibly be much larger or smaller. The user also specifies dimensions of the pond and characteristics of the outlet structure pipe. For a dry pond, the user has the option to specify the dimensions of an orifice opening on the side of the riser as well as one at the top of the riser. For a wet pond, the user can specify the dimensions of the opening at the top of the riser but does not have the option of specifying a side orifice opening. There is no riser structure for an infiltration trench.

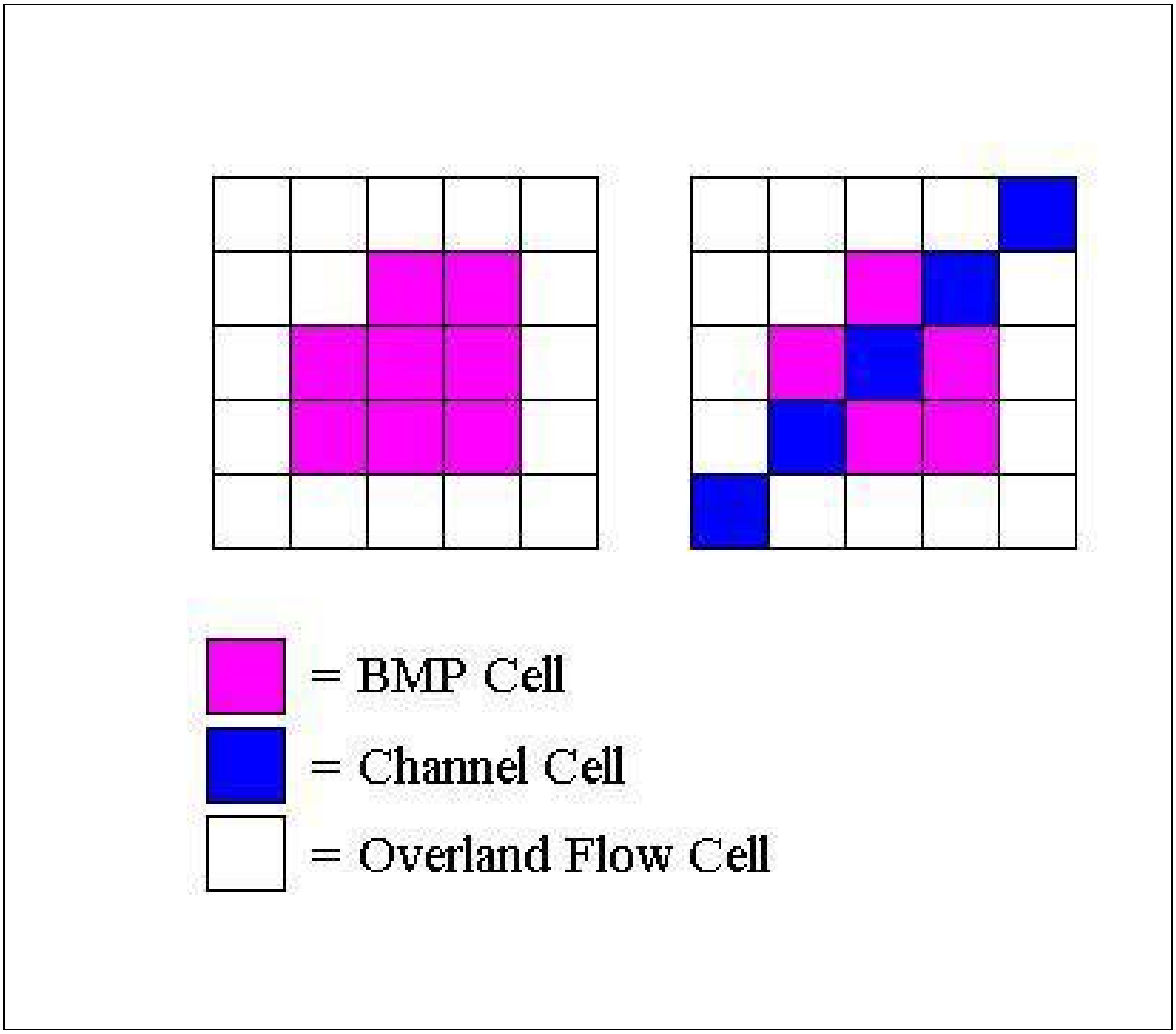

Figure 27. Possible BMP Configurations.

The two ponds are identical in size and layout. The first pond does not contain channel cells, so any output point can be specified. The second pond contains channel cells, so the outlet cell must be the channel cell in the lower left of the grid, assuming that the flow direction is toward the bottom of the grid.

The program computes the current depth of water for each time step. There are three governing equations for flow out of the pond through the outlet structure: weir flow, orifice flow, and full pipe flow. Weir flow applies until the orifice in the side of the riser is submerged; orifice flow applies to the submerged riser and to the orifice inside the riser; full pipe flow applies to the pipe taking the water out of the pond. The maximum flow for each of these is calculated and the minimum of these flows is taken as the maximum flow for water leaving the pond. See Figure 28 for a diagram of the outlet structure for the pond and dimensions used in the flow equations.

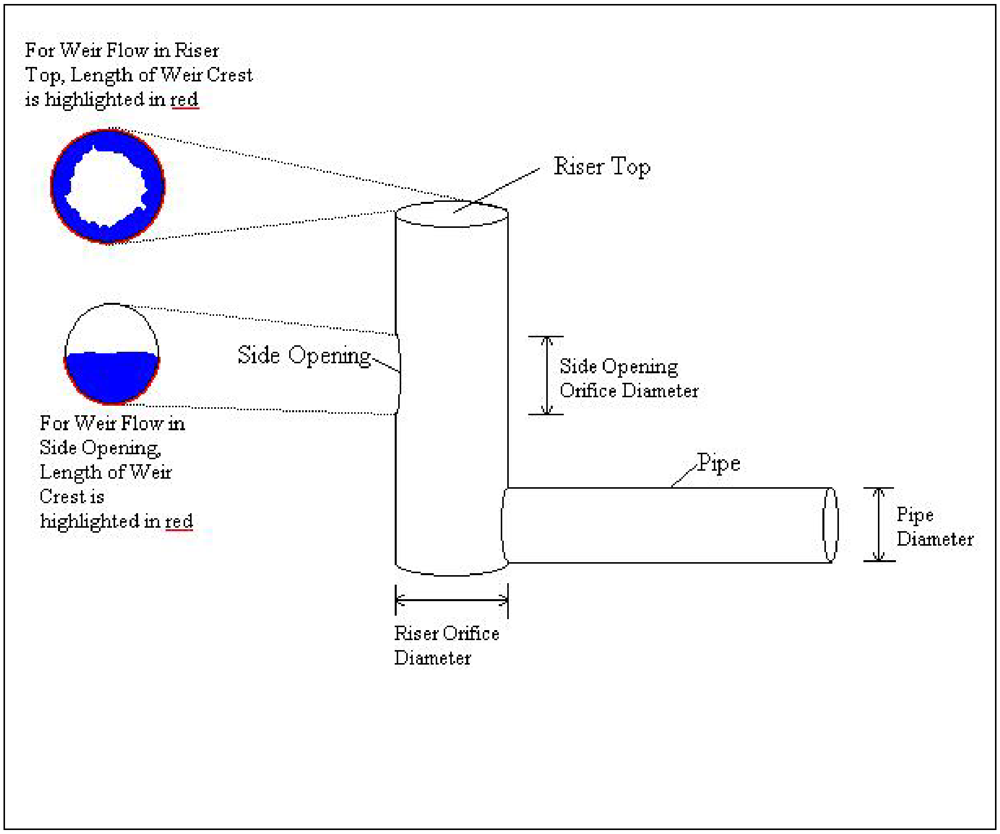

Figure 28. Riser Outlet Structure for a Pond BMP.

The water in a wet or dry pond can leave in one of four ways: through the outlet riser, over the emergency spillway, by infiltration, or by evaporation. All possible water exits from the pond are calculated at each time step and subtracted from the water volume of the pond. Should the calculated water loss be greater than the available water, the water will first satisfy the outlet structure loss, then the embankment loss, then the infiltration loss, and finally the evaporation loss. Sediment and sediment-bound nutrients enter the pond and are routed out based on the removal efficiency of the pond. The removal efficiency of the pond is calculated as:

$$RE = FV * \frac{A_s}{Q} \tag{12}$$

$$DP = RE * SI \tag{13}$$

Where: A_s = surface area of the pond, m^2

RE = removal efficiency, as decimal

FV = fall velocity of particle, m/s

Q = flow rate out of basin, m^3/s

DP = deposited sediment, kg/s

SI = sediment inflow to pond, kg/s

Deposited sediment is subtracted from the pond volume (thus, the pond volume will decrease over time). Dissolved nutrients are assumed well-mixed and leave the pond in proportion to the water that exits the pond.

Water can only leave an infiltration trench via infiltration. The capacity of the trench is determined from the user specified length, width, and depth, less the volume of gravel that is in the trench. Once the capacity of the trench has been filled, the water flows over the top of the trench to the adjacent receiving cells as though there were no structure present. Sediment that comes into the infiltration trench is subtracted from the trench volume.

Atmospheric Deposition

A new subroutine was created to account for atmospheric deposition of sediment and nutrients. The ANSWERS-2000 input files were modified to accept inputs of atmospheric deposition of sediment and nutrients in the crop description section. Allowing the atmospheric deposition to vary between crops allows the user to account for the spatial variability of atmospheric deposition even in a small area. Accumulation of dry atmospheric deposition is calculated as the rate per day multiplied by the number of days since last rainfall event in each season. That is, if the last rainfall event was in Spring and the current simulation day is in Summer, the number of days in the Spring season that have passed are multiplied by the deposition per day in Spring; the number of days in the summer season that have passed are multiplied by the deposition per day in Summer; then the depositions for each season are added to the existing sediment on the element. This section of the code looks very complicated, but all it does is calculate the number of days in each season between the last rainfall event and the current day. The accumulated dry deposited sediment and dry deposited nutrients are added at the beginning of every day of rainfall to the sediment available on each urban cell and the initial concentration of nutrients for each cell as appropriate (represented by SEL2 and XXXDEP, respectively, where XXX is the 3 letter abbreviation of the nutrient type), before any sediment calculations are made. The subroutine is called in the RAINFA subroutine at the beginning of each rainfall event.

Wet deposition of sediment and nutrients is input in answers.inp for each crop for each season. The WETDEP subroutine is called from the main program during each time step during a rainfall event. The subroutine selects the correct deposition rate for the current season and multiplies the deposition rate in mg/L by the volume of rainfall occurring in the time step. Deposited nutrients and sediment are added to the incoming nutrients/sediment for each cell (represented by AINO3, AINH4, SPI, and SI).

Irrigation

A new subroutine was added to ANSWERS-2000 to make the program capable of simulating irrigation: subroutine IRRIGATE. Irrigation is associated with the different crop types. This subroutine has been tested but not validated, so use with care. The subroutine can simulate irrigation using one of three different frequency types (one frequency type per irrigation period per crop – different crops and/or different irrigation periods can have different frequency types). The first type is irrigation that is applied every set number of days, rain or shine. The second type of irrigation is that which is applied a set number of days past the last rainfall (or irrigation). This avoids application on rainfall days without requiring the user to know anything about the soil moisture conditions. The third and final type of irrigation is applied when the soil moisture reaches a user-defined deficit level. Water is applied until the soil reaches the user-defined target soil moisture.

This subroutine is divided into two parts. The first part is called at the beginning of each day, and determines whether or not irrigation water should be applied that day, dependent upon the type definitions. For the frequency types 1 and 2, the difference from the last irrigation/rainfall day is determined and compared to the set number of days. For frequency type

3, the soil moisture of the cells with the appropriate crop type is determined, and if there are cells in a crop type that are deficient, the entire crop is irrigated.

The second part of the subroutine is called during the hydrograph generation part of the subroutine. This portion of the subroutine determines if the duration of rainfall has been exceeded yet, and if so, ceases irrigation for the day. This portion of the subroutine also includes flags to skip over the rainfall calculations if it is not a rainfall day, or if the rainfall has ceased for the day before the duration of the irrigation is reached.

Once the end of the irrigation file is reached, the read returns to its beginning. In this way, the user only need define irrigation parameters for one year of simulation and they will be used throughout the simulation. The user can define parameters for any length of time evenly divisible by a year: if irrigation parameters are constant on a two-year cycle, four year cycle, etc., they can be specified for two or four years, etc., and they will be repeated every two, four, etc. years. Fractions of years are not acceptable because irrigation is applied according to the Julian date, and thus trying to cycle a 1.5 year cycle will be the same as cycling 2 years as far as the computer is concerned, as the beginning of the file will not be used again until the beginning of the year comes around again.

IMPORTANT NOTE: the necessary positioning of the '…irrigating' message in the code (the message displayed in the DOS window when the program executes), it is not possible to check to see if the crop that is supposed to be irrigated is actually in rotation before displaying the message. Therefore, if the user specifies for a crop to be irrigated during a time it is not actually present in the watershed, this message will come up even though the crop is not actually being irrigated. The calculations in the program are still correct; it is just because of the positioning of the message that there might be some small confusion.

A general guide for irrigation application is presented in Table 15. These values will need to be converted to mm/hr for placement in irrigation.inp, so the duration of irrigation needs to be known. This table is presented as a general guide; however, the user should make every attempt to determine the actual planned irrigation rates for the area to be simulated.

Table 15. Irrigation Guide.

Soil Profile	Net Amount of Moisture to Apply – Acre-inches per Acre*						
	12”	18”	24”	30”	36”	48”	72”
	For various root depths						
Coarse sandy soils, uniform in texture, 6 ft	0.45	0.60	0.85	1.20	1.30	1.75	2.60
Coarse sandy soils over more compact sub-soils	0.45	0.60	1.50	1.75	2.00	2.50	3.00
Fine sandy loams uniform in texture to 6 ft	0.85	1.30	1.75	2.20	2.60	3.00	4.00
Fine sandy loams over more compact sub-soils	0.85	1.50	2.00	2.40	2.80	3.25	5.00
Silt loams uniform to 6 ft	1.10	1.70	2.25	2.75	3.00	4.00	6.00
Silt loams over more compact sub-soils	1.10	1.70	2.50	3.00	3.25	4.25	6.25
Heavy clay or clay loam soils	0.90	1.40	2.00	2.40	2.85	3.85	5.50

*taken from Pair, *et al*., Irrigation, 5th edition, 1983

Sediment

On an impervious/nonerodible cell (such as a road, rooftop, or sidewalk), sediment detachment cannot exceed the available sediment deposited from a previous storm; i.e., you cannot detach sediment from the surface itself, only the sediment previously deposited on the surface. ANSWERS-2000 calculates the detachment capacity for a cell using a soil erodibility factor and differences in shear stress - see equations 16 and 108 in Byne, 2000.

This was not acceptable for use with nonerodible cells because the baseline rill erodibility and the effective shear stress used in those equations are rooted in calculations that have no meaning for nonerodible cells. Therefore an assumption was made. It was assumed that the limiting factor on sediment detachment/transport from a nonerodible cell would be the soil available to detach. To explain: on an erodible cell, there is soil on the cell that might not be available to detach (hence the soil erodibility parameter) – namely most of the soil profile. However, the amount of sediment in existence on a nonerodible cell was considered to be readily detachable such that if the transport capacity could handle it, the sediment would be carried away.

In order to accommodate the impervious areas, the sediment subroutine was copied in full from ANSWERS and pasted into the urbanization subroutine. Then the subroutine was modified in a few places to accommodate the impervious areas. First, roads are considered to have a channel sitting on each side, representative of gutters or curbs. The road width in meters (ROADWIDTH) is set by the user in the input file and this is used to determine the number of gutters on each cell (if the road width is greater than the cell width, there will only be one gutter; if it is less than the cell width, there will be two gutters (one on each side of the road)).

The primary item of importance for the modifications was keeping accurate track of the sediment in each particle size class that is deposited on the impervious area. A new variable was created for this purpose, SEL2. This variable keeps track of the mass of sediment on a cell in each particle size class and cannot fall below zero. Transport capacity is calculated as in the main program using Yalin's equation. Flow detachment is the primary area that was modified. Instead of using shear stress, all sediment on an impervious element is assumed to be detachable. Therefore the detachment on an element is limited to the lesser of the available sediment (DETCAP) or the transport capacity above sediment in transport (TRANSCAP).

Modified Input files

Answers.inp

Soils

When the urban soil flag ('NO. URBAN SOILS'), located after the 'NUMBER OF SOILS' line in the input file, is set to 1, the program reads the the first soil type, by default, as the impervious/nonerodible soil type. This is very important: if you specify in the flag at the beginning of the input file that there is urban area in the watershed then the first soil type **must be** the urban soil type, consisting of the flag that states "urbsoil=1" and values for specific surface area for each particle size class. The program will not read the input correctly if you do not follow this convention.

All urban practices (roads, houses, etc.) have the same soil type. At this time it does not seem necessary for more than one urban 'soil' type to exist, although the code was written to accept more than one urban 'soil' type should the need arise.

The recommended values for the specific surface area are: 20.0 for clay, 4.0 for silt, and 0.05 for sand. The formatting for the urbsoil=1 flag and specific surface area is: [9X,I1,1X,8F8.4].

Crops

Following the line specifying the number of crop types in the watershed, you must specify how many urban 'crop' types are present. The urban crop types must be listed first in the crop description section. Fewer parameters are needed to describe urban 'crops.' Each urban 'crop' (road, house, etc.) gets its own description. In your ArcView file, the urban crop types and the urban soil types MUST coincide with each other. If a cell has a crop type specified as urban and has a non-urban soil type, the program will not run correctly. The same is true if you have an urban soil type and a non-urban crop type. Parameter descriptions follow below; the letter-number combinations following each description in parentheses are the format descriptors for that variable.

Crop (I,1): ' urb' *(for urban crop types, this is ALWAYS ' urb' regardless of which crop type it is-this is used by the program)* (A4)

Crop (I,2): descriptor for the particular 'crop' type. This needs to be a four letter long description, so use 'road' for roads, 'hous' for houses, etc. The descriptor is for your reference and is not used in the program, so it can be anything you like as long as it is no longer than four letters. (A4)

PIT (1,I): potential interception volume. This should normally be set to zero unless you have an extraordinary number of trees overhanging the road, in which case choose from the range 1.0-2.5. Another exception would be if the gutters from roofs in the area drain to an underground storage (i.e., they do not channel the water to be released at ground level). For this case, set PIT to 99.99. **Remember that this is for the urban 'crop' type – areas covered by impervious surface. This does not refer to any vegetation represented by its own cells and breaking up the impervious area.** (F5.2)

PER (I): percentage of 'crop' land covered by the interception-causing entity. This should be set to zero unless you have one of the situations described in the PIT description. If you have one of the situations described, then make an estimate of the amount of urban area **for that 'crop' type** covered by the overhanging branches or roofs having underground storage-channeling gutters. (F4.2)

ROUGH (I): roughness coefficient. This ranges in value from about 0.3 to 0.6 for agricultural lands (Beasley, Huggins, and Monke, 1980). It follows no predictable trend (i.e., does not appear to increase or decrease with degree of roughness) (Huggins and Monke, 1966) and should be determined by calibration. The model is not extremely sensitive to this parameter and the user should not waste overmuch time attempting to figure it out. (F4.2)

HU (I): roughness height (mm). See the ANSWERS-2000 input file variable guide (figure 4) for a description of how to measure this parameter. Suggested values are: 2.0 for roads, 3.0 for houses, and 0.5 for sidewalks. (F6.2)

DIRM (I): maximum physical retention depth. Suggested values are: 0.2 for impervious surfaces. (F5.3)

Format for above variables:

[11X,2A4,6X,F5.2,6X,F4.2,5X,F4.2,4X,F6.2,4X,F5.3]

RANROU(I): random roughness of the 'soil' surface (mm). This value ranges from 9 to 43 mm for agricultural practices (Lane and Nearing, 1989), and is higher for more rough surfaces. Suggested Value for urban areas: 3 for roads, 0.5 for houses**,** unless the surface is unusually rough. (F5.1)

MNSOIL(I): Manning's n for the bare soil; and MNTOT (I): Manning's n for the surface and cover. These should normally be the same. I cannot think of any exceptions at this time. If they are set differently, MNSOIL must be less than MNTOT. Recommended values are listed in Table 16. (F5.3,1X,F5.3)

ROADWIDTH(I): Road with or sidewalk width, meters. If this is not a road or sidewalk, then this value should be set to zero. (F5.2)

Format for above variables:

[1X,F5.1,1X,F5.3,1X,F5.3,F5.2]

The atmospheric deposition values complete the remainder of the crop section. These values must be specified for urban and non-urban crop types alike. The model is very sensitive to these parameters, so if you do not know the appropriate values for deposition, LEAVE THEM BLANK. There are four lines: one for each season. On each line, the following eight values are specified, in order:

ATMDEP(L,J): daily atmospheric deposition of sediment for 'crop' type L in season J ($kg/m^2/day$). Note that deposition of sediment is widely variable in an area, dependent upon the surface around the area. Also, atmospheric deposition is widely variable at different times of the year. The program allows for four inputs of atmospheric deposition of sediment for spring, summer, fall, and winter (which should occupy the first, second, third, and fourth positions respectively). If atmospheric deposition is not known, this value can be set to zero, or you can try and approximate it from the values in the tables in Appendix A. If you have a value for atmospheric deposition of sediment averaged for the entire watershed, enter it for each crop. This value is used in subroutine ATMDEPOSIT. (F5.2)

TKNDEP(L,J), AMNDEP(L,J), SEPDEP(L,J): daily DRY atmospheric deposition of organic nitrogen, ammonia, and orthophosphorus for 'crop' type L in season J ($kg/m^2/day$). These follow the same reasoning as ATMDEP above. Set them to zero if you do not have values for them. These values are used in subroutine ATMDEPOSIT. (3F5.2)

NO3ZDEP(L,J), WATNHDEP(L,J), SOLUBPDEP(L,J), TSSDEP(L,J): WET atmospheric deposition of nitrate, ammonia, orthophosphorus, and suspended sediment for 'crop' type L in season J (mg/L). This nutrient deposition only occurs during times of rainfall, and is due to the water 'scrubbing' the air as it comes down. Nutrient deposition is entered per crop and per season as described for ATMDEP. If the values are not known, they can be set to zero without adversely affecting the program. These values are used in subroutine WETDEP. (4F5.2)

Format for above variables:

[7X,8(F5.2,1X),/,7X,8(F5.2,1X),/,7X,8(F5.2,1X),/,7X,8(F5.2,1X)]

Table 16. Recommended Manning's n Values for Urban Surfaces.

Manning's n Values for Urban Areas	
Surface Type	Roughness Coefficient
smooth asphalt	0.012
street pavement	0.013
asphalt or concrete paving	0.014
packed clay	0.03
light turf	0.20
dense turf	0.35
dense shrubbery or forest litter	0.40
short grass	0.03-0.035
high grass-submerged	0.025-0.05
heavy weeds-scattered grass	0.05-0.07
From Novotny and Olem, 1994, pg. 154	

Weather.inp

This file in and of itself was unchanged. However, currently QUESTIONS uses CLIGEN to generate the weather file. This is a theoretical weather file based on statistics and is not capable of simulating actual weather events. Therefore, I wrote two short FORTRAN 90 programs to analyze the NOAA data (one for hourly and one for daily data) and create a weather.inp file readable by ANSWERS. One important feature of the new weather programs is in the timing of the end of the storm. ANSWERS-2000 is written to run until the end of the last time period specified for a storm in the weather file. Therefore it is necessary to set the last time period to end at the end of the day to ensure that all runoff from a storm is completed before simulation starts. This feature was lacking in the CLIGEN weather generator. This last time period has zero intensity rainfall so ANSWERS-2000 will just simulate runoff for the remainder of the day.

The equations used for the hourly weather data are very simple. Each time entry on the NOAA file during a rainstorm becomes a breakpoint for the weather data. The total rainfall for that time entry is divided by the minutes since the last time entry to give an average rainfall rate in in/min, which is then converted to mm/hr.

The daily weather data program is somewhat more complex. The hourly hydrographs were inspected to determine trends in hydrograph types for different rainfall amounts. Based on the hydrographs, the rainfall was divided up into appropriate subintervals and total durations. More detail on the programs can be found in Rebecca Zeckoski's M.S. Thesis (Zeckoski, 2002).

Both weather programs must be adapted to read the user's raw weather files. This requires only modification of the formatting statements in the programs and can be done by an amateur programmer.

New Input Files

BMP.inp

This file contains the BMP information for the watershed. An example of the basic format follows:

```
 CELL TYPE OUTLET SUB? LENGTH   WIDTH PIPE PIPE  PIPE ORIFICE ORIFICE RISER  RISER OVERFLOW ANNUAL
           CELL                        N    DIAM  LEN  HEIGHT   DIAM   HEIGHT DIAM   HEIGHT  F.W. EVAP
04824  2   04931   1   000.000 000.00 0.00 00.00 00.0 00.000  00.000  00.000 00.000 00.00   0.000
04931  2   04812   0   243.310 034.75 0.02 00.81 11.3 03.000  00.000  00.700 00.946 01.40   0.980
```

The first two lines are reserved for headers. The next section details the variables read from the BMP.inp file. The word in parentheses is the variable name used in the code; the letter-number combination at the end of each description is the format descriptor for the variable.

CELL (CELL): the cell where the BMP is located. Given as the index number. The index number can be determined easily from using the input generation program, Questions. If you wish to determine it manually from your input file, there are two ways: first, you can count down to the cell where the BMP is located. Cells are numbered from top to bottom, left to right (as if you were reading the cells). Second, you can run the R2Vpoint script, and this will create a point theme in your watershed that has a point for every cell in the watershed. The attribute table for this theme will number the points accurately. (I5)

TYPE (TIPE): the type of BMP. Type 1 is a dry pond; type 2 is a wet pond; and type 3 is an infiltration trench. If type is 3, the user need not input values for the orifice or pipe parameters. However, it is crucial that type 3 ponds have length, width, overflow height, cell, and annual free water evaporation values specified. (I1)

OUTLET CELL (NRO): the receiving cell for the riser outlet structure, given as an index number. The index number can be determined as for the CELL parameter. The receiving cell receives all flow that goes through the opening on the side of the riser and through the top of the riser. (I5)

SUB? (SUB): a flag to indicate whether this cell is part of a larger pond. This is used for multiple cell ponds whose area is greater than the area of one cell. By setting this value to one for all but the lowest pond cell, all inflow to the cell will output to the lowest pond cell, thus filling the pond. If SUB is one, the OUTLET CELL should be the cell in the pond with the lowest elevation (i.e., the cell to which all water should drain). The user does not need to input any values for the remainder of the parameters. If SUB is zero, this is either the lowest cell in a multiple-cell pond or a single-cell pond. In either case, all the parameters of the pond are associated with this cell. (I1)

LENGTH (LENGTH): the length of the BMP on a side, meters. The program assumes a rectangular geometry for the surface area. If the surface area is not rectangular, the user should simply create a length and width which, when multiplied together, yield the correct surface area. The surface area is important to the simulation, but the surface geometry is not. (F7.3)

WIDTH (PONDWIDTH): the width of the BMP on a side, meters. The program assumes a rectangular geometry for the surface area. If the surface area is not rectangular, the user should simply create a length and width which, when multiplied together, yield the correct surface area. The surface area is important to the simulation, but the surface geometry is not. (F6.2)

PIPE N (PIPEN): Manning's n for the outlet pipe. Manning's n values for various pipe surfaces are readily available from hydrology books. (F4.2)

PIPE DIAM (PIPED): the diameter of the outlet pipe, meters. (F5.2)

PIPE LEN (PIPEL): the length of the outlet pipe, meters. This should be measured from the base of the outlet structure to the opening at the other end of the pipe that deposits into the receiving cell. (F4.1)

ORIFICE HEIGHT (ORIFICEH): the height of the side opening orifice center, meters. If the pond has relatively straight vertical sides, this is the height of the orifice center. If the pond slopes gently, the user should input an orifice height which, when multiplied by the surface area, will yield the volume of the pond when the water surface comes to the center of the orifice. Volume is the crucial issue. If a wet pond is being simulated or the user does not wish to simulate a side opening on the riser structure, this value should be set at least 0.5 m higher than the embankment height. (F6.3)

ORIFICE DIAM (ORIFICED): the diameter of the side orifice opening, meters. (F6.3)

RISER HEIGHT (RISE): the height of the top of the riser outlet structure, meters. As with the orifice height, the it is important that this value multiplied by length and width of the pond yields the correct volume when the pond is filled to the top of the riser. (F6.3)

RISER DIAM (RISD): the diameter of the top of the riser, meters. (F6.3)

OVERFLOW HEIGHT (WEIRH): the height of the emergency spillway, meters. If the pond has relatively straight vertical sides, this is the height of the emergency spillway. If the pond slopes gently, the user should input an overflow height which, when multiplied by the surface area, will yield the volume of the pond when the water surface comes to the height of the emergency spillway. (F5.2)

ANNUAL F.W. EVAP (AFWEV): annual free water surface evaporation for the watershed, m^3/year. This should be the same for each BMP. (F5.3)

Format for BMP.inp: (1X,I5,2X,I1,3X,I5,3X,I1,3X,F7.3,1X,F6.2,1X,F4.2,1X,F5.2,1X,
F4.1,1X,F6.3,2X,F6.3,2X,F6.3,1X,F6.3,1X,F5.2,3X,F5.3)

Irrigation.inp

This file contains the irrigation information for the watershed. An example of the basic format follows:

```
IRRIGATION INPUTS FOR ANSWERS SIMULATION
 CROP|START|END|FREQ|EFF.|RATE|DUR/TARG|LIMIT|
   3   005  020  3   0.90 15.0   00.85   083
```

The first two lines are reserved for headers. The word in parentheses is the variable name used in the code; the letter-number combination at the end of each description is the format descriptor for the variable.

CROP: (IRRCROP) the crop type to which the irrigation water is applied. (I2)

START: (STARTDAY) the beginning Julian day of the irrigation cycle. IMPORTANT: the entries to this file need to be in order of ascending start days. If the start days are not in order, every time the program reaches a start day prior to its current day, it will not use the data (nor read the rest of the file) until that date comes along next year. If you wish to put more than one year in the cycle, then the start day entries for each file must be in order within the year block. There is no place in the input file to enter the year. (I3)

END: (ENDDAY) the last day of the irrigation cycle. IMPORTANT: startday and endday define the beginning and end of the CYCLE, not the irrigation itself. i.e., water is not applied continuously from startday to endday. Water is applied according to your specified frequency type (see below), and will not be applied on the crop after the end day. (I3)

FREQ: (FREQ) the frequency type. **This must be 1, 2, or 3.**

type 1: the water is applied every certain number of days, rain or shine.

type 2: the water is applied a certain number of days after the last rainfall and is never applied on a rainfall day.

type 3: the water is applied when the soil moisture reaches a certain deficit level and application ceases when it reaches a target soil moisture.

the parameters mentioned above (days, moisture levels) are specified as per instructions below. (I1)

EFF.: (IRREFF) the efficiency of application. This is the ratio of water actually supplied to the crop (after losses according to evaporation of droplets, pipe losses, etc.) to the water applied to the crop. The program will consider losses due to interception, so these need not be considered. This is expressed as a decimal (90%=0.90). (F4.2)

RATE: (IRRATE) the rate of irrigation application. This is assumed constant for the irrigation cycle and is most likely set by the type of pump being used. This is the rate prior to any losses. This is expressed in millimeters/hour. (F4.1)

DUR/TARG: (VARIABLE) the *duration* of irrigation or *target* soil moisture, depending on the frequency type. If the frequency type is 1 or 2, this value is given to the variable DURATION. This is the duration of the irrigation in minutes. If the frequency type is 3, this value is given to the variable DEFLIMIT. This is the target soil moisture after irrigation, expressed as a decimal percent (90%=0.90) of total porosity (this percent of total porosity follows the same convention as the soil parameters, which are entered as a percent of total porosity). Once the soil moisture reaches this value, irrigation ceases. (F6.2)

LIMIT: (LIMIT) the *number of days* between irrigations or the *limiting* soil moisture, dependent upon the frequency type. For frequency type 1, this is the number of days between irrigations. For frequency type 2, this is the number of days after the last rainfall or irrigation event that must pass before the next irrigation is applied. For frequency type 3, this is the limiting soil moisture expressed as an integer percent (90%=90) of total porosity; once the soil moisture falls below this designated level, irrigation begins. The value is given to the variable DEFLIMIT for this frequency type. Because of the way this variable is used in the program, this MUST BE AN INTEGER, do not attempt to enter as a decimal percent (as in DUR/TARG) and do not try to enter fractions of a percent (e.g., 90.5). (I3)

Format for irrigation.inp: (2X,I2,3X,I3,2X,I3,2X,I1,3X,F4.2,1X,F4.1,2X,F6.2,3X,I3)

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Appendix D

Sample Calculations

Sample Calculations – Converting Logger Data to Runoff

Two lines from a Sample Logger File for the QVA Station:

110,1999,11,1700,11.13,.473,.139,1680,7
110,1999,11,1710,11.13,.414,.128,1680,7

In Excel, these are changed:

Year	Day	Mil.Time	Batt.Vol.	mV			
1999	11	1700	11.13	0.473	0.139	1680	7
1999	11	1710	11.13	0.414	0.128	1680	7

Runoff is then computed in the following fashion:

Stage = 0.2012 * mV + 0.254

Flow Rate = 13.252 * Stage^2 - 0.6286 * Stage – 0.329

Flow Volume = Flow Rate * Δt * 60

Flow Volume2 = Flow Volume * 28.32

Watershed Runoff = Flow Volume2 * 0.0001 / Area

Where:
- mV = reading from logger, mV
- Stage = flow height, ft
- Flow Rate = rate of flow, cfs
- Flow Volume = volume of flow, ft^3
- Δt = change in military time since last logger entry, min
- Flow Volume2 = volume of flow, L
- Watershed Runoff = watershed runoff for time increment, mm
- Area = watershed area, ha

The runoff is the total calculated flow rate less the flow rate of the maximum baseflow that day, converted to mm (watershed runoff).

Appendix E

Results

Table E 1. Measured Sediment and Nutrient Output from QVA Watershed in 1999 from Lovern (2000).

Julian Day	TSS (g/L)	TSS (kg/ha)	NO_3 (mg/L)	NO_3 (kg)	NH_4 (mg/L)	NH_4 (kg)	PO_4 (mg/L)	PO_4 (kg)	TKN (mg/L)	TKN (kg)
33	30	0.0	2.04	0.00	0.031	0.000	0.001	0.000	0.190	0.00
43	66	53.1	2.81	0.33	0.031	0.004	0.001	0.000	0.000	0.00
49	27	569.7	0.95	2.88	0.031	0.095	0.001	0.003	0.040	0.12
59	14	68.7	1.89	1.34	0.039	0.028	0.001	0.001	0.000	0.00
63	98	174.6	1.62	0.42	0.031	0.008	0.001	0.000	0.000	0.00
69	18	2.5	1.89	0.04	0.043	0.001	0.001	0.000	0.000	0.00
91	52	464.1	1.25	1.61	0	0.000	0.026	0.034	0.050	0.06
99	83	38.6	1.63	0.11	0	0.000	0.026	0.002	0.115	0.01
105	36	226.6	1.31	1.19	0	0.000	0.026	0.024	0.065	0.06
117	46	21.0	1.30	0.09	0.014	0.001	0.026	0.002	0.075	0.00
128	79	85.7	1.33	0.21	0.032	0.005	0.034	0.005	0.150	0.02
134	42	810.3	1.03	2.86	0.013	0.036	0.053	0.148	0.180	0.50
168	25	139.6	1.11	0.89	0.034	0.027	0.000	0.000	1.935	1.56
172	20	58.3	1.34	0.57	0.084	0.035	0.030	0.013	1.440	0.61
179	29	56.5	1.65	0.47	0.078	0.022	0.008	0.002	1.060	0.30
192	20	96.6	1.64	1.14	0.064	0.045	0.008	0.006	1.040	0.73
193	27	1320.1	0.96	6.80	0.055	0.389	0.008	0.057	1.435	10.14
210	134	166.4	1.53	0.27	0.046	0.008	0.008	0.001	1.325	0.24
226	88	0.0	1.61	0.00	0.046	0.000	0.020	0.000	1.240	0.00
232	77	629.6	1.47	1.74	0.046	0.054	0.016	0.019	1.555	1.84
236	740	141.3	1.31	0.04	0.059	0.002	0.011	0.000	1.805	0.05
238	44	1387.3	0.00	0.00	0	0.000	0.000	0.000	0.000	0.00
249	122	1180.4	1.44	2.01	0.046	0.064	0.030	0.042	2.655	3.71
264	138	48.7	0.73	0.04	0.528	0.027	0.075	0.004	1.875	0.10
271	15	18.2	0.00	0.00	0	0.000	0.000	0.000	0.000	0.00
272	32	200.4	0.74	0.67	0.139	0.126	0.094	0.085	1.265	1.14
282	5	54.9	0.97	1.54	0.105	0.167	0.035	0.056	1.435	2.28
292	16	58.9	0.00	0.00	0	0.000	0.000	0.000	0.000	0.00

Table E 2. Measured Runoff for the QVA Watershed (1999).

Day	Rainfall (mm)	Runoff (mm)	Day	Rainfall (mm)	Runoff (mm)	Day	Rainfall (mm)	Runoff (mm)	Day	Rainfall (mm)	Runoff (mm)
7	0.51	0.00	105	10.93	0.63	205	1.52	0.05	330	9.14	0.68
9	4.82	0.86	109	1.26	0.01	209	24.37	3.00	340	4.82	0.26
14	25.14	3.63	110	2.29	0.07	210	4.57	0.12	344	10.66	0.83
17	1.78	0.04	116	7.12	0.24	213	9.39	0.85	347	7.12	0.63
18	1.26	0.02	117	2.8	0.05	220	2.8	0.07	348	12.45	1.38
23	25.14	3.76	118	8.63	0.62	225	7.62	0.56	354	3.81	0.22
24	9.9	1.55	127	10.66	0.80	226	0.51	0.00	355	3.05	0.12
32	15.76	1.25	128	1.78	0.11	232	10.42	0.82	356	0.51	0.00
33	0.51	0.00	133	4.57	0.13	235	17.78	3.91			
38	5.32	0.34	134	19.81	1.93	236	1.52	0.02			
43	2.29	0.08	138	27.17	2.29	237	8.9	0.45			
48	1.52	0.02	144	4.31	0.18	238	18.29	3.15			
49	20.58	2.11	153	3.81	0.12	248	4.57	0.26			
50	2.29	0.02	167	6.35	0.32	249	1.78	0.97			
55	1.26	0.00	168	7.37	0.56	258	1.78	0.00			
56	1.78	0.00	171	2.8	0.15	263	25.92	2.77			
59	7.37	0.49	172	6.61	0.29	264	1.26	0.04			
62	9.66	1.01	175	0.76	0.00	270	9.39	0.35			
63	0.76	0.18	176	0.51	0.00	271	2.54	0.12			
65	0.51	0.00	178	0.51	0.00	272	7.87	0.63			
68	2.03	0.06	179	4.06	0.19	277	7.87	0.37			
69	3.3	0.01	182	4.06	0.00	282	15.26	1.10			
73	13.46	1.25	183	0.51	0.00	284	0.51	0.06			
74	13.2	1.30	184	6.35	0.34	292	9.9	0.37			
80	16	1.36	188	4.82	0.05	294	0.51	0.00			
83	2.8	0.10	191	5.07	0.12	306	10.42	0.54			
91	12.7	0.89	192	7.87	0.48	315	0.51	0.00			
99	2.29	0.05	193	40.63	4.89	325	0.76	0.00			
101	23.37	2.23	199	5.85	0.99	329	6.86	0.37			

Table E 3. Measured Output from Commuter Lot B below Dry Pond (1995).

NOAA Date	Outflow (mm)	TSS (µg/L)	TSS (kg/ha)	NO3 (µg/L)	NO3 (kg)	NH4 (µg/L)	NH4(kg)	PO4 (µg/L)	PO4 (kg)	TKN (µg/L)	TKN (kg)
231	34.67		0		0		0		0		0
240	8.71		0		0		0		0		0
257	1.45	1035	0.01	67.7	0.01	2.4	0.0003	0	0.000	284.4	0.04
260	17.73	4032	0.71	291.8	0.49	0	0.0000	3.5	0.006	548.2	0.91
266	0.00		0.00		0.00		0.0000		0.000		0.00
268	0.00		0.00		0.00		0.0000		0.000		0.00
270	2.34	2093	0.05	78.9	0.02	0	0.0000	0	0.000	220.7	0.05
278	27.28	42116	11.49	247.5	0.63	8.4	0.0215	23.8	0.061	2577.7	6.61
287	4.87	4851	0.24	68.9	0.03	2.7	0.0012	8.2	0.004	540.6	0.25
294	10.44	7154	0.75	215.2	0.21	1.5	0.0015	7.6	0.007	30	0.03
301	0.00		0.00		0.00		0.0000		0.000		0.00
305	0.00		0.00		0.00		0.0000		0.000		0.00
307	3.74	2759	0.10	36.8	0.01	0	0.0000	10.2	0.004	13.9	0.00
312	14.65	26743	3.92	185.5	0.26	0.1	0.0001	68.8	0.095	180.3	0.25
316	7.61	137049	10.43	35.9	0.03	0	0.0000	2.2	0.002	892.2	0.64

Table E 4. Measured Output from Commuter Lot B above Dry Pond (1995).

NOAA Date	Inflow (mm)	TSS (µg/L)	TSS (kg/ha)	NO3 (µg/L)	NO3 (kg)	NH4 (µg/L)	NH4 (kg)	PO4 (µg/L)	PO4 (kg)	TKN (µg/L)	TKN (kg)
231	41.08	291646	119.81	2344.6	9.054	141	0.544	148.9	0.575	2584	9.98
240	9.85	875	0.09	132	0.122	6.1	0.006	0	0.000	121.6	0.11
257	2.50	10325	0.26	362.3	0.085	59	0.014	0	0.000	444.7	0.10
260	25.00	16580	4.14	809.5	1.902	28.9	0.068	4	0.009	791.9	1.86
266	0.17	556	0.00	24.9	0.000	0.2	0.000	0	0.000	38.9	0.00
268	0.12	328	0.00	6.9	0.000	0	0.000	0	0.000	11.4	0.00
270	3.20	11213	0.36	190.6	0.057	22.1	0.007	0	0.000	253.4	0.08
278	34.57	131126	45.34	679.5	2.208	27.6	0.090	33.6	0.109	4029.7	13.10
287	5.47	10025	0.55	125.5	0.065	6.7	0.003	1.2	0.001	122.6	0.06
294	14.98	24234	3.63	456.2	0.642	35.5	0.050	0	0.000	284.2	0.40
301	0.94	3484	0.03	59	0.005	1.3	0.000	0.5	0.000	12	0.00
305	0.47	1053	0.00	10.9	0.000	0	0.000	0.4	0.000	0	0.00
307	4.38	11351	0.50	72.9	0.030	11	0.005	2.4	0.001	115.9	0.05
312	18.62	26375	4.91	285.7	0.500	4.9	0.009	2.4	0.004	690.6	1.21
316	7.85	47584	3.74	87.5	0.065	0.4	0.000	10.1	0.007	772.6	0.57

Answers.inp file for the QVA evaluation:

```
  QVA Watershed - with rec fields
METRIC  UNITS ARE USED ON INPUT/OUTPUT                  PRINT
STORM BY STORM OUTPUT = 1
EXTRA OUTPUT ON DAYS  =
PRINT HYDROGRAPHS = 01
RAINFALL DATA FOR 1 RAINGAGES
BEGINNING JULIAN DAY OF SIMULATION 001 1999
DURATION OF SIMULATION DAYS 0365
GAUGE NUMBER    1
 SIMULATION CONSTANTS FOLLOW
NUMBER OF LINES OF HYDROGRAPH OUTPUT =0101
TIME INCREMENT =030.0 SECONDS
INFILTRATION CAPACITY CALCULATED EVERY00030 SECONDS
EXPECTED RUNOFF PEAK =0150.00 MM/HR
 SOIL INFILTRATION, DRAINAGE AND GROUNDWATER CONSTANTS FOLLOW
NUMBER OF SOILS =0014
NO. URBAN SOILS =0001
Urbsoil=1 020.0000004.0000000.0500
S02, TP =.53, FP =.72, FC =00.36, A =1.000, DF =177.8, ASM =.72
CONDUCTIVITY OPTION = 0
22.5 28.1 41.9 3.00 00.1 18.1
S03, TP =.53, FP =.72, FC =00.36, A =1.000, DF =177.8, ASM =.72
CONDUCTIVITY OPTION = 0
22.5 28.1 41.9 3.00 00.1 18.1
S04, TP =.48, FP =.83, FC =00.42, A =1.000, DF =254.0, ASM =.83
CONDUCTIVITY OPTION = 0
20.0 23.8 43.7 1.50 02.5 18.8
S05, TP =.48, FP =.83, FC =00.42, A =1.000, DF =254.0, ASM =.83
CONDUCTIVITY OPTION = 0
20.0 23.8 43.7 1.50 02.5 18.8
S06, TP =.47, FP =.66, FC =00.33, A =1.000, DF =254.0, ASM =.66
CONDUCTIVITY OPTION = 0
17.0 40.5 30.0 1.50 02.5 13.0
S07, TP =.47, FP =.66, FC =00.33, A =1.000, DF =254.0, ASM =.66
CONDUCTIVITY OPTION = 0
17.0 40.5 30.0 1.50 02.5 13.0
S08, TP =.47, FP =.66, FC =00.33, A =1.000, DF =254.0, ASM =.66
CONDUCTIVITY OPTION = 0
17.0 40.5 30.0 1.50 02.5 13.0
S09, TP =.47, FP =.66, FC =00.33, A =1.000, DF =254.0, ASM =.66
CONDUCTIVITY OPTION = 0
17.0 40.5 30.0 1.50 02.5 13.0
S10, TP =.47, FP =.66, FC =00.33, A =1.000, DF =254.0, ASM =.66
CONDUCTIVITY OPTION = 0
17.0 40.5 30.0 1.50 02.5 13.0
S11, TP =.47, FP =.66, FC =00.33, A =1.000, DF =254.0, ASM =.66
CONDUCTIVITY OPTION = 0
17.0 40.5 30.0 1.50 02.5 13.0
S12, TP =.39, FP =.96, FC =00.50, A =1.000, DF =228.6, ASM =.99
CONDUCTIVITY OPTION = 0
24.5 36.7 38.8 2.50 00.1 16.7
S13, TP =.39, FP =.50, FC =00.33, A =1.000, DF =254.0, ASM =.66
CONDUCTIVITY OPTION = 0
24.5 16.7 58.8 2.50 05.0 16.7
S14, TP =.39, FP =.50, FC =00.33, A =1.000, DF =254.0, ASM =.66
CONDUCTIVITY OPTION = 0
24.5 16.7 58.8 2.50 05.0 16.7
 PARTICLE SIZE AND TRANSPORT DATA FOLLOWS
NUMBER OF PARTICLE SIZE CLASSES  = 05
NUMBER OF WASH LOAD CLASSES      = 01
  SIZE      SPECIFIC GRAVITY  FALL VELOCITY
000000.0020000000000000002.6500000000.0000030
```

```
000000.0100000000000000002.6500000000.0000800
000000.2000000000000000002.6400000000.0240000
000000.0300000000000000001.8000000000.0003500
000000.5000000000000000001.6000000000.0400000
00.00000.00100.00000.00000.000 S01
00.22500.41900.28100.18100.001 S02
00.22500.41900.28100.18100.001 S03
00.20000.43700.23800.18800.025 S04
00.20000.43700.23800.18800.025 S05
00.17000.30000.40500.13000.025 S06
00.17000.30000.40500.13000.025 S07
00.17000.30000.40500.13000.025 S08
00.17000.30000.40500.13000.025 S09
00.17000.30000.40500.13000.025 S10
00.17000.30000.40500.13000.025 S11
00.24500.38800.36700.16700.001 S12
00.24500.38800.36700.16700.001 S13
00.24500.58800.16700.16700.050 S14
006.1901020.0000004.0000000.0500
006.1901020.0000004.0000000.0500
005.7599020.0000004.0000000.0500
005.7599020.0000004.0000000.0500
004.6203020.0000004.0000000.0500
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006.4704020.0000004.0000000.0500
007.2604020.0000004.0000000.0500
DRAINAGE EXPONENT =03
DRAINAGE COEFFICIENT FOR TILE DRAINS =09.55 MM/24HR
GROUNDWATER RELEASE FRACTION =000000.005
FERTILIZER APPLIED =01
IRRIGATION APPLIED =00
 IMPOUNDMENT SPECIFICATIONS FOLLOW
NUMBER OF IMPOUNDMENTS = 00
 SURFACE ROUGHNESS AND CROP CONSTANTS FOLLOWS
NUMBER OF CROPS AND SURFACES =008
NUMBER OF URBAN 'CROP' TYPES =003
C01,       urbroad,     00.00      0.00     1.00    000.20    0.200
000.3 0.013 0.013 06.70
Spring80.80 00.00 00.10 00.00 00.13 00.01 00.00 80.00
Summer80.80 00.00 00.10 00.00 01.00 00.01 00.00 80.00
Winter80.80 00.00 00.10 00.00 01.40 00.01 00.00 80.00
Fall  80.80 00.00 00.10 00.00 02.80 00.01 00.00 80.00
C02,       urbhous,     00.00      0.00     0.60    000.20    0.200
000.3 0.013 0.013 00.00
Spring80.80 00.00 00.10 00.00 00.13 00.01 00.00 80.00
Summer80.80 00.00 00.10 00.00 01.00 00.01 00.00 80.00
Winter80.80 00.00 00.10 00.00 01.40 00.01 00.00 80.00
Fall  80.80 00.00 00.10 00.00 02.80 00.01 00.00 80.00
C03,       urbside,     00.20      0.20     0.60    000.20    0.200
000.3 0.012 0.012 01.00
Spring80.80 00.00 00.10 00.00 00.13 00.01 00.00 80.00
Summer80.80 00.00 00.10 00.00 01.00 00.01 00.00 80.00
Winter80.80 00.00 00.10 00.00 01.40 00.01 00.00 80.00
Fall  80.80 00.00 00.10 00.00 02.80 00.01 00.00 80.00
C04,      Pasture ,     00.40      0.96     0.65    003.00    0.300
095.0 005.0 000.8 008.0 002.0 085.0 0.07 0.07 0.04
0.00 0.70 1.80 3.00 3.00 3.00 2.90 2.70 1.96 0.90 0.50
001 365 0.00 00.000 00.00 00000.0 100 3.00
```

```
 012.0 0.085 0.070 00.50 01.00 0.050 0.050 00 00
 Spring60.60 00.01 00.10 00.00 00.13 00.01 00.00 00.00
 Summer60.60 00.01 00.10 00.00 01.00 00.01 00.00 12.00
 Winter60.60 00.01 00.10 00.00 01.40 00.01 00.00 24.00
 Fall  60.60 00.01 00.10 00.00 02.80 00.01 00.00 36.00
 C05,      Forest  ,     02.00      0.95     0.65    003.00    0.300
 095.0 005.0 000.8 010.0 002.0 095.0 0.25 0.20 0.13
 2.50 2.50 4.50 4.50 4.50 4.50 4.50 4.50 4.50 2.50 2.50
 001 365 1.30 -0.264 02.50 09400.0 900 4.50
 012.0 0.000 3.000 00.50 01.00 0.050 0.200 00 00
 Spring60.60 00.01 00.10 00.00 00.13 00.01 00.00 00.00
 Summer60.60 00.01 00.10 00.00 01.00 00.01 00.00 12.00
 Winter60.60 00.01 00.10 00.00 01.40 00.01 00.00 24.00
 Fall  60.60 00.01 00.10 00.00 02.80 00.01 00.00 36.00
 C06,      fal1    ,     00.01      0.10     0.65    003.00    0.300
 002.0 098.0 005.0 100.0 000.0 000.0 0.05 0.05 0.02
 0.00 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01
 001 365 0.00 00.000 00.00 00000.0 000 0.01
 012.0 0.050 0.000 00.01 01.00 0.050 0.080 00 00
 Spring60.60 00.01 00.10 00.00 00.13 00.01 00.00 00.00
 Summer60.60 00.01 00.10 00.00 01.00 00.01 00.00 12.00
 Winter60.60 00.01 00.10 00.00 01.40 00.01 00.00 24.00
 Fall  60.60 00.01 00.10 00.00 02.80 00.01 00.00 36.00
 C07,      fal2    ,     00.01      0.01     0.45    003.00    0.300
 000.1 099.9 005.0 100.0 000.0 000.0 0.00 0.00 0.00
 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
 001 365 0.00 00.000 00.00 00000.0 000 0.01
 012.0 0.050 0.000 00.01 01.00 0.050 0.080 00 00
 Spring60.60 00.01 00.10 00.00 00.13 00.01 00.00 00.00
 Summer60.60 00.01 00.10 00.00 01.00 00.01 00.00 12.00
 Winter60.60 00.01 00.10 00.00 01.40 00.01 00.00 24.00
 Fall  60.60 00.01 00.10 00.00 02.80 00.01 00.00 36.00
 C08,      badturf ,     00.60      0.80     0.55    050.00    3.000
 080.0 020.0 000.8 008.0 002.0 085.0 0.10 0.05 0.03
 0.50 0.70 1.80 2.50 2.50 2.50 2.50 2.50 1.80 0.70 0.50
 001 365 0.55 50.000 03.00 00070.0 300 2.50
 010.0 0.200 0.030 00.50 01.00 0.040 0.050 00 00
 Spring60.60 00.01 00.10 00.00 00.13 00.01 00.00 00.00
 Summer60.60 00.01 00.10 00.00 01.00 00.01 00.00 12.00
 Winter60.60 00.01 00.10 00.00 01.40 00.01 00.00 24.00
 Fall  60.60 00.01 00.10 00.00 02.80 00.01 00.00 36.00
 NUMBER OF ALL ROTATIONS      =008
 01 01 1999365
***lines removed
 02 02 1999365
***lines removed
 03 03 1999365
***lines removed
 04 04 1999365
***lines removed
 05 05 1999365
***lines removed
 06 06 1999365
***lines removed
 07 07 1999365
***lines removed
 08 08 1999365
***lines removed

  CHANNEL SPECIFICATIONS FOLLOW
 NUMBER OF CHANNEL NETWORKS  =001
 NUMBER OF TYPES OF CHANNELS =002
 CHAN01 WID =00.5(m),  SOIL N =00.050 CHAN N =00.100 0.07 0.05
```

```
 CHAN02 WID =02.0(m),  SOIL N =00.050 CHAN N =00.100 0.07 0.75
  ELEMENT SPECIFICATIONS FOR BASELINE SENSITIVITY ANALYSIS
 EACH ELEMENT IS0015.00m. SQUARE
 NETWORK 1 OUTFLOW FROM ROW0076 COLUMN 0069     06457
 18131 0 13  45      13   5    1  0     0  0   0   0    4610   46  184    4
  262    6  808    31 0 0     0 0
 18132 0 13 315      13   5    1  0     0  0   0   0    4610   46  184    4
  262    6  808    31 0 0     0 0
 18133 0 27 211      13   5    1  0     0  0   0   0    4610   46  184    4
  262    6  808    31 0 0     0 0
 18134 0 24 192      13   5    1  0     0  0   0   0    4610   46  184    4
  262    6  808    31 0 0     0 0
 19131 0 30  19       1   1    1  0     0  0   0   0    4610   46  184    4
  262    6  808    31 1 0     0 0.
.
.
.
```

etc. for the remaining 6452 cells

Fertilizer.inp file for QVA evaluation:

```
FERTILIZER INPUTS FOR ANSWERS SIMULATION
 YEAR|DAY|CROP#|---NO3---|---NH4---|---PO4---|
 1998 090   6       0.       39.5      59.9
 1998 196   6       0.0      39.5      59.9
 1999 090   6       0.       39.5      59.9
 1999 196   6       0.0      39.5      59.9
 2000 090   6       0.       39.5      59.9
 2000 196   6       0.0      39.5      59.9
```

Weather.inp file for QVA evaluation:

```
   -6   -6  336 0        1  1- 1-1999
   -6   -6  336 0        2  1- 2-1999
   -4   -4  336 1        3  1- 3-1999
 GAUGE NUMBER    1
0      0.      0.00
0     26.     21.07
0     52.     11.36
0     78.      6.12
0    104.      3.30
0    130.      1.78
0    156.      0.96
0    182.      0.52
0    208.      0.28
0    234.      0.33
1    334.      0.00
   -4   -4  336 0        4  1- 4-1999
   -9   -9  336 0        5  1- 5-1999
  -12  -12  336 0        6  1- 6-1999
   -6   -6  336 1        7  1- 7-1999
 GAUGE NUMBER    1
0      0.      0.00
0     25.      1.22
1    125.      0.00
    0    0  336 0        8  1- 8-1999
```

```
    3    3  336 1        9  1- 9-1999
  GAUGE NUMBER    1
0      0.      0.00
0     36.      1.17
0     72.      1.17
0    108.      1.17
0    144.      4.02
0    180.      0.50
1    280.      0.00
   -1   -1  336 0       10  1-10-1999
   -6   -6  336 0       11  1-11-1999
    0    0  336 0       12  1-12-1999
    4    4  336 0       13  1-13-1999
    7    7  336 1       14  1-14-1999
  GAUGE NUMBER    1
0      0.      0.00
0     50.      0.50
0    100.     22.63
0    150.      1.76
0    200.      1.76
0    250.      1.76
0    300.      1.76
1    400.      0.00
    3    3  336 0       15  1-15-1999
   -2   -2  336 0       16  1-16-1999
    4    4  336 1       17  1-17-1999
  GAUGE NUMBER    1
0      0.      0.00
0     40.      0.89
0     80.      0.89
0    120.      0.89
1    220.      0.00
    2    2  336 1       18  1-18-1999
  GAUGE NUMBER    1
0      0.      0.00
0     40.      0.63
0     80.      0.63
0    120.      0.63
1    220.      0.00
    7    7  336 0       19  1-19-1999
    4    4  336 0       20  1-20-1999
    4    4  336 0       21  1-21-1999
    6    6  336 0       22  1-22-1999
   11   11  336 1       23  1-23-1999
  GAUGE NUMBER    1
0      0.      0.00
0     50.      0.50
0    100.     22.63
0    150.      1.76
0    200.      1.76
0    250.      1.76
0    300.      1.76
1    400.      0.00
   14   14  336 1       24  1-24-1999
  GAUGE NUMBER    1
0      0.      0.00
0     23.      0.50
0     46.     19.38
0     69.      0.85
0     92.      0.85
0    115.      0.85
0    138.      0.85
0    161.      0.85
```

```
0    184.       0.85
0    207.       0.85
1    307.       0.00
    3    3  336 0       25  1-25-1999
    4    4  336 0       26  1-26-1999
    3    3  336 0       27  1-27-1999
    8    8  336 0       28  1-28-1999
   12   12  336 0       29  1-29-1999
    5    5  336 0       30  1-30-1999
    6    6  336 0       31  1-31-1999
   -1   -1  387 1       32  2- 1-1999
 GAUGE NUMBER    1
0      0.       0.00
0    120.       0.50
0    240.       5.91
0    360.       1.47
1    460.       0.00
   -1   -1  387 1       33  2- 2-1999
 GAUGE NUMBER    1
0      0.       0.00
0     25.       1.22
1    125.       0.00
    7    7  387 0       34  2- 3-1999
    7    7  387 0       35  2- 4-1999
    5    5  387 0       36  2- 5-1999
    6    6  387 0       37  2- 6-1999
    7    7  387 1       38  2- 7-1999
 GAUGE NUMBER    1
0      0.       0.00
0     36.       1.31
0     72.       1.31
0    108.       1.31
0    144.       4.44
0    180.       0.50
1    280.       0.00
    8    8  387 0       39  2- 8-1999
    4    4  387 0       40  2- 9-1999
    6    6  387 0       41  2-10-1999
    8    8  387 0       42  2-11-1999
    9    9  387 1       43  2-12-1999
 GAUGE NUMBER    1
0      0.       0.00
0     36.       0.47
0     72.       0.47
0    108.       0.47
0    144.       1.91
0    180.       0.50
1    280.       0.00
    7    7  387 0       44  2-13-1999
   -6   -6  387 0       45  2-14-1999
   -3   -3  387 0       46  2-15-1999
    3    3  387 0       47  2-16-1999
    4    4  387 1       48  2-17-1999
 GAUGE NUMBER    1
0      0.       0.00
0     40.       0.76
0     80.       0.76
0    120.       0.76
1    220.       0.00
    9    9  387 1       49  2-18-1999
 GAUGE NUMBER    1
0      0.       0.00
0     26.      21.88
```

```
0      52.     11.80
0      78.      6.36
0     104.      3.43
0     130.      1.85
0     156.      1.00
0     182.      0.54
0     208.      0.29
0     234.      0.34
1     334.      0.00
    4    4  387 1       50  2-19-1999
 GAUGE NUMBER    1
0       0.      0.00
0      36.      0.47
0      72.      0.47
0     108.      0.47
0     144.      1.91
0     180.      0.50
1     280.      0.00
   -1   -1  387 0       51  2-20-1999
   -1   -1  387 0       52  2-21-1999
   -5   -5  387 0       53  2-22-1999
   -4   -4  387 0       54  2-23-1999
   -6   -6  387 1       55  2-24-1999
 GAUGE NUMBER    1
0       0.      0.00
0      40.      0.63
0      80.      0.63
0     120.      0.63
1     220.      0.00
   -3   -3  387 1       56  2-25-1999
 GAUGE NUMBER    1
0       0.      0.00
0      40.      0.89
0      80.      0.89
0     120.      0.89
1     220.      0.00
   -1   -1  387 0       57  2-26-1999
    1    1  387 0       58  2-27-1999
    4    4  387 1       59  2-28-1999
 GAUGE NUMBER    1
0       0.      0.00
0      36.      1.88
0      72.      1.88
0     108.      1.88
0     144.      6.14
0     180.      0.50
1     280.      0.00
    6    6  422 0       60  3- 1-1999
    2    2  422 0       61  3- 2-1999
    8    8  422 1       62  3- 3-1999
 GAUGE NUMBER    1
0       0.      0.00
0      23.      0.50
0      46.     18.88
0      69.      0.83
0      92.      0.83
0     115.      0.83
0     138.      0.83
0     161.      0.83
0     184.      0.83
0     207.      0.83
1     307.      0.00
    3    3  422 1       63  3- 4-1999
```

```
 GAUGE NUMBER    1
0      0.      0.00
0     40.      0.38
0     80.      0.38
0    120.      0.38
1    220.      0.00
   -4   -4  422 0       64  3- 5-1999
    1    1  422 1       65  3- 6-1999
 GAUGE NUMBER    1
0      0.      0.00
0     25.      1.22
1    125.      0.00
    3    3  422 0       66  3- 7-1999
   -5   -5  422 0       67  3- 8-1999
   -3   -3  422 1       68  3- 9-1999
 GAUGE NUMBER    1
0      0.      0.00
0     36.      0.40
0     72.      0.40
0    108.      0.40
0    144.      1.69
0    180.      0.50
1    280.      0.00
   -2   -2  422 1       69  3-10-1999
 GAUGE NUMBER    1
0      0.      0.00
0     36.      0.75
0     72.      0.75
0    108.      0.75
0    144.      2.75
0    180.      0.50
1    280.      0.00
   -2   -2  422 0       70  3-11-1999
   -2   -2  422 0       71  3-12-1999
    0    0  422 0       72  3-13-1999
    1    1  422 1       73  3-14-1999
 GAUGE NUMBER    1
0      0.      0.00
0    120.      0.50
0    240.      5.05
0    360.      1.18
1    460.      0.00
   -1   -1  422 1       74  3-15-1999
 GAUGE NUMBER    1
0      0.      0.00
0    120.      0.50
0    240.      4.95
0    360.      1.15
1    460.      0.00
    0    0  422 0       75  3-16-1999
    4    4  422 0       76  3-17-1999
   12   12  422 0       77  3-18-1999
    9    9  422 0       78  3-19-1999
    4    4  422 0       79  3-20-1999
    6    6  422 1       80  3-21-1999
 GAUGE NUMBER    1
0      0.      0.00
0    120.      0.50
0    240.      6.00
0    360.      1.50
1    460.      0.00
    4    4  422 0       81  3-22-1999
    2    2  422 0       82  3-23-1999
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    7    7  422 1       83  3-24-1999
 GAUGE NUMBER    1
0      0.      0.00
0     36.      0.61
0     72.      0.61
0    108.      0.61
0    144.      2.33
0    180.      0.50
1    280.      0.00
    7    7  422 0       84  3-25-1999
    6    6  422 0       85  3-26-1999
    3    3  422 0       86  3-27-1999
    4    4  422 0       87  3-28-1999
    9    9  422 0       88  3-29-1999
    7    7  422 0       89  3-30-1999
    7    7  422 0       90  3-31-1999
    8    8  439 1       91  4- 1-1999
 GAUGE NUMBER    1
0      0.      0.00
0     23.      0.50
0     46.     24.85
0     69.      1.11
0     92.      1.11
0    115.      1.11
0    138.      1.11
0    161.      1.11
0    184.      1.11
0    207.      1.11
1    307.      0.00
   12   12  439 0       92  4- 2-1999
   15   15  439 0       93  4- 3-1999
   17   17  439 0       94  4- 4-1999
   17   17  439 0       95  4- 5-1999
   12   12  439 0       96  4- 6-1999
   13   13  439 0       97  4- 7-1999
   13   13  439 0       98  4- 8-1999
   16   16  439 1       99  4- 9-1999
 GAUGE NUMBER    1
0      0.      0.00
0     36.      0.47
0     72.      0.47
0    108.      0.47
0    144.      1.91
0    180.      0.50
1    280.      0.00
   19   19  439 0      100  4-10-1999
   16   16  439 1      101  4-11-1999
 GAUGE NUMBER    1
0      0.      0.00
0     50.      0.50
0    100.     21.03
0    150.      1.63
0    200.      1.63
0    250.      1.63
0    300.      1.63
1    400.      0.00
   16   16  439 0      102  4-12-1999
    7    7  439 0      103  4-13-1999
    7    7  439 0      104  4-14-1999
   10   10  439 1      105  4-15-1999
 GAUGE NUMBER    1
0      0.      0.00
0     23.      0.50
```

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0     46.     21.37
0     69.      0.95
0     92.      0.95
0    115.      0.95
0    138.      0.95
0    161.      0.95
0    184.      0.95
0    207.      0.95
1    307.      0.00
    8    8  439 0       106  4-16-1999
    8    8  439 0       107  4-17-1999
    7    7  439 0       108  4-18-1999
    6    6  439 1       109  4-19-1999
  GAUGE NUMBER    1
0      0.      0.00
0     40.      0.63
0     80.      0.63
0    120.      0.63
1    220.      0.00
    8    8  439 1       110  4-20-1999
  GAUGE NUMBER    1
0      0.      0.00
0     36.      0.47
0     72.      0.47
0    108.      0.47
0    144.      1.91
0    180.      0.50
1    280.      0.00
    9    9  439 0       111  4-21-1999
   13   13  439 0       112  4-22-1999
   17   17  439 0       113  4-23-1999
   18   18  439 0       114  4-24-1999
    9    9  439 0       115  4-25-1999
   11   11  439 1       116  4-26-1999
  GAUGE NUMBER    1
0      0.      0.00
0     36.      1.81
0     72.      1.81
0    108.      1.81
0    144.      5.93
0    180.      0.50
1    280.      0.00
   11   11  439 1       117  4-27-1999
  GAUGE NUMBER    1
0      0.      0.00
0     36.      0.61
0     72.      0.61
0    108.      0.61
0    144.      2.33
0    180.      0.50
1    280.      0.00
   13   13  439 1       118  4-28-1999
  GAUGE NUMBER    1
0      0.      0.00
0     23.      0.50
0     46.     16.90
0     69.      0.73
0     92.      0.73
0    115.      0.73
0    138.      0.73
0    161.      0.73
0    184.      0.73
0    207.      0.73
```

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1    307.      0.00
    8    8  439 0      119  4-29-1999
    7    7  439 0      120  4-30-1999
   10   10  422 0      121  5- 1-1999
   11   11  422 0      122  5- 2-1999
   11   11  422 0      123  5- 3-1999
   12   12  422 0      124  5- 4-1999
   14   14  422 0      125  5- 5-1999
   16   16  422 0      126  5- 6-1999
   17   17  422 1      127  5- 7-1999
 GAUGE NUMBER    1
0      0.      0.00
0     23.      0.50
0     46.     20.87
0     69.      0.92
0     92.      0.92
0    115.      0.92
0    138.      0.92
0    161.      0.92
0    184.      0.92
0    207.      0.92
1    307.      0.00
   17   17  422 1      128  5- 8-1999
 GAUGE NUMBER    1
0      0.      0.00
0     40.      0.89
0     80.      0.89
0    120.      0.89
1    220.      0.00
   13   13  422 0      129  5- 9-1999
   14   14  422 0      130  5-10-1999
   16   16  422 0      131  5-11-1999
   16   16  422 0      132  5-12-1999
   18   18  422 1      133  5-13-1999
 GAUGE NUMBER    1
0      0.      0.00
0     36.      1.10
0     72.      1.10
0    108.      1.10
0    144.      3.81
0    180.      0.50
1    280.      0.00
   17   17  422 1      134  5-14-1999
 GAUGE NUMBER    1
0      0.      0.00
0     26.     21.07
0     52.     11.36
0     78.      6.12
0    104.      3.30
0    130.      1.78
0    156.      0.96
0    182.      0.52
0    208.      0.28
0    234.      0.33
1    334.      0.00
    9    9  422 0      135  5-15-1999
   12   12  422 0      136  5-16-1999
   13   13  422 0      137  5-17-1999
   17   17  422 1      138  5-18-1999
 GAUGE NUMBER    1
0      0.      0.00
0     50.      0.50
0    100.     24.46
```

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0    150.      1.91
0    200.      1.91
0    250.      1.91
0    300.      1.91
1    400.      0.00
   18   18  422 0      139  5-19-1999
   13   13  422 0      140  5-20-1999
   14   14  422 0      141  5-21-1999
   16   16  422 0      142  5-22-1999
   17   17  422 0      143  5-23-1999
   19   19  422 1      144  5-24-1999
 GAUGE NUMBER    1
0      0.      0.00
0     36.      1.03
0     72.      1.03
0    108.      1.03
0    144.      3.60
0    180.      0.50
1    280.      0.00
   12   12  422 0      145  5-25-1999
   14   14  422 0      146  5-26-1999
   14   14  422 0      147  5-27-1999
   14   14  422 0      148  5-28-1999
   16   16  422 0      149  5-29-1999
   18   18  422 0      150  5-30-1999
   19   19  422 0      151  5-31-1999
   19   19  413 0      152  6- 1-1999
   20   20  413 1      153  6- 2-1999
 GAUGE NUMBER    1
0      0.      0.00
0     36.      0.89
0     72.      0.89
0    108.      0.89
0    144.      3.18
0    180.      0.50
1    280.      0.00
   21   21  413 0      154  6- 3-1999
   18   18  413 0      155  6- 4-1999
   18   18  413 0      156  6- 5-1999
   17   17  413 0      157  6- 6-1999
   19   19  413 0      158  6- 7-1999
   21   21  413 0      159  6- 8-1999
   22   22  413 0      160  6- 9-1999
   23   23  413 0      161  6-10-1999
   23   23  413 0      162  6-11-1999
   19   19  413 0      163  6-12-1999
   21   21  413 0      164  6-13-1999
   21   21  413 0      165  6-14-1999
   23   23  413 0      166  6-15-1999
   19   19  413 1      167  6-16-1999
 GAUGE NUMBER    1
0      0.      0.00
0     36.      1.60
0     72.      1.60
0    108.      1.60
0    144.      5.29
0    180.      0.50
1    280.      0.00
   16   16  413 1      168  6-17-1999
 GAUGE NUMBER    1
0      0.      0.00
0     36.      1.88
0     72.      1.88
```

```
0    108.      1.88
0    144.      6.14
0    180.      0.50
1    280.      0.00
   14   14  413 0       169  6-18-1999
   14   14  413 0       170  6-19-1999
   14   14  413 1       171  6-20-1999
 GAUGE NUMBER    1
0      0.      0.00
0     36.      0.61
0     72.      0.61
0    108.      0.61
0    144.      2.33
0    180.      0.50
1    280.      0.00
   15   15  413 1       172  6-21-1999
 GAUGE NUMBER    1
0      0.      0.00
0     36.      1.67
0     72.      1.67
0    108.      1.67
0    144.      5.50
0    180.      0.50
1    280.      0.00
   18   18  413 0       173  6-22-1999
   16   16  413 0       174  6-23-1999
   18   18  413 1       175  6-24-1999
 GAUGE NUMBER    1
0      0.      0.00
0     40.      0.38
0     80.      0.38
0    120.      0.38
1    220.      0.00
   19   19  413 1       176  6-25-1999
 GAUGE NUMBER    1
0      0.      0.00
0     25.      1.22
1    125.      0.00
   19   19  413 0       177  6-26-1999
   23   23  413 1       178  6-27-1999
 GAUGE NUMBER    1
0      0.      0.00
0     25.      1.22
1    125.      0.00
   25   25  413 1       179  6-28-1999
 GAUGE NUMBER    1
0      0.      0.00
0     36.      0.96
0     72.      0.96
0    108.      0.96
0    144.      3.39
0    180.      0.50
1    280.      0.00
   26   26  413 0       180  6-29-1999
   24   24  413 0       181  6-30-1999
   23   23  413 1       182  7- 1-1999
 GAUGE NUMBER    1
0      0.      0.00
0     36.      0.96
0     72.      0.96
0    108.      0.96
0    144.      3.39
0    180.      0.50
```

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1    280.      0.00
   23   23  413 1      183  7- 2-1999
  GAUGE NUMBER    1
0      0.      0.00
0     25.      1.22
1    125.      0.00
   23   23  413 1      184  7- 3-1999
  GAUGE NUMBER    1
0      0.      0.00
0     36.      1.60
0     72.      1.60
0    108.      1.60
0    144.      5.29
0    180.      0.50
1    280.      0.00
   25   25  413 0      185  7- 4-1999
   26   26  413 0      186  7- 5-1999
   27   27  413 0      187  7- 6-1999
   27   27  413 1      188  7- 7-1999
  GAUGE NUMBER    1
0      0.      0.00
0     36.      1.17
0     72.      1.17
0    108.      1.17
0    144.      4.02
0    180.      0.50
1    280.      0.00
   26   26  413 0      189  7- 8-1999
   23   23  413 0      190  7- 9-1999
   24   24  413 1      191  7-10-1999
  GAUGE NUMBER    1
0      0.      0.00
0     36.      1.24
0     72.      1.24
0    108.      1.24
0    144.      4.23
0    180.      0.50
1    280.      0.00
   24   24  413 1      192  7-11-1999
  GAUGE NUMBER    1
0      0.      0.00
0     23.      0.50
0     46.     15.41
0     69.      0.66
0     92.      0.66
0    115.      0.66
0    138.      0.66
0    161.      0.66
0    184.      0.66
0    207.      0.66
1    307.      0.00
   18   18  413 1      193  7-12-1999
  GAUGE NUMBER    1
0      0.      0.00
0     50.      0.50
0    100.     36.58
0    150.      2.92
0    200.      2.92
0    250.      2.92
0    300.      2.92
1    400.      0.00
   14   14  413 0      194  7-13-1999
   16   16  413 0      195  7-14-1999
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   19   19  413 0       196  7-15-1999
   23   23  413 0       197  7-16-1999
   23   23  413 0       198  7-17-1999
   23   23  413 1       199  7-18-1999
  GAUGE NUMBER    1
0      0.      0.00
0     36.      1.46
0     72.      1.46
0    108.      1.46
0    144.      4.87
0    180.      0.50
1    280.      0.00
   23   23  413 0       200  7-19-1999
   23   23  413 0       201  7-20-1999
   22   22  413 0       202  7-21-1999
   24   24  413 0       203  7-22-1999
   27   27  413 0       204  7-23-1999
   27   27  413 1       205  7-24-1999
  GAUGE NUMBER    1
0      0.      0.00
0     40.      0.76
0     80.      0.76
0    120.      0.76
1    220.      0.00
   24   24  413 0       206  7-25-1999
   23   23  413 0       207  7-26-1999
   24   24  413 0       208  7-27-1999
   23   23  413 1       209  7-28-1999
  GAUGE NUMBER    1
0      0.      0.00
0     50.      0.50
0    100.     21.95
0    150.      1.70
0    200.      1.70
0    250.      1.70
0    300.      1.70
1    400.      0.00
   23   23  413 1       210  7-29-1999
  GAUGE NUMBER    1
0      0.      0.00
0     36.      1.10
0     72.      1.10
0    108.      1.10
0    144.      3.81
0    180.      0.50
1    280.      0.00
   23   23  413 0       211  7-30-1999
   25   25  413 0       212  7-31-1999
   27   27  430 1       213  8- 1-1999
  GAUGE NUMBER    1
0      0.      0.00
0     23.      0.50
0     46.     18.39
0     69.      0.80
0     92.      0.80
0    115.      0.80
0    138.      0.80
0    161.      0.80
0    184.      0.80
0    207.      0.80
1    307.      0.00
   25   25  430 0       214  8- 2-1999
   21   21  430 0       215  8- 3-1999
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   21   21  430 0      216  8- 4-1999
   21   21  430 0      217  8- 5-1999
   21   21  430 0      218  8- 6-1999
   21   21  430 0      219  8- 7-1999
   22   22  430 1      220  8- 8-1999
 GAUGE NUMBER    1
0      0.      0.00
0     36.      0.61
0     72.      0.61
0    108.      0.61
0    144.      2.33
0    180.      0.50
1    280.      0.00
   23   23  430 0      221  8- 9-1999
   18   18  430 0      222  8-10-1999
   20   20  430 0      223  8-11-1999
   23   23  430 0      224  8-12-1999
   23   23  430 1      225  8-13-1999
 GAUGE NUMBER    1
0      0.      0.00
0     36.      1.95
0     72.      1.95
0    108.      1.95
0    144.      6.35
0    180.      0.50
1    280.      0.00
   24   24  430 1      226  8-14-1999
 GAUGE NUMBER    1
0      0.      0.00
0     25.      1.22
1    125.      0.00
   21   21  430 0      227  8-15-1999
   21   21  430 0      228  8-16-1999
   23   23  430 0      229  8-17-1999
   24   24  430 0      230  8-18-1999
   22   22  430 0      231  8-19-1999
   22   22  430 1      232  8-20-1999
 GAUGE NUMBER    1
0      0.      0.00
0     23.      0.50
0     46.     20.38
0     69.      0.90
0     92.      0.90
0    115.      0.90
0    138.      0.90
0    161.      0.90
0    184.      0.90
0    207.      0.90
1    307.      0.00
   19   19  430 0      233  8-21-1999
   18   18  430 0      234  8-22-1999
   19   19  430 1      235  8-23-1999
 GAUGE NUMBER    1
0      0.      0.00
0    120.      0.50
0    240.      6.67
0    360.      1.72
1    460.      0.00
   21   21  430 1      236  8-24-1999
 GAUGE NUMBER    1
0      0.      0.00
0     40.      0.76
0     80.      0.76
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0    120.      0.76
1    220.      0.00
   21   21  430 1      237  8-25-1999
 GAUGE NUMBER    1
0      0.      0.00
0     23.      0.50
0     46.     17.39
0     69.      0.76
0     92.      0.76
0    115.      0.76
0    138.      0.76
0    161.      0.76
0    184.      0.76
0    207.      0.76
1    307.      0.00
   21   21  430 1      238  8-26-1999
 GAUGE NUMBER    1
0      0.      0.00
0     26.     19.45
0     52.     10.49
0     78.      5.65
0    104.      3.05
0    130.      1.64
0    156.      0.89
0    182.      0.48
0    208.      0.26
0    234.      0.30
1    334.      0.00
   20   20  430 0      239  8-27-1999
   21   21  430 0      240  8-28-1999
   21   21  430 0      241  8-29-1999
   21   21  430 0      242  8-30-1999
   14   14  430 0      243  8-31-1999
   14   14  422 0      244  9- 1-1999
   17   17  422 0      245  9- 2-1999
   18   18  422 0      246  9- 3-1999
   19   19  422 1      247  9- 4-1999
 GAUGE NUMBER    1
0      0.      0.00
0     50.      0.50
0    100.     49.38
0    150.      3.99
0    200.      3.99
0    250.      3.99
0    300.      3.99
1    400.      0.00
   20   20  422 1      248  9- 5-1999
 GAUGE NUMBER    1
0      0.      0.00
0     36.      1.10
0     72.      1.10
0    108.      1.10
0    144.      3.81
0    180.      0.50
1    280.      0.00
   19   19  422 1      249  9- 6-1999
 GAUGE NUMBER    1
0      0.      0.00
0     40.      0.89
0     80.      0.89
0    120.      0.89
1    220.      0.00
   19   19  422 0      250  9- 7-1999
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   21   21  422 0       251  9- 8-1999
   21   21  422 0       252  9- 9-1999
   20   20  422 0       253  9-10-1999
   15   15  422 0       254  9-11-1999
   16   16  422 0       255  9-12-1999
   17   17  422 0       256  9-13-1999
   17   17  422 0       257  9-14-1999
   19   19  422 1       258  9-15-1999
  GAUGE NUMBER    1
0      0.      0.00
0     40.      0.89
0     80.      0.89
0    120.      0.89
1    220.      0.00
   16   16  422 0       259  9-16-1999
   14   14  422 0       260  9-17-1999
   12   12  422 0       261  9-18-1999
   13   13  422 0       262  9-19-1999
   14   14  422 1       263  9-20-1999
  GAUGE NUMBER    1
0      0.      0.00
0     50.      0.50
0    100.     23.32
0    150.      1.82
0    200.      1.82
0    250.      1.82
0    300.      1.82
1    400.      0.00
   17   17  422 1       264  9-21-1999
  GAUGE NUMBER    1
0      0.      0.00
0     40.      0.63
0     80.      0.63
0    120.      0.63
1    220.      0.00
   13   13  422 0       265  9-22-1999
    9    9  422 0       266  9-23-1999
   12   12  422 0       267  9-24-1999
   14   14  422 0       268  9-25-1999
   16   16  422 0       269  9-26-1999
   17   17  422 1       270  9-27-1999
  GAUGE NUMBER    1
0      0.      0.00
0     23.      0.50
0     46.     18.39
0     69.      0.80
0     92.      0.80
0    115.      0.80
0    138.      0.80
0    161.      0.80
0    184.      0.80
0    207.      0.80
1    307.      0.00
   19   19  422 1       271  9-28-1999
  GAUGE NUMBER    1
0      0.      0.00
0     36.      0.54
0     72.      0.54
0    108.      0.54
0    144.      2.12
0    180.      0.50
1    280.      0.00
   21   21  422 1       272  9-29-1999
```

```
 GAUGE NUMBER    1
0      0.      0.00
0     23.      0.50
0     46.     15.41
0     69.      0.66
0     92.      0.66
0    115.      0.66
0    138.      0.66
0    161.      0.66
0    184.      0.66
0    207.      0.66
1    307.      0.00
   16   16  422 0      273  9-30-1999
   10   10  422 0      274 10- 1-1999
   12   12  422 0      275 10- 2-1999
   13   13  422 0      276 10- 3-1999
   14   14  422 1      277 10- 4-1999
 GAUGE NUMBER    1
0      0.      0.00
0     23.      0.50
0     46.     15.41
0     69.      0.66
0     92.      0.66
0    115.      0.66
0    138.      0.66
0    161.      0.66
0    184.      0.66
0    207.      0.66
1    307.      0.00
   13   13  422 0      278 10- 5-1999
    8    8  422 0      279 10- 6-1999
   10   10  422 0      280 10- 7-1999
   11   11  422 0      281 10- 8-1999
   13   13  422 1      282 10- 9-1999
 GAUGE NUMBER    1
0      0.      0.00
0    120.      0.50
0    240.      5.72
0    360.      1.41
1    460.      0.00
   14   14  422 0      283 10-10-1999
   17   17  422 1      284 10-11-1999
 GAUGE NUMBER    1
0      0.      0.00
0     25.      1.22
1    125.      0.00
   17   17  422 0      285 10-12-1999
   14   14  422 0      286 10-13-1999
   13   13  422 0      287 10-14-1999
    9    9  422 0      288 10-15-1999
   10   10  422 0      289 10-16-1999
   13   13  422 0      290 10-17-1999
   14   14  422 0      291 10-18-1999
    9    9  422 1      292 10-19-1999
 GAUGE NUMBER    1
0      0.      0.00
0     23.      0.50
0     46.     19.38
0     69.      0.85
0     92.      0.85
0    115.      0.85
0    138.      0.85
0    161.      0.85
```

```
0    184.       0.85
0    207.       0.85
1    307.       0.00
   10   10  422 0       293 10-20-1999
    4    4  422 1       294 10-21-1999
 GAUGE NUMBER    1
0      0.       0.00
0     25.       1.22
1    125.       0.00
    7    7  422 0       295 10-22-1999
    8    8  422 0       296 10-23-1999
    4    4  422 0       297 10-24-1999
    3    3  422 0       298 10-25-1999
    7    7  422 0       299 10-26-1999
    9    9  422 0       300 10-27-1999
    8    8  422 0       301 10-28-1999
    9    9  422 0       302 10-29-1999
   12   12  422 0       303 10-30-1999
   13   13  422 0       304 10-31-1999
   14   14  353 0       305 11- 1-1999
   15   15  353 1       306 11- 2-1999
 GAUGE NUMBER    1
0      0.       0.00
0     23.       0.50
0     46.      20.38
0     69.       0.90
0     92.       0.90
0    115.       0.90
0    138.       0.90
0    161.       0.90
0    184.       0.90
0    207.       0.90
1    307.       0.00
   10   10  353 0       307 11- 3-1999
    0    0  353 0       308 11- 4-1999
    4    4  353 0       309 11- 5-1999
    7    7  353 0       310 11- 6-1999
   11   11  353 0       311 11- 7-1999
    7    7  353 0       312 11- 8-1999
   10   10  353 0       313 11- 9-1999
   12   12  353 0       314 11-10-1999
   14   14  353 1       315 11-11-1999
 GAUGE NUMBER    1
0      0.       0.00
0     25.       1.22
1    125.       0.00
   13   13  353 0       316 11-12-1999
    8    8  353 0       317 11-13-1999
   11   11  353 0       318 11-14-1999
   11   11  353 0       319 11-15-1999
    5    5  353 0       320 11-16-1999
    1    1  353 0       321 11-17-1999
    1    1  353 0       322 11-18-1999
    4    4  353 0       323 11-19-1999
    7    7  353 0       324 11-20-1999
   11   11  353 1       325 11-21-1999
 GAUGE NUMBER    1
0      0.       0.00
0     40.       0.38
0     80.       0.38
0    120.       0.38
1    220.       0.00
   12   12  353 0       326 11-22-1999
```

```
   14   14  353 0       327 11-23-1999
   14   14  353 0       328 11-24-1999
   16   16  353 1       329 11-25-1999
  GAUGE NUMBER    1
0      0.      0.00
0     36.      1.74
0     72.      1.74
0    108.      1.74
0    144.      5.72
0    180.      0.50
1    280.      0.00
   13   13  353 1       330 11-26-1999
  GAUGE NUMBER    1
0      0.      0.00
0     23.      0.50
0     46.     17.89
0     69.      0.78
0     92.      0.78
0    115.      0.78
0    138.      0.78
0    161.      0.78
0    184.      0.78
0    207.      0.78
1    307.      0.00
   10   10  353 0       331 11-27-1999
    8    8  353 0       332 11-28-1999
    6    6  353 0       333 11-29-1999
    2    2  353 0       334 11-30-1999
   -3   -3  310 0       335 12- 1-1999
   -2   -2  310 0       336 12- 2-1999
    3    3  310 0       337 12- 3-1999
    7    7  310 0       338 12- 4-1999
    8    8  310 0       339 12- 5-1999
    7    7  310 1       340 12- 6-1999
  GAUGE NUMBER    1
0      0.      0.00
0     36.      1.17
0     72.      1.17
0    108.      1.17
0    144.      4.02
0    180.      0.50
1    280.      0.00
    6    6  310 0       341 12- 7-1999
    1    1  310 0       342 12- 8-1999
    4    4  310 0       343 12- 9-1999
    5    5  310 1       344 12-10-1999
  GAUGE NUMBER    1
0      0.      0.00
0     23.      0.50
0     46.     20.87
0     69.      0.92
0     92.      0.92
0    115.      0.92
0    138.      0.92
0    161.      0.92
0    184.      0.92
0    207.      0.92
1    307.      0.00
    6    6  310 0       345 12-11-1999
    3    3  310 0       346 12-12-1999
    6    6  310 1       347 12-13-1999
  GAUGE NUMBER    1
0      0.      0.00
```

```
0     36.      1.81
0     72.      1.81
0    108.      1.81
0    144.      5.93
0    180.      0.50
1    280.      0.00
    7    7  310 1       348 12-14-1999
 GAUGE NUMBER    1
0      0.      0.00
0     23.      0.50
0     46.     24.35
0     69.      1.09
0     92.      1.09
0    115.      1.09
0    138.      1.09
0    161.      1.09
0    184.      1.09
0    207.      1.09
1    307.      0.00
    4    4  310 0       349 12-15-1999
    5    5  310 0       350 12-16-1999
    1    1  310 0       351 12-17-1999
    3    3  310 0       352 12-18-1999
    4    4  310 0       353 12-19-1999
    4    4  310 1       354 12-20-1999
 GAUGE NUMBER    1
0      0.      0.00
0     36.      0.89
0     72.      0.89
0    108.      0.89
0    144.      3.18
0    180.      0.50
1    280.      0.00
    6    6  310 1       355 12-21-1999
 GAUGE NUMBER    1
0      0.      0.00
0     36.      0.68
0     72.      0.68
0    108.      0.68
0    144.      2.54
0    180.      0.50
1    280.      0.00
    2    2  310 1       356 12-22-1999
 GAUGE NUMBER    1
0      0.      0.00
0     25.      1.22
1    125.      0.00
   -3   -3  310 0       357 12-23-1999
   -1   -1  310 0       358 12-24-1999
   -6   -6  310 0       359 12-25-1999
   -8   -8  310 0       360 12-26-1999
    2    2  310 0       361 12-27-1999
   -1   -1  310 0       362 12-28-1999
   -4   -4  310 0       363 12-29-1999
   -1   -1  310 0       364 12-30-1999
    4    4  310 0       365 12-31-1999
```

Answers.inp file for Commuter Lot B evaluation (with dry pond):

```
  Second Try on VT Parking Lot with Dry Pond at foot
METRIC  UNITS ARE USED ON INPUT/OUTPUT                 PRINT
STORM BY STORM OUTPUT = 1
EXTRA OUTPUT ON DAYS  =
PRINT HYDROGRAPHS = 01
RAINFALL DATA FOR 1 RAINGAGES
BEGINNING JULIAN DAY OF SIMULATION 213 1995
DURATION OF SIMULATION DAYS 0103
GAUGE NUMBER    1
 SIMULATION CONSTANTS FOLLOW
NUMBER OF LINES OF HYDROGRAPH OUTPUT =0101
TIME INCREMENT =030.0 SECONDS
INFILTRATION CAPACITY CALCULATED EVERY00030 SECONDS
EXPECTED RUNOFF PEAK =1200.00 MM/HR
 SOIL INFILTRATION, DRAINAGE AND GROUNDWATER CONSTANTS FOLLOW
NUMBER OF SOILS =0003
NO. URBAN SOILS =0001
Urbsoil=1 020.0000004.0000000.0500
S02, TP =.47, FP =.83, FC =00.42, A =1.000, DF =254.0, ASM =.99
CONDUCTIVITY OPTION = 0
43.7 23.8 20.0 1.50 02.5 13.0
S03, TP =.30, FP =.66, FC =00.33, A =1.000, DF =254.0, ASM =.66
CONDUCTIVITY OPTION = 0
17.0 40.5 30.0 1.50 02.5 13.0
 PARTICLE SIZE AND TRANSPORT DATA FOLLOWS
NUMBER OF PARTICLE SIZE CLASSES  = 05
NUMBER OF WASH LOAD CLASSES      = 01
  SIZE      SPECIFIC GRAVITY  FALL VELOCITY
000000.0020000000000000002.6500000000.0000030
000000.0100000000000000002.6500000000.0000800
000000.2000000000000000002.6400000000.0240000
000000.0300000000000000001.8000000000.0003500
000000.5000000000000000001.6000000000.0400000
00.00000.00100.00000.00000.000 S01
00.43700.20000.23800.13000.025 S02
00.17000.30000.40500.13000.025 S03
009.5519020.0000004.0000000.0500
004.6203020.0000004.0000000.0500
DRAINAGE EXPONENT =03
DRAINAGE COEFFICIENT FOR TILE DRAINS =09.55 MM/24HR
GROUNDWATER RELEASE FRACTION =000000.005
FERTILIZER APPLIED =00
IRRIGATION APPLIED =00
 IMPOUNDMENT SPECIFICATIONS FOLLOW
NUMBER OF IMPOUNDMENTS = 00
 SURFACE ROUGHNESS AND CROP CONSTANTS FOLLOWS
NUMBER OF CROPS AND SURFACES =004
NUMBER OF URBAN 'CROP' TYPES =002
C01,       urbroad,     00.00      0.00     1.00    000.20    0.200
000.3 0.013 0.013 06.70
Spring33.33 50.00 00.05 00.05 01.00 00.05 00.05 70.00
Summer33.33 50.00 00.05 00.05 01.00 00.05 00.05 70.00
Winter33.33 50.00 00.05 00.05 01.00 00.05 00.05 70.00
Fall  33.33 50.00 00.05 00.05 01.00 00.05 00.05 70.00
C02,       urbside,     00.20      0.20     0.60    000.20    0.200
000.3 0.012 0.012 01.00
Spring33.33 50.00 00.05 00.05 01.00 00.05 00.05 70.00
Summer33.33 50.00 00.05 00.05 01.00 00.05 00.05 70.00
Winter33.33 50.00 00.05 00.05 01.00 00.05 00.05 70.00
```

```
 Fall  33.33 50.00 00.05 00.05 01.00 00.05 00.05 70.00
 C03,      Pasture ,     00.40      0.96     0.65    003.00    0.300
 095.0 005.0 001.0 010.0 099.9 099.9 0.07 0.07 0.04
 0.00 0.70 1.80 3.00 3.00 3.00 2.90 2.70 1.96 0.90 0.50
 001 365 0.00 00.000 00.00 00000.0 100 3.00
 012.0 0.085 0.070 00.50 01.00 0.050 0.200 00 00
 Spring00.00 00.00 00.00 00.00 00.00 00.00 00.00 00.00
 Summer00.00 00.00 00.00 00.00 00.00 00.00 00.00 00.00
 Winter00.00 00.00 00.00 00.00 00.00 00.00 00.00 00.00
 Fall  00.00 00.00 00.00 00.00 00.00 00.00 00.00 00.00
 C04,      Forest  ,     01.40      0.85     0.65    003.00    0.300
 085.0 015.0 000.9 030.0 001.0 099.0 0.20 0.18 0.10
 2.50 2.50 4.00 4.00 4.00 4.00 4.00 4.00 4.00 2.50 2.50
 001 365 1.30 -0.264 02.50 08000.0 900 4.00
 012.0 0.000 3.000 00.50 01.00 0.050 0.180 00 00
 Spring00.00 00.00 00.00 00.00 00.00 00.00 00.00 00.00
 Summer00.00 00.00 00.00 00.00 00.00 00.00 00.00 00.00
 Winter00.00 00.00 00.00 00.00 00.00 00.00 00.00 00.00
 Fall  00.00 00.00 00.00 00.00 00.00 00.00 00.00 00.00
 NUMBER OF ALL ROTATIONS      =004
 01 01 1995365 01 1996365
***lines removed
 02 02 1995365 02 1996365
***lines removed
 03 03 1995365 03 1996365
***lines removed
 04 04 1995365 04 1996365
***lines removed

  CHANNEL SPECIFICATIONS FOLLOW
 NUMBER OF CHANNEL NETWORKS  =001
 NUMBER OF TYPES OF CHANNELS =001
 CHAN01 WID =01.5(m),  SOIL N =00.050 CHAN N =00.100 0.07 0.75
  ELEMENT SPECIFICATIONS FOR BASELINE SENSITIVITY ANALYSIS
 EACH ELEMENT IS0010.00m. SQUARE
 NETWORK 1 OUTFLOW FROM ROW0030 COLUMN 0002     00939
  6 13 0 95 270       3   3    1  0     0  0   0   0    4610   46  184    4
  001    1  001    01 0 0     0 0
  6 14 0 95 270       3   3    1  0     0  0   0   0    4610   46  184    4
  001    1  001    01 0 0     0 0
  6 15 0 95 270       3   3    1  0     0  0   0   0    4610   46  184    4
  001    1  001    01 0 0     0 0
  6 16 0 95 270       3   3    1  0     0  0   0   0    4610   46  184    4
  001    1  001    01 0 0     0 0.
       .
       .
```

etc. for the remaining 935 cells

BMP.inp file for Commuter Lot B evaluation:

```
  CELL TYPE OUTLET SUB? LENGTH   WIDTH PIPE PIPE  PIPE ORIFICE ORIFICE RISER
            CELL                       N    DIAM  LEN  HEIGHT   DIAM   HEIGHT
 00854  1   00904   1
 00904  1   00903   0   022.490 022.49 0.02 01.29 18.3 00.051  00.076  01.220

                           RISER OVERFLOW ANNUAL
                           DIAM   HEIGHT  F.W. EVAP
                           01.260 01.50   0.980
```

Weather.inp file for Commuter Lot B evaluation:

```
   24   24  430 0      213  8- 1-1995
   24   24  430 0      214  8- 2-1995
   24   24  430 0      215  8- 3-1995
   23   23  430 0      216  8- 4-1995
   23   23  430 0      217  8- 5-1995
   24   24  430 0      218  8- 6-1995
   22   22  430 1      219  8- 7-1995
 GAUGE NUMBER    1
0      0.      0.00
0     40.      0.89
0     80.      0.89
0    120.      0.89
1   1440.      0.00
   19   19  430 1      220  8- 8-1995
 GAUGE NUMBER    1
0      0.      0.00
0     25.      1.22
1   1440.      0.00
   17   17  430 1      221  8- 9-1995
 GAUGE NUMBER    1
0      0.      0.00
0     25.      1.22
1   1440.      0.00
   19   19  430 0      222  8-10-1995
   21   21  430 0      223  8-11-1995
   23   23  430 1      224  8-12-1995
 GAUGE NUMBER    1
0      0.      0.00
0     25.      1.22
1   1440.      0.00
   23   23  430 0      225  8-13-1995
   25   25  430 0      226  8-14-1995
   27   27  430 0      227  8-15-1995
   27   27  430 0      228  8-16-1995
   27   27  430 0      229  8-17-1995
   27   27  430 0      230  8-18-1995
   24   24  430 1      231  8-19-1995
 GAUGE NUMBER    1
0      0.      0.00
0    200.      2.89
0    400.      2.89
0    600.      2.89
0    800.      2.89
0   1000.      2.89
0   1200.      2.89
1   1440.      0.00
   22   22  430 0      232  8-20-1995
   22   22  430 0      233  8-21-1995
   23   23  430 0      234  8-22-1995
   23   23  430 0      235  8-23-1995
   22   22  430 0      236  8-24-1995
   22   22  430 0      237  8-25-1995
   23   23  430 0      238  8-26-1995
   21   21  430 0      239  8-27-1995
   19   19  430 1      240  8-28-1995
 GAUGE NUMBER    1
0      0.      0.00
0    120.      0.50
0    240.      4.95
0    360.      1.15
1   1440.      0.00
```

```
   22   22  430 0      241  8-29-1995
   23   23  430 0      242  8-30-1995
   23   23  430 0      243  8-31-1995
   24   24  422 0      244  9- 1-1995
   20   20  422 1      245  9- 2-1995
  GAUGE NUMBER    1
0      0.      0.00
0     36.      1.17
0     72.      1.17
0    108.      1.17
0    144.      4.02
0    180.      0.50
1   1440.      0.00
   16   16  422 0      246  9- 3-1995
   18   18  422 0      247  9- 4-1995
   19   19  422 0      248  9- 5-1995
   18   18  422 0      249  9- 6-1995
   19   19  422 0      250  9- 7-1995
   19   19  422 0      251  9- 8-1995
   19   19  422 0      252  9- 9-1995
   21   21  422 0      253  9-10-1995
   21   21  422 0      254  9-11-1995
   18   18  422 0      255  9-12-1995
   18   18  422 0      256  9-13-1995
   21   21  422 1      257  9-14-1995
  GAUGE NUMBER    1
0      0.      0.00
0     36.      0.82
0     72.      0.82
0    108.      0.82
0    144.      2.96
0    180.      0.50
1   1440.      0.00
   21   21  422 0      258  9-15-1995
   19   19  422 0      259  9-16-1995
   14   14  422 1      260  9-17-1995
  GAUGE NUMBER    1
0      0.      0.00
0    100.      2.87
0    200.      2.87
0    300.      2.87
0    400.      2.87
0    500.      2.87
0    600.      2.87
1   1440.      0.00
   16   16  422 1      261  9-18-1995
  GAUGE NUMBER    1
0      0.      0.00
0     40.      0.89
0     80.      0.89
0    120.      0.89
1   1440.      0.00
   16   16  422 1      262  9-19-1995
  GAUGE NUMBER    1
0      0.      0.00
0     25.      1.22
1   1440.      0.00
   17   17  422 0      263  9-20-1995
   17   17  422 0      264  9-21-1995
   19   19  422 0      265  9-22-1995
   15   15  422 1      266  9-23-1995
  GAUGE NUMBER    1
0      0.      0.00
```

```
0     40.      0.76
0     80.      0.76
0    120.      0.76
1   1440.      0.00
    7    7  422 1      267  9-24-1995
 GAUGE NUMBER    1
0      0.      0.00
0     36.      0.54
0     72.      0.54
0    108.      0.54
0    144.      2.12
0    180.      0.50
1   1440.      0.00
    8    8  422 1      268  9-25-1995
 GAUGE NUMBER    1
0      0.      0.00
0     36.      0.40
0     72.      0.40
0    108.      0.40
0    144.      1.69
0    180.      0.50
1   1440.      0.00
   14   14  422 0      269  9-26-1995
   12   12  422 1      270  9-27-1995
 GAUGE NUMBER    1
0      0.      0.00
0     36.      1.24
0     72.      1.24
0    108.      1.24
0    144.      4.23
0    180.      0.50
1   1440.      0.00
   14   14  422 0      271  9-28-1995
   15   15  422 0      272  9-29-1995
   14   14  422 0      273  9-30-1995
   14   14  422 0      274 10- 1-1995
   17   17  422 0      275 10- 2-1995
   17   17  422 0      276 10- 3-1995
   18   18  422 1      277 10- 4-1995
 GAUGE NUMBER    1
0      0.      0.00
0     36.      1.31
0     72.      1.31
0    108.      1.31
0    144.      4.44
0    180.      0.50
1   1440.      0.00
   16   16  422 1      278 10- 5-1995
 GAUGE NUMBER    1
0      0.      0.00
0    100.      4.03
0    200.      4.05
0    300.      4.06
0    400.      4.03
0    500.      4.03
0    600.      4.03
1   1440.      0.00
   21   21  422 1      279 10- 6-1995
 GAUGE NUMBER    1
0      0.      0.00
0     50.      4.87
0    100.      4.90
0    150.      4.87
```

```
0    200.      4.87
0    250.      4.87
0    300.      4.87
1   1440.      0.00
   21   21  422 0      280 10- 7-1995
   13   13  422 0      281 10- 8-1995
   12   12  422 0      282 10- 9-1995
   13   13  422 0      283 10-10-1995
   14   14  422 0      284 10-11-1995
   14   14  422 0      285 10-12-1995
   15   15  422 0      286 10-13-1995
   14   14  422 1      287 10-14-1995
  GAUGE NUMBER    1
0      0.      0.00
0     23.      2.65
0     46.      2.65
0     69.      2.65
0     92.      2.65
0    115.      2.65
0    138.      2.65
0    161.      2.65
0    184.      2.65
0    207.      2.65
1   1440.      0.00
   13   13  422 0      288 10-15-1995
    9    9  422 0      289 10-16-1995
    7    7  422 0      290 10-17-1995
    8    8  422 0      291 10-18-1995
    9    9  422 0      292 10-19-1995
   12   12  422 0      293 10-20-1995
   11   11  422 1      294 10-21-1995
  GAUGE NUMBER    1
0      0.      0.00
0    120.      0.50
0    240.      6.38
0    360.      1.63
1   1440.      0.00
    4    4  422 1      295 10-22-1995
  GAUGE NUMBER    1
0      0.      0.00
0     40.      0.38
0     80.      0.38
0    120.      0.38
1   1440.      0.00
    9    9  422 0      296 10-23-1995
   11   11  422 0      297 10-24-1995
   13   13  422 0      298 10-25-1995
    8    8  422 0      299 10-26-1995
   10   10  422 0      300 10-27-1995
   12   12  422 1      301 10-28-1995
  GAUGE NUMBER    1
0      0.      0.00
0     36.      0.54
0     72.      0.54
0    108.      0.54
0    144.      2.12
0    180.      0.50
1   1440.      0.00
   11   11  422 1      302 10-29-1995
  GAUGE NUMBER    1
0      0.      0.00
0     36.      0.54
0     72.      0.54
```

```
0    108.       0.54
0    144.       2.12
0    180.       0.50
1   1440.       0.00
    6    6  422 0       303 10-30-1995
    7    7  422 0       304 10-31-1995
   11   11  353 1       305 11- 1-1995
 GAUGE NUMBER    1
0      0.       0.00
0     40.       0.89
0     80.       0.89
0    120.       0.89
1   1440.       0.00
   16   16  353 1       306 11- 2-1995
 GAUGE NUMBER    1
0      0.       0.00
0     36.       1.17
0     72.       1.17
0    108.       1.17
0    144.       4.02
0    180.       0.50
1   1440.       0.00
   14   14  353 1       307 11- 3-1995
 GAUGE NUMBER    1
0      0.       0.00
0     23.       2.43
0     46.       2.43
0     69.       2.43
0     92.       2.43
0    115.       2.43
0    138.       2.43
0    161.       2.43
0    184.       2.43
0    207.       2.43
1   1440.       0.00
    8    8  353 1       308 11- 4-1995
 GAUGE NUMBER    1
0      0.       0.00
0     40.       0.89
0     80.       0.89
0    120.       0.89
1   1440.       0.00
   -2   -2  353 0       309 11- 5-1995
   -1   -1  353 0       310 11- 6-1995
    5    5  353 0       311 11- 7-1995
    6    6  353 1       312 11- 8-1995
 GAUGE NUMBER    1
0      0.       0.00
0     26.      13.29
0     52.       9.91
0     78.       7.38
0    104.       5.50
0    130.       4.10
0    156.       3.05
0    182.       2.28
0    208.       1.70
0    234.       4.96
1   1440.       0.00
    0    0  353 0       313 11- 9-1995
    1    1  353 0       314 11-10-1995
    6    6  353 0       315 11-11-1995
    5    5  353 1       316 11-12-1995
 GAUGE NUMBER    1
```

```
0      0.      0.00
0     23.      0.50
0     46.     20.87
0     69.      0.92
0     92.      0.92
0    115.      0.92
0    138.      0.92
0    161.      0.92
0    184.      0.92
0    207.      0.92
1   1440.      0.00
   -1   -1  353 1      317 11-13-1995
  GAUGE NUMBER    1
0      0.      0.00
0     25.      1.22
1   1440.      0.00
    1    1  353 1      318 11-14-1995
  GAUGE NUMBER    1
0      0.      0.00
0     36.      1.88
0     72.      1.88
0    108.      1.88
0    144.      6.14
0    180.      0.50
1   1440.      0.00
   -1   -1  353 1      319 11-15-1995
  GAUGE NUMBER    1
0      0.      0.00
0     40.      0.38
0     80.      0.38
0    120.      0.38
1   1440.      0.00
   -2   -2  353 0      320 11-16-1995
   -1   -1  353 0      321 11-17-1995
    2    2  353 0      322 11-18-1995
    6    6  353 0      323 11-19-1995
    2    2  353 0      324 11-20-1995
    6    6  353 0      325 11-21-1995
    3    3  353 0      326 11-22-1995
   -1   -1  353 0      327 11-23-1995
    2    2  353 1      328 11-24-1995
  GAUGE NUMBER    1
0      0.      0.00
0     40.      0.63
0     80.      0.63
0    120.      0.63
1   1440.      0.00
    2    2  353 0      329 11-25-1995
    4    4  353 0      330 11-26-1995
    7    7  353 0      331 11-27-1995
    7    7  353 0      332 11-28-1995
    7    7  353 1      333 11-29-1995
  GAUGE NUMBER    1
0      0.      0.00
0     26.     12.70
0     52.      9.46
0     78.      7.05
0    104.      5.25
0    130.      3.91
0    156.      2.92
0    182.      2.17
0    208.      1.62
0    234.      4.74
```

```
1   1440.      0.00
    1    1  353 0      334 11-30-1995
    2    2  310 0      335 12- 1-1995
    6    6  310 0      336 12- 2-1995
    7    7  310 0      337 12- 3-1995
    8    8  310 0      338 12- 4-1995
    4    4  310 0      339 12- 5-1995
    4    4  310 1      340 12- 6-1995
 GAUGE NUMBER    1
0      0.      0.00
0     36.      0.61
0     72.      0.61
0    108.      0.61
0    144.      2.33
0    180.      0.50
1   1440.      0.00
   -1   -1  310 1      341 12- 7-1995
 GAUGE NUMBER    1
0      0.      0.00
0     36.      1.81
0     72.      1.81
0    108.      1.81
0    144.      5.93
0    180.      0.50
1   1440.      0.00
   -8   -8  310 0      342 12- 8-1995
   -7   -7  310 1      343 12- 9-1995
 GAUGE NUMBER    1
0      0.      0.00
0     36.      0.54
0     72.      0.54
0    108.      0.54
0    144.      2.12
0    180.      0.50
1   1440.      0.00
   -6   -6  310 1      344 12-10-1995
 GAUGE NUMBER    1
0      0.      0.00
0     36.      0.82
0     72.      0.82
0    108.      0.82
0    144.      2.96
0    180.      0.50
1   1440.      0.00
  -12  -12  310 0      345 12-11-1995
   -7   -7  310 0      346 12-12-1995
   -3   -3  310 0      347 12-13-1995
   -1   -1  310 0      348 12-14-1995
    4    4  310 0      349 12-15-1995
    9    9  310 1      350 12-16-1995
 GAUGE NUMBER    1
0      0.      0.00
0     40.      0.89
0     80.      0.89
0    120.      0.89
1   1440.      0.00
    3    3  310 0      351 12-17-1995
    3    3  310 0      352 12-18-1995
    2    2  310 1      353 12-19-1995
 GAUGE NUMBER    1
0      0.      0.00
0     26.     12.55
0     52.      9.35
```

```
0     78.      6.97
0    104.      5.19
0    130.      3.87
0    156.      2.88
0    182.      2.15
0    208.      1.60
0    234.      4.68
1   1440.      0.00
   -1   -1  310 1      354 12-20-1995
  GAUGE NUMBER    1
0      0.      0.00
0     23.      0.50
0     46.     24.85
0     69.      1.11
0     92.      1.11
0    115.      1.11
0    138.      1.11
0    161.      1.11
0    184.      1.11
0    207.      1.11
1   1440.      0.00
   -4   -4  310 0      355 12-21-1995
   -6   -6  310 0      356 12-22-1995
   -6   -6  310 0      357 12-23-1995
   -6   -6  310 0      358 12-24-1995
   -6   -6  310 0      359 12-25-1995
   -5   -5  310 0      360 12-26-1995
   -6   -6  310 0      361 12-27-1995
   -6   -6  310 0      362 12-28-1995
   -7   -7  310 0      363 12-29-1995
   -3   -3  310 0      364 12-30-1995
   -1   -1  310 0      365 12-31-1995
    3    3  336 1      366  1- 1-1996
  GAUGE NUMBER    1
0      0.      0.00
0     40.      0.63
0     80.      0.63
0    120.      0.63
1   1440.      0.00
    3    3  336 0      367  1- 2-1996
    3    3  336 1      368  1- 3-1996
  GAUGE NUMBER    1
0      0.      0.00
0     36.      1.31
0     72.      1.31
0    108.      1.31
0    144.      4.44
0    180.      0.50
1   1440.      0.00
   -2   -2  336 0      369  1- 4-1996
   -4   -4  336 0      370  1- 5-1996
   -3   -3  336 1      371  1- 6-1996
  GAUGE NUMBER    1
0      0.      0.00
0     36.      0.68
0     72.      0.68
0    108.      0.68
0    144.      2.54
0    180.      0.50
1   1440.      0.00
   -8   -8  336 1      372  1- 7-1996
  GAUGE NUMBER    1
0      0.      0.00
```

```
0     50.      8.54
0    100.      8.54
0    150.      8.54
0    200.      8.54
0    250.      8.54
0    300.      8.54
1   1440.      0.00
   -9   -9  336 1       373  1- 8-1996
 GAUGE NUMBER    1
0      0.      0.00
0     50.      7.06
0    100.      7.06
0    150.      7.06
0    200.      7.06
0    250.      7.06
0    300.      7.06
1   1440.      0.00
  -11  -11  336 0       374  1- 9-1996
   -7   -7  336 0       375  1-10-1996
   -7   -7  336 0       376  1-11-1996
   -7   -7  336 1       377  1-12-1996
 GAUGE NUMBER    1
0      0.      0.00
0     23.      0.50
0     46.     15.41
0     69.      0.66
0     92.      0.66
0    115.      0.66
0    138.      0.66
0    161.      0.66
0    184.      0.66
0    207.      0.66
1   1440.      0.00
   -6   -6  336 0       378  1-13-1996
   -3   -3  336 0       379  1-14-1996
    3    3  336 0       380  1-15-1996
    6    6  336 0       381  1-16-1996
    1    1  336 0       382  1-17-1996
    7    7  336 0       383  1-18-1996
   12   12  336 1       384  1-19-1996
 GAUGE NUMBER    1
0      0.      0.00
0     50.      5.48
0    100.      5.51
0    150.      5.48
0    200.      5.48
0    250.      5.48
0    300.      5.48
1   1440.      0.00
   -3   -3  336 0       385  1-20-1996
   -6   -6  336 0       386  1-21-1996
   -4   -4  336 1       387  1-22-1996
 GAUGE NUMBER    1
0      0.      0.00
0     40.      0.76
0     80.      0.76
0    120.      0.76
1   1440.      0.00
   -2   -2  336 0       388  1-23-1996
    3    3  336 0       389  1-24-1996
    2    2  336 1       390  1-25-1996
 GAUGE NUMBER    1
0      0.      0.00
```

```
0     36.      1.31
0     72.      1.31
0    108.      1.31
0    144.      4.44
0    180.      0.50
1   1440.      0.00
   -2   -2  336 0      391  1-26-1996
    1    1  336 1      392  1-27-1996
 GAUGE NUMBER    1
0      0.      0.00
0     50.      6.81
0    100.      6.81
0    150.      6.81
0    200.      6.81
0    250.      6.81
0    300.      6.81
1   1440.      0.00
    1    1  336 1      393  1-28-1996
 GAUGE NUMBER    1
0      0.      0.00
0     40.      0.38
0     80.      0.38
0    120.      0.38
1   1440.      0.00
   -3   -3  336 0      394  1-29-1996
   -1   -1  336 1      395  1-30-1996
 GAUGE NUMBER    1
0      0.      0.00
0     25.      1.22
1   1440.      0.00
    1    1  336 1      396  1-31-1996
 GAUGE NUMBER    1
0      0.      0.00
0     40.      0.76
0     80.      0.76
0    120.      0.76
1   1440.      0.00
   -2   -2  387 0      397  2- 1-1996
   -6   -6  387 1      398  2- 2-1996
 GAUGE NUMBER    1
0      0.      0.00
0     26.     11.05
0     52.      8.24
0     78.      6.14
0    104.      4.57
0    130.      3.41
0    156.      2.54
0    182.      1.89
0    208.      1.41
0    234.      4.12
1   1440.      0.00
   -9   -9  387 1      399  2- 3-1996
 GAUGE NUMBER    1
0      0.      0.00
0     26.     11.35
0     52.      8.46
0     78.      6.30
0    104.      4.70
0    130.      3.50
0    156.      2.61
0    182.      1.94
0    208.      1.45
0    234.      4.23
```

```
1   1440.      0.00
  -14  -14  387 1      400  2- 4-1996
 GAUGE NUMBER    1
0      0.      0.00
0     40.      0.63
0     80.      0.63
0    120.      0.63
1   1440.      0.00
  -17  -17  387 0      401  2- 5-1996
  -13  -13  387 0      402  2- 6-1996
   -7   -7  387 0      403  2- 7-1996
   -1   -1  387 0      404  2- 8-1996
    6    6  387 1      405  2- 9-1996
 GAUGE NUMBER    1
0      0.      0.00
0     36.      1.67
0     72.      1.67
0    108.      1.67
0    144.      5.50
0    180.      0.50
1   1440.      0.00
    3    3  387 0      406  2-10-1996
    7    7  387 0      407  2-11-1996
    3    3  387 1      408  2-12-1996
 GAUGE NUMBER    1
0      0.      0.00
0     40.      0.51
0     80.      0.51
0    120.      0.51
1   1440.      0.00
   -5   -5  387 0      409  2-13-1996
   -2   -2  387 0      410  2-14-1996
    4    4  387 1      411  2-15-1996
 GAUGE NUMBER    1
0      0.      0.00
0     40.      0.76
0     80.      0.76
0    120.      0.76
1   1440.      0.00
   -1   -1  387 1      412  2-16-1996
 GAUGE NUMBER    1
0      0.      0.00
0     23.      0.50
0     46.     16.40
0     69.      0.71
0     92.      0.71
0    115.      0.71
0    138.      0.71
0    161.      0.71
0    184.      0.71
0    207.      0.71
1   1440.      0.00
   -8   -8  387 1      413  2-17-1996
 GAUGE NUMBER    1
0      0.      0.00
0     36.      1.31
0     72.      1.31
0    108.      1.31
0    144.      4.44
0    180.      0.50
1   1440.      0.00
   -7   -7  387 0      414  2-18-1996
   -4   -4  387 0      415  2-19-1996
```

```
    3    3  387 1      416  2-20-1996
  GAUGE NUMBER    1
0      0.      0.00
0     40.      0.38
0     80.      0.38
0    120.      0.38
1   1440.      0.00
    5    5  387 1      417  2-21-1996
  GAUGE NUMBER    1
0      0.      0.00
0     36.      0.47
0     72.      0.47
0    108.      0.47
0    144.      1.91
0    180.      0.50
1   1440.      0.00
   11   11  387 0      418  2-22-1996
    9    9  387 1      419  2-23-1996
  GAUGE NUMBER    1
0      0.      0.00
0     36.      0.40
0     72.      0.40
0    108.      0.40
0    144.      1.69
0    180.      0.50
1   1440.      0.00
   11   11  387 0      420  2-24-1996
    7    7  387 0      421  2-25-1996
   11   11  387 0      422  2-26-1996
   13   13  387 0      423  2-27-1996
   16   16  387 1      424  2-28-1996
  GAUGE NUMBER    1
0      0.      0.00
0     36.      0.96
0     72.      0.96
0    108.      0.96
0    144.      3.39
0    180.      0.50
1   1440.      0.00
    5    5  387 0      425  2-29-1996
```

Appendix F

Sensitivity Analysis

Table F 1. Atmospheric Deposition Sensitivity Analysis Input Parameters.

	Dry (kg/ha-year)				Wet (mg/L)			
	Sediment	Org-N	Ammonia	Ortho-P	Sediment	Nitrate	Ammonia	Ortho-P
Baseline	60.6	3.73	2.06	0.2	1.47	0.97	0.4	18
Minus 25%	45.45	2.80	1.55	0.15	1.10	0.73	0.3	13.5
Minus 10%	54.54	3.36	1.85	0.18	1.32	0.87	0.36	16.2
Plus 10%	66.66	4.10	2.27	0.22	1.61	1.07	0.44	19.8
Plus 25%	75.75	4.66	2.58	0.25	1.83	1.21	0.5	22.5

These scenarios were tested as follows:

1 All dry parameters -25
2 All dry parameters -10
3 All dry parameters +10
4 All dry parameters +15
5 All wet parameters -25
6 All wet parameters -10
7 All wet parameters +10
8 All wet parameters +25

Table F 2. Atmospheric Deposition Sensitivity Analysis Output Results and Relative Sensitivities.

Results:

Scenario	Sediment kg/ha	Relative Sensitivity	Dis-NO3 kg	Relative Sensitivity	Dis-NH4 kg	Relative Sensitivity	Sed-NH4 kg	Relative Sensitivity	Dis-PO4 kg	Relative Sensitivity	Sed-PO4 kg	Relative Sensitivity	Sed-TKN kg	Relative Sensitivity
Baseline	2740.2		76.58		48.01		9.04		24.78		8.59		868.54	
No deposition	2731.1		3.83		0		0		4.98		7.72		852.17	
1	2740.2	0	76.58		48.01		6.80	1.00	24.78		8.38	0.10	864.46	0.019
2	2740.2	0	76.58		48.01		8.12	1.00	24.78		8.51	0.10	866.91	0.019
3	2740.2	0	76.58		48.01		9.96	1.00	24.78		8.68	0.10	870.16	0.019
4	2740.2	0	76.58		48.01		11.32	1.00	24.78		8.81	0.10	872.62	0.019
5	2737.9	0.0033	58.29	0.97	36.13	0.99	9.04		19.83	0.80	8.59		868.54	
6	2739.3	0.0032	69.16	0.94	43.06	1.03	9.04		22.80	0.80	8.59		868.54	
7	2741.1	0.0034	83.51	0.88	52.96	1.03	9.04		26.76	0.80	8.59		868.54	
8	2742.5	0.0034	94.40	0.94	59.89	0.99	9.04		29.73	0.80	8.59		868.54	

Table F 3. Input Parameters for BMP Sensitivity Analysis.

	area			pipe	pipe	side	side	riser	riser	embankment
	length	*width*	pipe n*	diameter	length	orifice ht.	orifice dia.	height	diameter	height**
-25%	19.48	19.48	--	0.97	13.7	0.038	0.057	0.915	0.945	1.23
-10%	21.34	21.34	0.01	1.16	16.5	0.046	0.068	1.098	1.134	1.35
baseline	22.49	22.49	0.02	1.29	18.3	0.051	0.076	1.22	1.26	1.5
+10%	23.59	23.59	0.03	1.42	20.1	0.056	0.084	1.342	1.386	1.65
+25%	25.14	25.14	--	1.61	22.9	0.064	0.095	1.525	1.575	1.88

All values in the above table are expressed in meters, with the exception of the unitless pipe n.

* pipe n values are not actually +- 10 and 25 % due to the magnitude of the value; instead these were considered as 'low','mid', and 'high' values.

**1.23 is not actually -25%, but this value had to be greater than the baseline riser height for the program to work correctly.

Table F 4. Output for Sensitivity Analysis of BMP Parameters.

		RUNOFF MM	SEDIMENT KG/HA	NO_3 KG	DIS-NH_4 KG	SED-NH_4 KG	DIS-PO_4 KG	SED-PO_4 KG	SED-TKN KG
baseline									
		254.2	181.84	102.5	18.5393	0.9256	0	0.9311	0.001
area									
	-25%	254.2	181.12	108.6	18.5755	0.9273	0	0.9322	0.001
	-10%	254.2	181.22	105.1	18.0671	0.9021	0	0.9064	0.001
	+10%	254.2	181.13	100.1	17.6555	0.8813	0	0.8856	0.001
	+25%	254.2	178.04	96.3	18.0506	0.901	0	0.9059	0.001
pipe n									
	low	254.2	181.84	102.5	18.5393	0.9256	0	0.9311	0.001
	high	254.2	181.84	102.5	18.5393	0.9256	0	0.9311	0.001
pipe diam.									
	-25%	254.2	181.84	102.5	18.5393	0.9256	0	0.9311	0.001
	-10%	254.2	181.84	102.5	18.5393	0.9256	0	0.9311	0.001
	+10%	254.2	181.84	102.5	18.5393	0.9256	0	0.9311	0.001
	+25%	254.2	181.84	102.5	18.5393	0.9256	0	0.9311	0.001
pipe len.									
	-25%	254.2	181.84	102.5	18.5393	0.9256	0	0.9311	0.001
	-10%	254.2	181.84	102.5	18.5393	0.9256	0	0.9311	0.001
	+10%	254.2	181.84	102.5	18.5393	0.9256	0	0.9311	0.001
	+25%	254.2	181.84	102.5	18.5393	0.9256	0	0.9311	0.001
side orifice height									
	-25%	254.2	183.23	103.8	18.145	0.9059	0	0.9112	0.001
	-10%	254.2	181.51	102.8	17.9815	0.8978	0	0.9028	0.001
	+10%	254.2	182.74	102.9	17.7187	0.8851	0	0.8892	0.001
	+25%	254.2	182.71	103	17.7211	0.8852	0	0.8893	0.001
side orifice diameter									
	-25%	254.2	182.11	94.4	18.4019	0.9187	0	0.9236	0.001
	-10%	254.2	181.62	100.1	18.779	0.9374	0	0.9427	0.001
	+10%	254.2	182.11	104.8	20.29	1.0131	0	1.0193	0.001
	+25%	254.2	182.58	107	18.0051	0.8991	0	0.9037	0.001

Table F4. Continued

riser height								
-25%	254.2	179.8	103.4	18.2707	0.9124	0	0.9172	0.001
-10%	254.2	180.28	102.8	18.977	0.9474	0	0.9539	0.001
+10%	254.2	181.99	102.2	17.8573	0.8918	0	0.8965	0.001
+25%	254.2	182.6	88.3	20.432	1.0202	0	1.0261	0.0007
riser diam.								
-25%	254.2	181.24	102.5	18.5648	0.927	0	0.9327	0.001
-10%	254.2	181.82	102.6	18.303	0.914	0	0.9185	0.001
+10%	254.2	182.65	102.4	18.6737	0.9324	0	0.9373	0.001
+25%	254.2	182.25	102.3	18.331	0.9154	0	0.92	0.001
overflow height								
-25%	254.2	182.25	102.2	17.6547	0.8816	0	0.8858	0.001
-10%	254.2	183.98	102.4	18.5392	0.9256	0	0.9311	0.001
+10%	254.2	181.84	102.5	18.5393	0.9256	0	0.9311	0.001
+25%	254.2	181.84	102.5	18.5393	0.9256	0	0.9311	0.001

Table F 5. Relative Sensitivities of Model Output to Changes in BMP Parameters.

		RUNOFF	SEDIMENT	NO_3	DIS-NH_4	SED-NH_4	DIS-PO_4	SED-PO_4	SED-TKN
area									
	-25%	0.02	-0.24	-0.01	-0.01	0.00	0.00	0.00	-0.04
	-10%	0.03	-0.25	0.26	0.25	0.00	0.27	0.00	-0.09
	+10%	-0.04	-0.23	-0.48	-0.48	0.00	-0.49	0.00	-0.03
	+25%	-0.08	-0.24	-0.11	-0.11	0.00	-0.11	0.00	-0.03
pipe n									
	low	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	high	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
pipe diam.									
	-25%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	-10%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+10%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+25%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
pipe len.									
	-25%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	-10%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+10%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+25%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
side orifice height									
	-25%	-0.03	-0.05	0.08	0.08	0.00	0.08	0.00	-0.05
	-10%	0.02	-0.03	0.31	0.31	0.00	0.31	0.00	-0.10
	+10%	0.05	0.04	-0.45	-0.45	0.00	-0.46	0.00	0.00
	+25%	0.02	0.02	-0.17	-0.17	0.00	-0.18	0.00	0.00
side orifice diameter									
	-25%	-0.01	0.32	0.03	0.03	0.00	0.03	0.00	0.01
	-10%	0.01	0.22	-0.12	-0.12	0.00	-0.12	0.00	0.03
	+10%	0.01	0.21	0.90	0.90	0.00	0.90	0.00	0.09
	+25%	0.02	0.18	-0.12	-0.11	0.00	-0.12	0.00	0.05
riser height									
	-25%	0.04	-0.04	0.06	0.06	0.00	0.06	0.00	-0.01
	-10%	0.09	-0.03	-0.24	-0.24	0.00	-0.24	0.00	-0.03
	+10%	0.01	-0.03	-0.37	-0.37	0.00	-0.37	0.00	0.00
	+25%	0.02	-0.55	0.41	0.41	0.00	0.41	0.00	-0.55

Table F5. Continued.									
riser diam.									
	-25%	0.01	0.00	-0.01	-0.01	0.00	-0.01	0.00	-0.01
	-10%	0.00	-0.01	0.13	0.13	0.00	0.14	0.00	-0.03
	+10%	0.04	-0.01	0.07	0.07	0.00	0.07	0.00	0.00
	+25%	0.01	-0.01	-0.04	-0.04	0.00	-0.05	0.00	0.00
overflow height									
	-25%	-0.01	0.02	0.27	0.26	0.00	0.27	0.00	0.03
	-10%	-0.12	0.01	0.00	0.00	0.00	0.00	0.00	0.00
	+10%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+25%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Vita

Rebecca Winfrey Zeckoski was born to William Randolph and Catherine Winfrey on October 1, 1978 in Lynchburg, Virginia. She has lived in Blacksburg since age 5. She entered the Biological Systems Engineering undergraduate program in 1997 and the graduate program in 2000. She was married in May 2000 to Aaron Daniel Zeckoski.