A PCSWMM / GIS Based Water Balance Model for the Reesor Creek Watershed

By

Derek Smith
Bachelor of Arts Environmental Geography
Nipissing University
North Bay, Ontario, Canada
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Abstract

One of the driving pressures of land-use changes is urban development. In the Greater Toronto Area (GTA), there have been drastic changes to local watersheds as urban areas sprawl over surrounding rural areas. It is necessary to understand the water balance of a watershed in order to develop and implement watershed procedures that are addressed in a watershed plan. In an urbanized watershed, the runoff rate and volume will increase. While Duffins Creek may be one of the healthiest watersheds in the GTA, it is also one that is producing the most concern for the Toronto and Region Conservation Authority where findings suggested that proposed urbanization will impact the water quality and quantity.

There are three objectives for this research. The first is to develop a modelling methodology that integrates GIS (e.g. ArcGIS) and hydrologic models (e.g. SWMM) in a water balance analysis on a watershed basis and demonstrate the methodology by a case study for the Reesor Creek watershed. The second objective is to calibrate the GIS--based water balance model by observing how differing techniques, in this case, lumped, clustered, grid, and kriging analyses can discretize both the landscape and incoming precipitation. And the last objective is to observe the effects of spatially distributed rainfall measurements and their affects on the three modelling approaches.

Results show that discretization of a watershed does affect the percentage difference in measured and generated runoff volumes; however this can be refined with calibration. Also, kriging rainfall can predict rainfall at ungauged (virtual) sites only under certain conditions and that a strong correlation between measured rainfall values does not confirm a strong relationship with generated runoff.

Recommendations included the use of a longer time series of rainfall, streamflow, and predicted rainfall to observe temporal variations, as well as to use climate data such as evaporation and temperature in the models. It was also recommended that a larger number of sample points to be used in the kriging with various surface interpolation techniques to observe model differences.

Acknowledgements

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Dedication

This is dedicated to my family, the Nolan family, and my friends who supported me. I especially dedicate this to my mother and father who never lost faith in me—I love you both.

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Chapter 1
Introduction

1. Watershed Planning in Ontario

The Ontario Ministry of the Environment (MOE) (1993a) describes a watershed as the land that is drained by a river and its tributaries, and a subwatershed as the land drained by an individual tributary to the main watercourse. In other words, a watershed is a discrete hydrologic system, the state of which is affected by the environmental conditions of its subwatersheds and the mainstream river.

Land-use changes in a watershed and subwatersheds have been found to have significant impacts on the hydrologic processes that occur within them (Ellis, 1999; Nix, 1994; and Taniguchi, 1997). Spatial variations in the total percentage imperviousness by land-use type can significantly affect soil and groundwater storage, which in turn, influence watershed runoff ratios and baseflow characteristics by increasing or decreasing flow volumes. The removal of natural vegetation and the grading of land by urban development can eliminate both interception and depression storage by covering the land with impervious surfaces (MOE, 2003). The MOE (2003) states that grading and impervious surfaces change the hydraulic roughness of land and result in greater runoff velocities, thus, reducing runoff travel times and soil infiltration rates.

One of the driving pressures of land-use changes is urban development. In the Greater Toronto Area (GTA), there have been drastic changes to local watersheds as urban areas sprawl over surrounding rural areas. Changes such as increased flooding and decreased ground water recharge have occurred due to urban development (Toronto and Region Conservation Authority (TRCA), 2002a). It is wise to develop water management plans for future urban development in order to avoid degradation to the natural environment. Water management plans can be designed to minimize the impacts associated with human land-use and enhance the natural environment wherever possible. Ultimately, this integrated approach protects natural resources, allows for informed planning decisions, involves stakeholders, increases approval efficiency, and saves money to all involved (Li, 2002).

A watershed management plan recommends the actions that should be taken for each ecological area in a watershed in concert with prevention and protection, enhancement, and rehabilitation. In terms of protection, the MOE, local municipalities, and the TRCA need to promote the appropriate initiatives that are necessary for protecting ecosystem health headwaters, aquifer recharge/discharge areas, wetlands, and fish habitat. Enhancement conditions should specify opportunities that will serve to improve the function and health of the ecosystems, such as, infiltration, vegetative linkages, buffers, fish habitat, sanctuaries, public access points, treed parks, creation of rural beaches/water contact sport areas, and riparian vegetation. Finally, rehabilitation criteria should prioritize the sites' problems, as well as the resources required to rehabilitate them. The plan can outline preferred measures or strategies for improved land management and for the abatement of all point and non-point sources (MOE, 1993a).

The MOE (1994) suggests that "watershed planning...addresses the inter-relationships of the hydrologic regime, water use patterns, and land-use...[as the] preferred basis for water management decisions". The first step in watershed planning is to identify a goal and the unique objectives needed in order to achieve that goal. For example, a goal for a watershed plan may be to protect the natural environment and rehabilitate degraded environments, while the collateral objectives might be to eliminate sewer discharges, increase green spaces and pervious surfaces, and improve urban runoff water quality. As a result, the goals and objectives of a watershed plan will reflect the characteristics and issues of the watershed under study (Li, 2002; IWRRI, 1998).

Achievement of water management objectives should be measured with respect to indicators and/or parameters. One example is the *Toronto Wet Weather Flow Management Plan (WWFMP)*, which has 12 objectives listed against its respective indicators and/or parameters in order to weight each one. Table 1 depicts some of the criteria or indicators in the Toronto Study (Li, 2002).

Table 1. The objectives, indicators and parameters of the Toronto Wet Weather Flow Management study (Li, 2002).

Objectives	Indicators	Parameters
Rehabilitation of natural hydrologic cycle	Water budget	Total runoff volume
Reduction of erosion impacts on habitats and property	In-stream erosion potential	In-stream erosion index
Reduction of fish advisories	Contaminant guidelines	Sportfish tissue contaminants
Healthy aquatic communities	Representative aquatic communities	Indicator species/communities
Re-establishment and rehabilitation of natural features	In-stream corridors	Barriers (structures, velocity/depth, chemical)
Virtual elimination of toxics through pollution prevention	Spill prevention/emergency response	Number of reported spills
Meeting Federal, provincial, municipal sediment and water quality guidelines	E. Coli guidelines	5 day geometric mean
Elimination of Sanitary Sewer Discharges	CSO/SSO overflows	Number of overflows
Improved water quality for body contact recreation Improved aesthetics	Beach closures Algae, turbidity, odour, fish kills	Number of days closed Number of complaints
Reduction of basement flooding Reduction of infiltration/inflow	Reported incidents Sewer flows	Number of complaints Dry weather flow (sanitary/storm)
Protection of life/property from flooding	Protection of life/property	Ratio of site protected/site identified

"Watershed management plans and policies can be developed by analyzing the ecological impacts of various development scenarios and evaluating their success for attaining watershed objectives. Comparison of alternative development scenarios requires that relative weights be assigned to watershed objectives and a consistent rating system for various levels of achievement be adopted. The final development scenario and the associated watershed wide policy (which maximizes the overall achievement of watershed objectives) will be recommended" (Li, 2002 and MOE, 1993b, and MOE, 1993c).

In Ontario, the principal planning document in the municipal land use planning process is the official plan. The plan identifies municipal goals and objectives for land use within its jurisdiction and provides explicit policy direction that guides land development in agreement with provincial policies and guidelines. Official plans reflect the direction, goals, and targets established in the water management plan. The relationship between water management planning and land use process is illustrated in Figure 1.

Today, modelling is one of the key approaches to watershed management and one of the greatest concerns in watershed modelling is the extent of spatial and temporal detail used (Kelly and Wool, 1995). Zhu and Mackay (2001) examined the effects of spatial detail on soil information on a watershed basis, and its implications on hydrologic modelling. Impacts were assessed by the comparing the simulated hydro-ecological response based on the spatial detail of the soil information from fuzzy-logic and soil map sources. Their results showed that spatial soil information does impact hydrologic results in lumped watershed models, while a clustered (subwatershed) approach was less affected by the variable soil information. A phenomenon like peak runoff was observed to significantly fluctuate with soil parameterization primarily in the lumped parameter model.

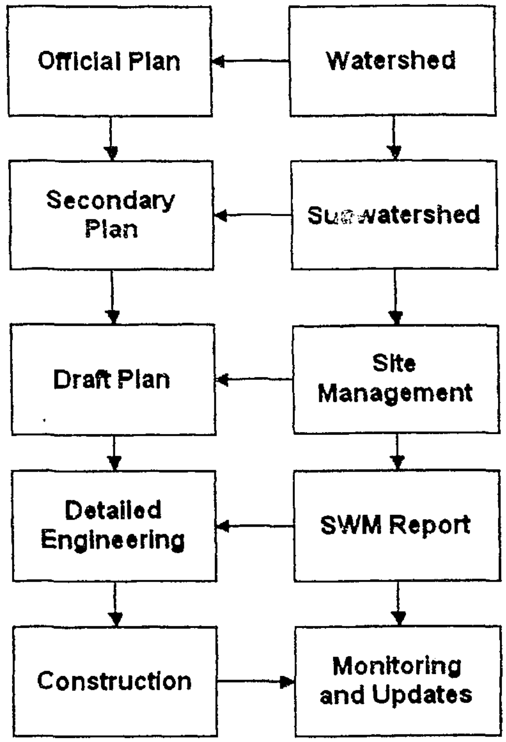


Figure 1. The relationship between water management planning and land use process (MOE, 1993c).

2. Stormwater Management in Ontario

Wanielista and Yousef (1993) state that stormwater management (SWM) is a discipline that is used to understand, control, and utilize water and that its applications are evident in many management activities such as water supply, flood control, urban runoff, and ecological conservation. Characteristics such as the peak rate, volume, and runoff rate influence the planning and design of SWM practices. Prior to urbanization, these characteristics are a function of the natural watershed with characteristics such as soil type, topography, and vegetation cover. Urbanization alters watershed characteristics, which in turn change natural runoff characteristics (Li, 2002; Hsu et al., 2000 and Li, 1991).

In an urbanized watershed, the runoff rate and volume will increase (Leopold et al., 1964). This is because paved surfaces, rooftops, altered drainage systems, and sewer systems convey runoff at greater rates because of their imperviousness and minimal friction coefficients (Figure 2). Downstream, storage watersheds such as local streams, wetlands, ponds, and lakes can exceed their capacities and flooding can occur within an expanded floodplain. Another related problem is channel erosion, which depends on runoff rate and its duration (Deebo and Reese, 1995).

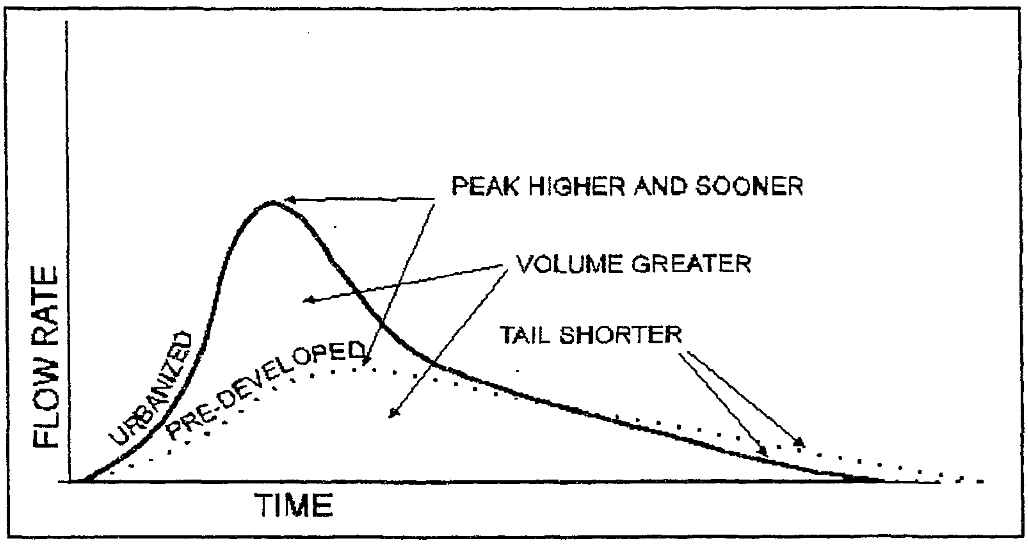


Figure 2. Runoff hydrograph for pre-developed and urbanized lands (Li, 2002).

As a result, urbanization not only increases runoff rates and volumes, but also increases the frequency of urban runoff. In this case, frequency refers to the number of urbanized runoff events over a period expressed as a percentage of time. Frequency is important since it has a direct impact on natural drainage erosion and sediment transport (Li, 2002).

In terms of water quality, runoff loading from urbanized environments differs from non-urban environments. For instance, runoff from an urbanized environment might carry large concentrations of: chlorides from road salt, oil and grease form automobiles, hydrocarbons from fuel spills, residential fertilizer nutrients, and bacteria from domestic animal waste and soil particles. Non-urban runoff might carry concentrations of pesticides, herbicides, and bacteria from farming practices, eroded sediments, and naturally occurring nutrients. The change of runoff quality can result in a general degradation of water quality in the receiving waters (Debo and Reese, 1995; Li, 2002).

Li (2002) states that in a traditional sense, SWM planning focuses primarily on individual sites that are undergoing urban development. It is a planning process where SWM practices are selected so that pre-development runoff peak rates and groundwater recharge is preserved. However, peak flow control at individual sites does not guarantee preservation of the natural watercourse. Thus, SWM planning should be implemented on a watershed basis.

Lot level and conveyance controls are those that are used at individual lots, those which form part of the conveyance system, and controls that may serve multiple lots but are only suitable for small drainage areas (< 2 hectares). On the other hand, end-of-pipe controls receive water from a conveyance system and discharge to receiving water. Typically, these facilities serve numerous lots or whole subdivisions. The term "treatment train" is used to describe the combination of controls usually required in an overall stormwater management plan. Several SWM objectives list in the plan for new developments, can be grouped into the following:

- Prevent loss of life and minimize property damage and health hazards.

- Minimize inconvenience from surface ponding and flooding.

- Minimize adverse impact on the local groundwater systems and baseflows in receiving watercourses.

- Minimize downstream flooding erosion.

- Minimize pollution discharge to watercourses.

- Minimize soil losses and sediments to sewer systems and water bodies from construction activity.

- Minimize impairment of aquatic life and habitat.

- Promote orderly development in a cost-effective manner.

In Ontario, the MOE *Stormwater Management Planning and Design Manual* (2003) identifies the current approved practices that can be used for stormwater management and their capability to improve stormwater runoff from urban development (Table 2).

Table 2. Current Ontario Stormwater Management practices (MOE, 2003)

SWMP	Water Balance	Water Quality	Erosion	Water Quantity
Lot Level and Conveyance Controls				
Rooftop storage	Low	Low	Low	High
Parking lot storage	Low	Low	Low	High
Superpipe storage	Low	Low	Low	High

SWMP	Water Balance	Water Quality	Erosion	Water Quantity
Lot Level and Conveyance Controls				
Reduced lot grading	High	Medium	Medium	Low
Roof leader to ponding area	High	Medium	Medium	Low
Roof leader to soakaway pit	High	Medium	Medium	Low
Infiltration trench	High	High	Medium	Low
Grassed swales	High	Medium	Medium	Medium
Pervious pipes	High	High	Medium	Low
Pervious catchbasins	High	Medium	Medium	Low
Vegetated filter strips	High	Medium	Medium	Low
Natural buffer strips	Medium	Medium	Medium	Low
Rooftop gardens	Low	Medium	Medium	Low
End-of-Pipe Controls				
Wet pond	Low	High	High	High
Artificial Wetland	Low	High	High	High
Dry pond	Low	Medium	High	High
Infiltration basin	Medium	High	Medium	Low
Filters*	Low	High	Low	Low
Oil/grit separators*	Low	Medium	Low	Low

*** Water Quality suitability is highly dependent on sizing and by-pass design.**

In context with the Toronto WWFMP flow issues and objectives will be recognized in the City's Strategic Plan, Official Plan policies, zoning by-laws and Environment Plans, and the City will use both by-laws and incentives to achieve its goals. The City of Toronto, the TRCA, government agencies and community groups will undertake WWFMP management activities in a cooperative manner with emphasis on private stewardship and community involvement. Wet weather flow problems that originate beyond the City's boundaries will be addressed in a coordinated manner with headwater (upstream) municipalities (City of Toronto, 2003).

The ultimate goal of the WWFMP is to reduce and eliminate the adverse impacts of stormwater runoff from developed and natural environment in a timely and sustainable manner and to achieve a measurable improvement in ecosystem health of the watersheds (City of Toronto, 2003). Stormwater management goals are usually related to historical preservation, environmental protection, and economic development. In many cases, economics is the driving force that constrains the protection and preservation, and justifies undertaking a SWM plan (e.g. prior to urban development).

While not discussed in the MOE stormwater guidelines, another form of SWM is modelling. In Toronto, the TRCA has initiated and undertaken extensive groundwater and surface water modelling of local watersheds. Its goal in terms of watershed management is stated: to ensure that watershed ecosystems become an important attribute in community planning of road, sewer, and water supply systems, as well as protecting, preserving, and enhancing Toronto's watersheds. There are nine watersheds in the GTA; one of which is Duffins Creek. The Duffins Creek watershed covers 285 km^2, with the Oak Ridges Moraine at its headwater providing abundant groundwater volumes that support speckled trout, and large areas of forest and wetlands (TRCA, 2002a).

Because of economic and development pressures, the TRCA felt that a watershed strategy should be developed for the Duffins Creek watershed. It was recommended that the development of a SWM plan will help identify: features worth preserving, where development should occur, best management practices for subdivision development, and management practices green space corridors (TRCA, 2002a). "There are pressures on [all Toronto] watersheds due to a growing economy and an expanding urban boundary. Strategies are needed to ensure the resources in the watersheds are identified, protected, and preserved" (TRCA, 2002a).

While Duffins Creek may be one of the healthiest watersheds in the Greater Toronto Area, it is also one that is producing the most concern for the TRCA. In a hydrologic study for the Duffins Creek watershed conducted by Eyles et al. (1997), findings suggested that proposed urbanization would impact the water quality and quantity of two significant streams—Ganatsekiagon and Urfe Creeks. In this case, they stated that baseflow would decrease and that their findings anticipated stream impairment from urban runoff.

3. Research Need

In 1994, a report distributed by the TRCA recognized that stormwater runoff is one of the main contributors of pollutants into Toronto's natural drainage systems. It was further suggested that stormwater runoff receives the least amount of attention in terms of remediation (TRCA, 1994). This is not a new concept. For many years, researchers have found that increased urbanization has resulted in watershed changes of both the quality and quantity of water (Li, 1991; Wang and Yin, 1997; Brun and Band, 2000). However, only in the past ten years has society begun to see a revolution in watershed modelling.

This revolution is in part a result of GIS use as a tool for both visual output and statistical analysis.

The TRCA (2002b) states that in order to manage the Duffins Creek watershed, great care must be taken in order to ensure the natural balance of water movement. A water balance model accounts for the amount of water flowing within a watershed. The land-use changes accompanying urbanization are known to alter the overall water balance by the introduction of impervious surfaces and altering of natural drainage systems (Graham, 2002). Therefore, the nature of this land coverage must be quantified in order to produce effective watershed studies.

In 1997, the TRCA produced a report on the *Seaton Lands Hydrologic Data Base Development*, it was mentioned that the current modelling in the Duffins Creek watershed is sufficient for developing large scale planning strategies, but that existing hydrologic modelling practices lack detailed calibrated information.

It was recommended that given the hydrologic data collected over the past 30 years, an overall water budget analysis for the Duffins Creek watershed needs to be undertaken to assist in defining the issues related to the impacts of development on the watershed.

"Effective stormwater management criteria are one of the important management initiatives currently being practiced in the [Duffins Creek] watershed. The science of stormwater management is continually evolving and it is essential that watershed managers continue to demand the highest level of available technology and encourage the use of innovative design techniques" (TRCA, 2002b, 21). In order to limit the changes in a water balance system, a greater understanding of the distribution of local precipitation must be achieved. Since precipitation is variable in terms of space, intensity, and volume, there is a need to determine the how its spatial variation can influence runoff modelling.

4. Research Objectives

There are three objectives for this research:

- To develop a modelling methodology that integrates GIS and hydrologic models in a water balance analysis on a watershed basis.
- To demonstrate the effectiveness of PCSWMM GIS and ArcGIS in a water balance model for Reesor Creek.
- To calibrate the GIS-based water balance model by observing how differing techniques, in this case, lumped, clustered, and grid analyses can discretize both the landscape (e.g. landuse and soil type) and incoming precipitation. The efforts are to determine the flexibility of the models by observing generated runoff differences. Results will contribute to the understanding of which technique is best suited for modelling watershed features.
- To observe the effects of spatially distributed rainfall measurements and their effect on the three modelling approaches.

5. Research Scope

Historical practice has been to use lumped representation because of computational limitations or because data was not available to populate a clustered or grid model database (Vieux, 2001, 1). This is no longer the case today where modelling databases are becoming increasingly more discrete by the introduction of digital databases, analysis software, and the improved PC computational power to handle all of it.

By studying lumped, clustered, and grid modelling the study is able to identify the limitations that evolve from the three approaches (Figure 3). Research has demonstrated that there are significant problems with lumped modelling such as those identified by Burke (1995), Pullar and Springer (2000), and Vieux (2001):

- The model is not physics-based, in other words, there is a lack of numerical representation used for modelling routing and runoff.
- The model cannot approximate the real world accurately due to errors in the spatial structure of the lumped data.
- There is no account for variations in the watershed (e.g. rainfall, topography)—all parameters are assumed constant.
- Calibration and validation are dependent on parameter estimation, thus, increasing uncertainty.
- Equally good results can sometimes be observed by adjusting parameter values (e.g. this study to date).

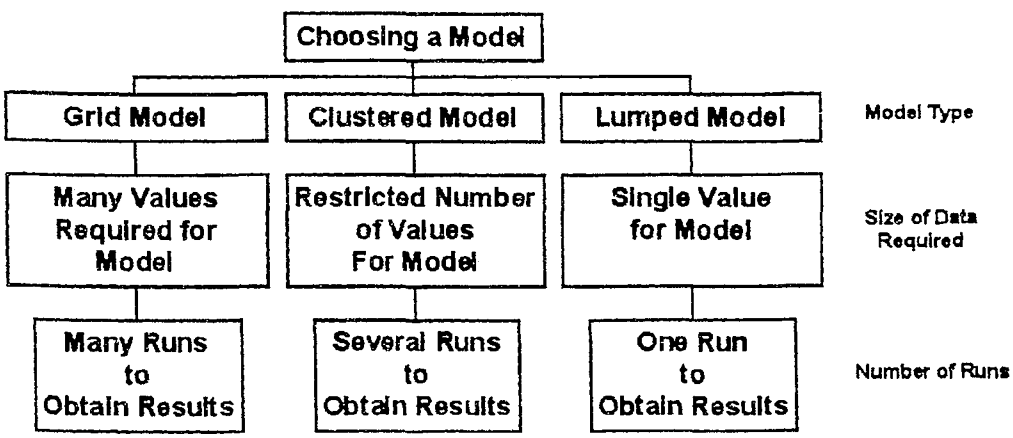


Figure 3. A flow chart depicting the discretization of a model (Burke, 1995).

A lumped model requires only a few average values to describe the attributes under study (e.g. average precipitation is 6.5mm for the entire watershed). Because of the few attribute values needed, usually one run of the model is all that is needed to obtain results. This type of model is usually generalized and can be significantly spatially and temporarily inaccurate. On the other hand, a grid model would require very detailed attribute data (e.g. average precipitation per pixel in the watershed) and result in many hours of analysis. However, the model would be more detailed both spatially and temporarily.

However, if the data permits, any lumped database can be turned into a semi-clustered model--this could be termed subwatershed modelling. This approach is still a lumped model approach, only slightly more discrete. An example of this would be the HEC-HMS/GIS model completed for the City of Cherokee in North-western Okalahoma. In this case, subwatersheds were assigned unit response function for incoming precipitation to characterize each subwatershed. The study began as a lumped data set (ASCE, 1999).

On the other hand, clustered modelling requires the watershed to be divided into a grid or smaller subwatersheds. Each cell or subwatershed will have its own detailed database representing its characteristics. The result is a far more discrete manner of analysis when compared to a lumped approach. However, clustered models are by no means perfect, and can only be as detailed as the data available. The sheer volume of the database that can be produced at a clustered or grid level would also increase when compared to a lumped approach (Burke, 1995). As stated previously, a clustered or grid model requires vast amounts of data.

For instance, Burke (1995) explains that in a water balance model for the Upper Guadiana watershed in Spain, a pixel resolution of 200m on a grid 900 by 850 pixels produces close to a million pixels. Each pixel was characterized with its own values for several attributes. A project like this will take some time to compute, and requires a significant amount of computer power. Today, ArcGIS on a high speed PC can complete this process, but will take several hours to calculate values for each pixel. The result was a highly detailed model of the watershed, which will only have value if the input data was also detailed and accurate.

In summary, Chapter 1 briefly reviewed the perspective of watersheds and stormwater management in Ontario. Emphasis however was orientated towards this study's need, objectives and scope. Chapter 2 will be a literature review of related modelling techniques and the methodology that supports the need for this research. Chapter 3 will describe the case study used for this research while Chapter 4 will describe the methodology applied to the case study. Chapter 5 describes the study's results in terms of lumped, clustered, and grid modelling and Chapter 6 discusses the results in context with data strengths and limitations, as well as what kind of new contributions the results has provided. Finally, Chapter 7 will conclude the findings of this study and elaborate recommendations.

Chapter 2

Literature Review

Chapter 2 is organized in a way that further clarifies the need, objectives and scope of this study. The purpose here is to identify how water balancing is a key component in watershed management. Recent technology advances in hydrologic modelling (e.g. USEPA SWMM model) and geographic information system (GIS) have paved a new direction is water balance analysis. This chapter will discuss the capabilities and contributions these technologies have made, and where they might continue to explore.

1. Water Balancing

In the early 1980s, watershed plans primarily addressed flooding and erosion concerns. Today, there are many issues that are addressed in a watershed plan; some of these include flooding, reduced baseflow, erosion control, protection of aquatic and terrestrial habitat, enhancement of water quantity and quality, to geomorphic changes and water balance (or budget) (MOE, 1993b). Natural watersheds maintain a balance between precipitation, runoff, infiltration, evaporation, and evapotranspiration (Cumming Cockburn Limited (CCL), 2001). It is necessary to understand the water balance of a watershed in order to develop and implement watershed procedures that are addressed in the watershed plan (CCL, 2001).

Generally, a water balance is composed of two inter-related components: the surface drainage area characterized by the topography and subsurface drainage, which is characterized by soil and bedrock features. As a result, water balance equations are used to define a watershed's hydrologic regime (CCL, 2001). On a regional basis, water balance in a watershed can be discussed as the change in storage (ΔS), which is equal to the sum of precipitation (P) and groundwater input (G_I), minus groundwater output (G_o), stream discharge (Q), and evapotranspiration (ET).

$$\Delta S = P + G_I - G_o - Q - ET \qquad 1.0$$

A second approach to evaluate water balance is to analyze the soil system. In this case, the change in soil moisture storage (ΔS_s) will equal the total infiltration (I), minus interflow (Q_s), groundwater recharge (R_g), and soil moisture evapotranspiration (ET_s) (CCL, 2001; Wanielista and Yousef, 1993).

$$\Delta S_s = I - Q_s - R_g - ET_s \qquad 2.0$$

It should be noted that the spatial and temporal characteristics of the watershed are contributing factors in water balance computation. Spatially, watershed topography will determine surface flow direction and quantity, while soil types and bedrock features will determine subsurface flow. On the other hand, temporally a watershed's storage capacity, precipitation rate, and percentage imperviousness will characterize how water is distributed within the watershed over time (CCL, 2001).

2. The Storm Water Management Model (SWMM)

The United States Environmental Protection Agency (USEPA) conceptualized and developed SWMM between the years 1969 and 1971 (Huber and Dickinson, 1992; Metcalf & Eddy, Inc, 1971; Nix, 1994; James and James, 2000.). Designed by a funding effort that was solely devoted to the development of hydrologic software, SWMM was the first of its kind and to date, reflects very little of the original version. Continual updates and additions have revised SWMM to become the most widely used urban runoff quantity and quality modelling program in the world (Huber and Dickinson, 1992). Table 3 outlines some of the revisions and versions that have improved the SWMM platform.

Table 3. Relevant SWMM upgrades (James and James, 2000; Nix, 1994; Huber and Dickinson, 1992; USEPA, 2002).

Date	Upgrade
1971	SWMM Version 1. • Metcalf and Eddy Inc. (MF) of Palo Alto wrote the runoff quality and STORAGE/treatment routines. • University of Florida (UF) wrote the TRANSPORT routines. In 1973, this became the EXTRAN (in 1977) developed from the original RECEIV block. • Water Resources Engineers Inc. (WRE) of Walnut Creek California wrote the original runoff quantity, RECEIV and GRAPH routines.
1976	SWMM Version 2 • Designed by UF, new additions included: design routines in TRANS, STORAG equations, and COMBINE block.
1981	SWMM Version 3 • Designed by UF new additions included: generic STORAG, line ID's, metric units, RAIN, TEMP and STATS block added, RECEIV block deleted.
1983	SWMM Version 3.3 • A personal computer (PC) version.
1984	PCSWMM • First PC user-friendly version of the SWMM program.
1988	SWMM Version 4 • USEPA developed for PC use with free-format data entry and natural cross-sections.
1991	SWMM Version 4.05 • Developed by UF.

Date	Upgrade
1992	SWMM Version 4.2 • Developed by UF.
1993	SWMM Version 4.21 • Developed by Oregon State University (OSU) • SWMM ported to Microsoft Windows environment, notably called PCSWMM.
1994	SWMM Version 4.3 developed by USEPA.
1995	SWMM Version 4.31 developed by OSU.
1997	SWMM Version 4.4 developed by OSU
1999	SWMM Version 4.4 gu developed by OSU, Camp, Dresser and Mckee (CDM)
2000	Enhancements to 4.4 gu by OSU (e.g. user interface)
2001-2	SWMM Version 4.4h developed by OSU and CDM • Reflect significant changes to the runoff block.
2003	SWMM Version 5 developed by USEPA and CDM for release in September. • A newly coded version of the SWMM (SWMM 5.0) computational engine that can be run either as a stand-alone application or as a Dynamic Link Library (DLL) of functions that can be called from other applications such as third party vendors of SWMM. • A GUI shell program that will run under Windows, access the SWMM engine through DLL calls, and include a context-sensitive, on-line Help system.

While all three original contractors have continued to modify and improve SWMM, there is no argument that SWMM improvements are largely a direct result of the continuous feedback from the public domain since recent versions reflect the input and critical assessments of many years of user experience (Huber and Dickinson, 1992).

SWMM is designed to simulate real storm events on the basis of rainfall (hyetographs) and other meteorological inputs, as well as system attributes (e.g. watershed, conveyance, storage/treatment) to predict stormwater runoff in terms of quantity and quality (Huber and Dickinson, 1992; James and James, 2000). Since study objectives may be directed toward temporal and spatial detail as well as to lumped effects (e.g. total contaminant discharge in kilograms), it is essential to have both time series output (e.g. hydrographs and pollutographs representing concentrations versus time) and daily, monthly, annual and total simulation summaries (continuous simulation) available for decision making (Huber and Dickinson, 1992).

SWMM was originally programmed using FORTRAN 77 code. Because of this, anyone who is familiar with FORTRAN can easily personalize SWMM to perform calculations that pertain to his or her study.

For any watershed, SWMM divides the watershed into subsystems—commonly termed blocks. An overview of the model structure is shown in Figure 4. In simplest terms, the program is described as follows:

- **The input sources:** the Runoff Block generates surface and subsurface runoff based on rainfall and/or snowmelt hyetographs, antecedent conditions, land use, and topography. Dry-weather flow and infiltration into the sewer system may be optionally generated using the Transport Block.
- **The central cores:** the Runoff, Transport and Extended Transport (EXTRAN) Blocks route flows and pollutants through the sewer or drainage system. (Pollutant routing is not available in the Extran Block.) Very sophisticated hydraulic routing may be performed with Extran.
- **The correctional devices:** the Storage/Treatment Block characterizes the effects of control devices upon flow and quality. Elementary cost computations are also made.

- **The effect (receiving waters):** the receiving water block (RECEIV) is no longer included within the SWMM framework since 1981. However, linkages have been developed for receiving water software such as EPA WASP and DYNHYD models (Ambrose et al., 1986; Huber and Dickinson, 1992).

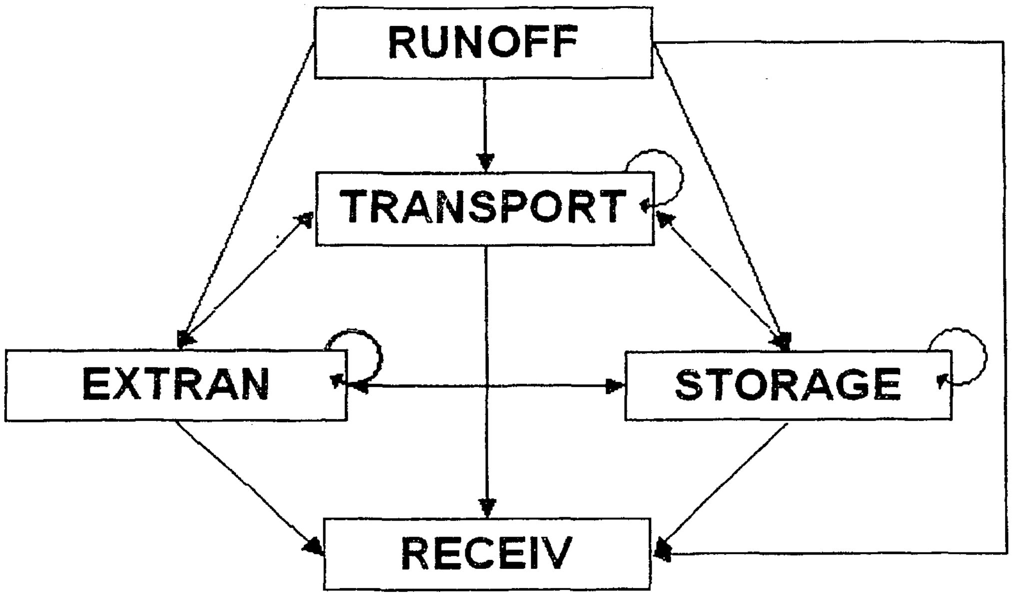


Figure 4. The SWMM model structure. It should be noted that the RECEIV block does not represent receiving water (Huber and Dickinson, 1992).

There is also several service blocks that can be linked to the above blocks that generate further analysis or data management (e.g. production of interface files). These blocks include: the statistics block, rain block, temperature block, and combine block. This study focused only on the runoff block.

2.1. Runoff Block

The runoff block (also termed module) was designed to simulate both the quantity and quality of overland runoff within a watershed. By dividing the watershed and adjusting subwatershed attributes (e.g. area, slope, and impervious area), the runoff block uses precipitation hyetographs (snow and/or rainfall), to calculate runoff attributes such as infiltration losses, depression storage, snowmelt, channel flow, and pollutographs that form subwatershed inlets (Huber and Dickinson, 1992, James and James, 2000).

For instance, Tsihrintzis and Hamid (1998) used SWMM to model the quantity and quality of urban storm runoff from four small watersheds in South Florida. The study's objective was to test the applicability of this model in small subtropical urban watershed's and provide modellers with a way to select appropriate input parameters to be used in planning study's. Using sixteen events (storms) for the simulation, results showed good comparisons with measured hydrographs and pollutant loading concentrations.

The runoff module may be run from time series that range from minutes to years. The watershed can be divided into a network of channels and pipes or inlets and outlets all of which can have parameters adjusted for characterization. Interface files are created for communication with other blocks or for analysis as pollutographs or hydrographs (Nix, 1994; James and James, 2000).

The runoff block is described as the most important aspect to modelling with SWMM, as well as the most likely portion of the SWMM model that will need to be calibrated (James and James, 2000). A typical input file for the runoff module would include attributes such as snowmelt, evaporation, precipitation, water quality, subwatershed, and conduit data that are all represented in the runoff block. While the runoff module can be interfaced with other modules (e.g. rain and transport blocks), the runoff block has the option to run stand alone. In other word, all of the attribute characteristics of a watershed can be modelled from one runoff block. Watershed simulation is represented by the aggregation of all of the watershed's subwatersheds, which can be represented as surface, gutter, or stream flow. For this study, the runoff generated by

SWMM will be representing overland runoff contributing to stream flow. In this case, calibration will be with the provincial stream gauging station 02HC039 (discussed later).

3. Geographic Information System (GIS) and Watershed Modelling

Today's computers have evolved into powerful analysis tools that exceeded the expectation of its predecessors. The introduction of the desktop GIS has revolutionized the way the world views geography and cartography. Goodchild et al. (2001) stated, "Science and practical problem solving are no longer distinct in their methods, that GIS can bridge the gap between the two".

"In the strictest sense, a GIS is a computer system capable of assembling, storing, manipulating, and displaying geographically referenced information (e.g. data identified according to their locations). Practitioners also regard the total GIS as including operating personnel and the data that go into the system...GIS technology can be used for scientific investigations, resource management, and development planning." (United States Geological Survey (USGS), 2002; Meloncon, et al., 1999; and Tarboton, 2000).

In a GIS, data is much more flexible in the way it can be represented. Spatial data in a GIS can be displayed just like a paper map features are represented complete with legend, border and titles, or it can be represented as a set of statistical tables, which can be converted to charts and graphs. The most important feature of GIS is that spatial data are stored as a spatial database (Digital Land Systems Research (DLSR), 2001).

There are two methods of storing mapped information: in vector format and in raster format. In vector format a GIS stores data as points, lines, and polygons, while in raster format, a GIS stores map features in grid format, and generalizes the location of features to a matrix of cells (Figure 5). In most cases, raster GIS data structures are preferred for digital elevation modelling (DEM), statistical analysis, remotely sensed data, simulation modelling and natural resource applications.

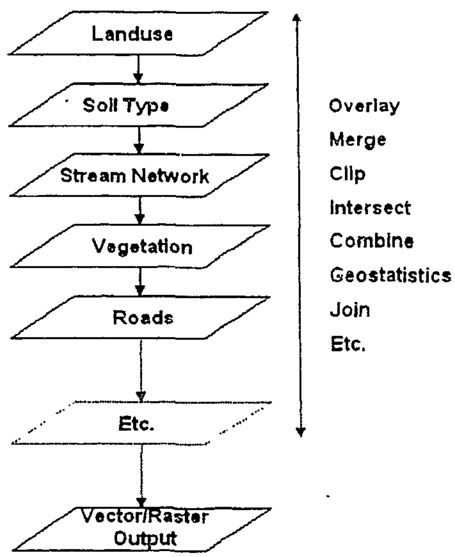


Figure 5. GIS analyzes data using layers (DLSR, 2001).

GIS provide the medium needed for improved processing and analysis of spatial and temporal information (Fiorentino and Singh, 1996). Information such as precipitation, evaporation, land-use, soil type, storage, and overland or groundwater flow are spatially variable information. GIS is beginning to provide the platform needed to develop improved modelling approaches that will increase the accuracy of water balance simulations (ESRI, 2002b; Maidment and Djokic, 2000; and Goodchild et al., 1993).

Cumming Cockburn Limited (CCL) (2001) and Maidment and Oliveria (1995) suggest that there are three roles of GIS in water balance modelling: data exchange, providing the GIS interface, and integrating the hydrologic model as a part of the GIS. In terms of data exchange, the GIS is able to calculate the parameters that apply to surface and groundwater models. For example, the many attributes that are needed in a hydrologic model, such as flow rates, precipitation, and land-use usually have very different formats. GIS is able to make all the differing layers of data compatible for analysis using spreadsheets and statistical software packages that are incorporated into the GIS.

Unlike conventional, non-spatial hydrologic packages, the GIS interface provides a direct communication link between the water balance model and spatial locations. The computing languages that are compatible with GIS software such as ArcGIS include Visual Basic, Visual C++, Avenue, and Delphi. This diverse language capability allows for the input files of the water balance model to be analyzed by the GIS and produce output files that can be used in the water balance model and which are now spatially registered (ESRI, 2002b and CCL, 2001). For example, by taking the results of several data files produced on hydrologic software such as SWMM of storage, drainage, flow rates, infiltration, etc. and overlaying them in the GIS, a statistical analysis of all layers can be run simultaneously. Anomalies can be adjusted from both the input hydrologic data (PCSWMM) and the GIS data. This makes for a user-defined environment and adjustable model, which includes spatially distributed parameters for independent and dependent variables.

Finally, in terms of the integrating the GIS and water balance properties, once the data of the hydrologic model are entered into the GIS the user can look at the model in hydrologic units. In other words, the GIS can apply a grid to the data layers and divide the data into cells that have their own characteristics (Figure 6), as is commonly used in hydrologic models (Nijssen et al., 1996 and CCL, 2001).

As a result, this approach to water balance analysis allows the water balance computations to be applied to an individual cell or pixel, instead of lumped together as a watershed or subwatershed (CCL, 2001). The result is a new hydrologic model that will have increased detail and be more representative of the real world

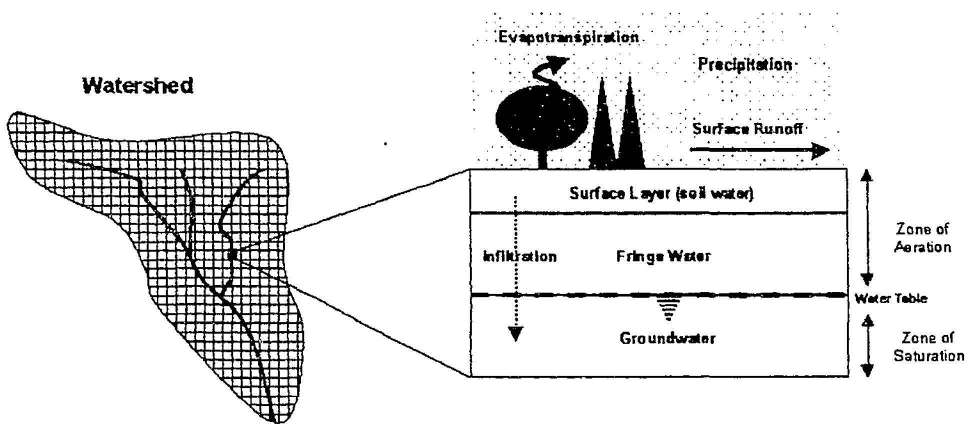


Figure 6. GIS can discretize a hydrologic model if the database permits (Vieux, 2001).

By using this integrated approach, a large data set must be made available and in order to compute the model; many runs (tests) must be completed—this is usually the most time consuming for this kind of study. The term "run" refers to the number of times the model is tested to produce an overall result. For example, if a water balance model is designed in a GIS, the number of runs is the differing statistical and spatial analysis that is conducted on the model to increase the models accuracy. As a result, the more runs that are conducted on a model, the more time is consumed.

"Considering the spatial character of parameters and precipitation controlling hydrologic processes, it is not surprising that GIS has become and integral part of hydrologic studies. Difficulties in managing and efficiently using spatial information have prompted hydrologists either to abandon it in favour of lumped models or to develop more sophisticated technology for managing spatial data" (Vieux, 2001, 1).

Similar to SWMM, there are volumes of literature available regarding GIS and its applications to watershed modelling. Many authors have used the GIS as a tool to prepare data for external program or analysis (Yoon, 1996; Mattikalli and Richards, 1996), and many other authors have used GIS strictly for mapping results or even discrete data analysis used it for discrete analysis (Brun and Band, 2000).. But whatever it is used for, they all have one thing in common—watershed modelling. The following will outline only some of the copious amount of resources available in this type of modelling.

In the simplest form GIS was used to display ecological risks to decision makers in a case study for the Brunette River watershed in British Columbia by Zandbergen (1998). A conceptual model was developed and sets of indicators were chosen to assess the impacts of urbanization on local streams. The indicators included: impervious area, riparian habitat, pollutant loadings, water quality, sediment quality, and fish and public health. The information extracted from each of the indicators was given a score. Two of indicators (imperviousness and water quality) were incorporated into a GIS to portray areas of concern with the watershed.

Prisloe et al. (2001) describes an ArcView GIS based model being developed by the Northeast Regional Earth Science Applications Centre that estimates imperviousness at the local watershed level. The model uses land-use land-cover data interpreted from multi-temporal 1995 Landsat TM imagery and land-use / land-cover-specific impervious surface coefficients derived from large-scale planimetric data from Connecticut towns that range from rural to urban. The model allows the user to evaluate all watersheds completely or partially within a town and generate a screen display, which depicts estimates of stream quality based on existing land-use and land-cover conditions. When assessing a single watershed there is an option to change existing forest and agricultural land to urban land uses to calculate future increases in impervious surface area and its impacts on water quality. Designed as a management tool, Prisloe's Research contributed interactive capabilities for decision makers that allow the user to visualize the affect landuse has on runoff.

Unlike the Brunette Beach study (previous page), a stormwater master plan using GIS was completed for the Blue River watershed in Johnston County, Kansas. The study focused on the developing a plan that addressed current affairs and provided guidance for further growth (Sauer and O'Neill, 2000). The study applied two modelling tools: the US Army Corps of Engineers HEC-Geo RAS and ArcInfo/ArcView. It should be noted that the HEC-GeoRAS used in this study to delineate the Reesor Creek drainage boundaries is the same as the tool used in Sauer and O'Neill (2000). In this case, ArcInfo was used to develop the parameters generated by the coverage's of landuse, soil type, elevation, and Manning's (n) value. In total, 368 subwatersheds were modelled. The HEC-GeoRAS and ArcInfo georeferenced dataset was used in the HEC-RAS model in order to delineate the stream network and geometry. The result was detailed input and output floodplain data which in turn generated floodplain polygons that could be overlaid in ArcView with other landuse coverage's for decision makers. In addition, using ArcView scripts, the floodplain coverage's could effectively be displayed, queried, and exported for use in HEC-RAS.

On the other hand, a detailed runoff simulation was completed by Saghafian et al. (2002) where a new method of time-area analysis is discussed. The method uses time variable isochrones, such as that the runoff hydrograph positively responds to temporal changes in rainfall intensity. The method uses a kinematic-based travel time scheme, which improves existing isochrone extraction techniques. A raster grid is discretizes and supports rainfall and runoff simulations in a modular distributed model. A DEM was used to extract values of ground slope, flow direction, and flow accumulation maps to characterize the terrain. The isochrone time series constituted the travel time for runoff hydrographs. The new algorithms generated by this model that re-defined traditional time-area/rainfall-runoff techniques to a distributed terrain-hydraulic based methodology. Thus, because the model is developed on variable isochrones, stationary constraints are relaxed.

Since there is extensive literature, several more readings regarding GIS and watershed modelling are recommended: Mason and Maidment (2000), Melancon et al. (1999), and Gao et al. in Maidment (1993). It was found that there was a lack of literature regarding the discretization of the watersheds using GIS in terms of grid modelling. While studies demonstrating lumped and clustered modeling were readily available, there was a lack of grid model literature. This may be because of the large database and advanced computing power needed in order to do so. While many authors recommended that the discretization of watersheds is the best way to observed landuse and spatial influences, in most cases, clustered (subwatershed) models was deemed suitable.

3.1. Rainfall Kriging

Interpolation in GIS assumes that the distance or direction between sample points reflect some kind of spatial correlation that can, in turn; explain variations in a surface (Burrough and McDonnell, 1998; ESRI, 2002**b**). Similar to inverse distance weighting, kriging weights surrounding measurements to predict a value for an unmeasured area. In other words, kriging is simply a surface interpolation technique that utilizes a statistical method of variance to form an estimate for a particular location (Vieux, 2001; ESRI, 2002**b** and Kirvoruchko, 2001).

Developed by Matheron Krig the general formula for is written:

$$Z(s_0) = \sum_{i-1}^{N} \lambda_i Z\,(s_i) \qquad 3.0$$

where Z (s_i) is the measured value at *ith* location, λ_i is an unknown weight for the measured value at *ith* location, and s_0 is the predicted location, and N is the number of values.

Kriging has two hypotheses: 1) the mean is constant throughout the region (Table 4), and 2) variance of differences is independent of position, but depends on separation (Figure 7) (Vieux, 2001 and ESRI 2002a). If the first does not occur, then a trend exists and must be removed. The second suggests that a variogram is determined for the data set; it may be used to estimate the variance for the region.

Table 4. The first kriging hypothesis assumes a constant mean throughout a region (Vieux, 2001 and ESRI 2002a).

Rain gauge Station	Average ppt. (mm/day)
Oshawa	2.8
Markham	2.2
Bowmanville	2.7
Buttonville Airport	2.4
Stouffville	2.6
Cherrywood	1.3
Bedford	2.3
Kimberly	2.0
Udora	3.2
Burketon	2.8
Janetville	3.1
Pontypool	2.3
Tyrone	2.1
Average	**2.4**

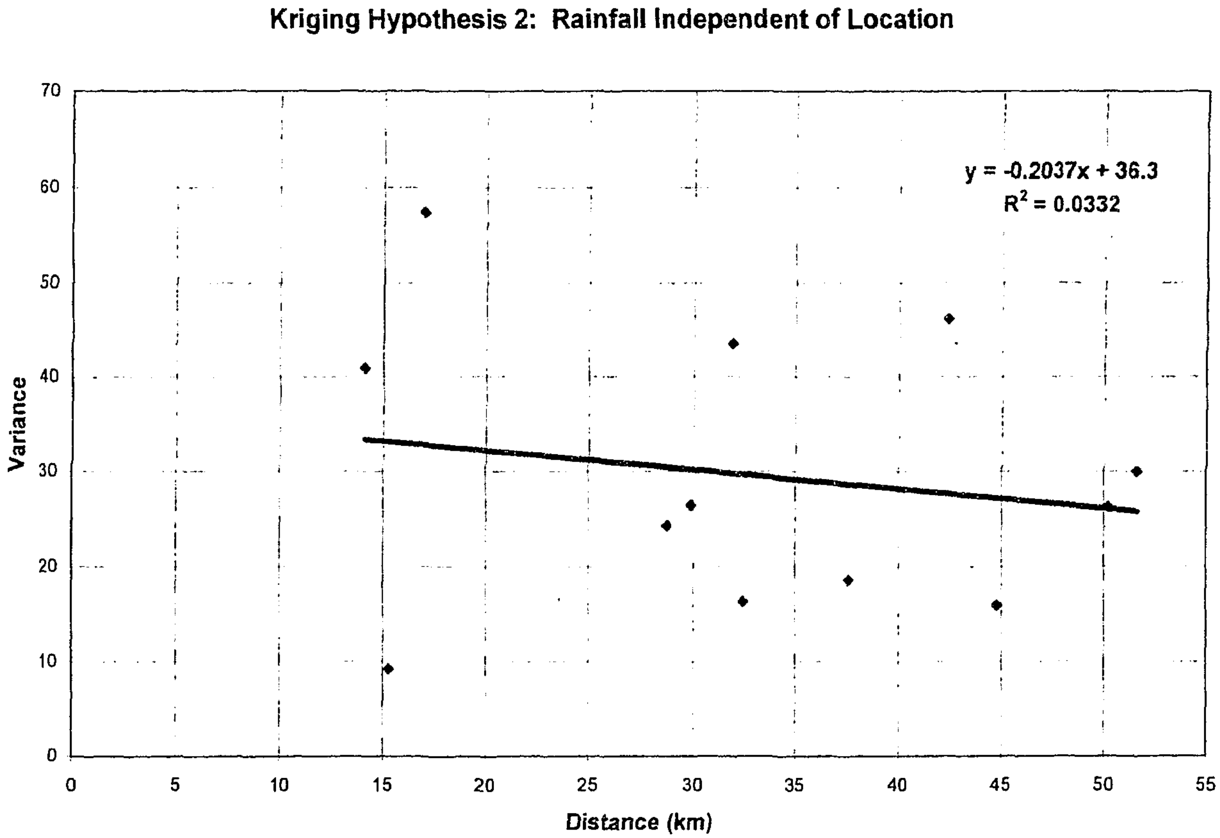


Figure 7. The second kriging hypothesis states that variance of differences is independent of position, but depends on separation (Vieux, 2001 and ESRI 2002a).

For this study, ordinary kriging will be used because it assumes that the constant mean for all the data measurements is unknown (ESRI, 2002b). A comparison of several models of ordinary kriging run on three rainfall events can be viewed in Appendix A. Since several of the rain gauges for this study are spatially distributed, kriging the rain gauge positions will produce layers of rainfall intensities. These layers can be hourly, daily, or monthly. The values produced by the layer can be re-run in the hydrologic model developed by PCSWMM.

Ordinary kriging is assumes the following:

$$Z(s) = \mu + \varepsilon(s) \qquad 4.0$$

Where μ is an unknown constant. One of the problems with ordinary kriging is determining if the assumption of a constant mean is representative. Johnston et al. (2001) suggests that there is good evidence to support the rejection of this assumption. Nevertheless, as a simple prediction tool, it is considered flexible and relatively accurate. Figure 8 depicts ordinary kriging in one dimension.

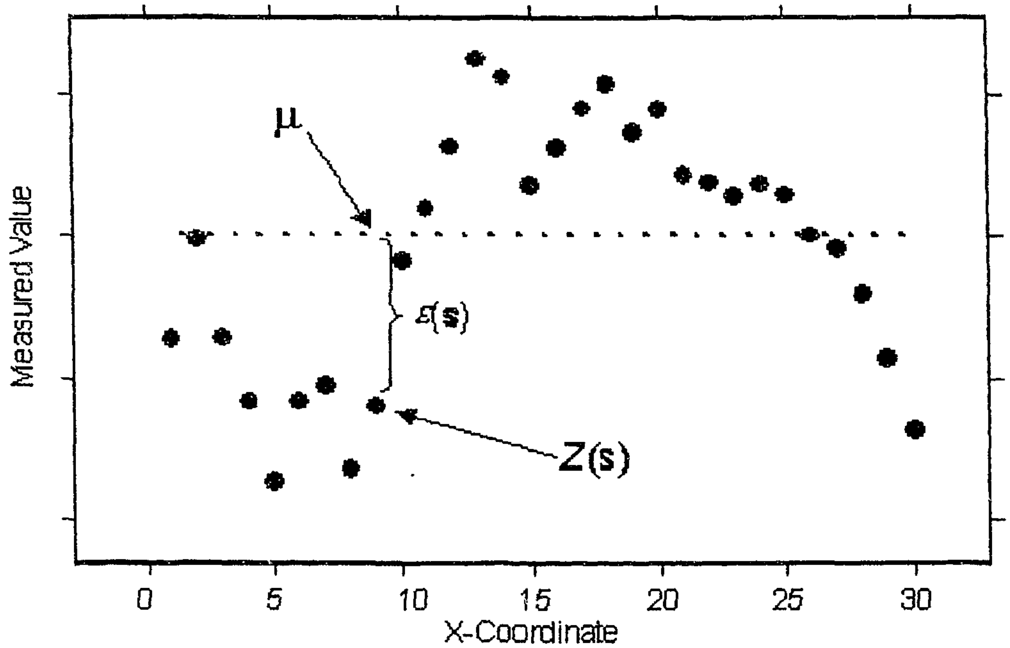


Figure 8. Ordinary kriging in one dimension (e.g. elevation along a transect) (Johnston et al. 2001).

The data in Figure 8 appears like the data is more variable on the left and becomes smoother on the right. In fact, this data was simulated from the ordinary kriging model with a constant mean μ. The dashed line depicts the true mean. Thus, ordinary kriging can be used for data that appears to have a trend. The trend cannot be determined by the data alone, whether the observed pattern is the result of autocorrelation alone (among the errors ε(s) with μ constant) or trend (with μ(s) changing with s). This is often a decision in context with a specific problem (Johnston et al., 2001).

A spatial dependent model, such as kriging, is termed a variogram—or commonly termed semivariogram. Another form of the variogram also includes covariance, however this study is only concerned with semivariance (Burrough and McDonnell, 1998). The semivariogram quantifies the assumption that distance things will be less similar to closer ones and that the strength of the statistical correlation is a direct function of distance (ESRI, 2002b). This characteristic is a direct relationship with the search neighbourhood. The shape of the neighbourhood restricts how far and where to look for the measured values to be used in the prediction. Other neighbourhood parameters restrict the locations that will be used within that shape (Johnston et al., 2001).

Semivariance is defined as:

$$\gamma(h) = 1 / 2N(h) \cdot \sum[Z(x_i) - Z(x_i+h)]^2 \qquad 6.0$$

Where $\gamma(h)$ is the estimated semivariance for the distance h, $N(h)$ is the number of measured point pairs in the distance class h, Z(…) is a measured value in (...).

Once the measured points are plotted, the semivariogram needs to be fitted accordingly. This is done by adjusting the *range*, the *sill*, and the *nugget*. Semivariograms plateau at certain distances; the point at which this plateau occurs is known as the range. The sill are the values in the semivariogram models in the range (y-axis), and the nugget is the distance along the y-axis between zero and the first semivariogram value that is not zero. It should be noted that the sill minus the nugget is termed the *partial sill* (Figure 9)

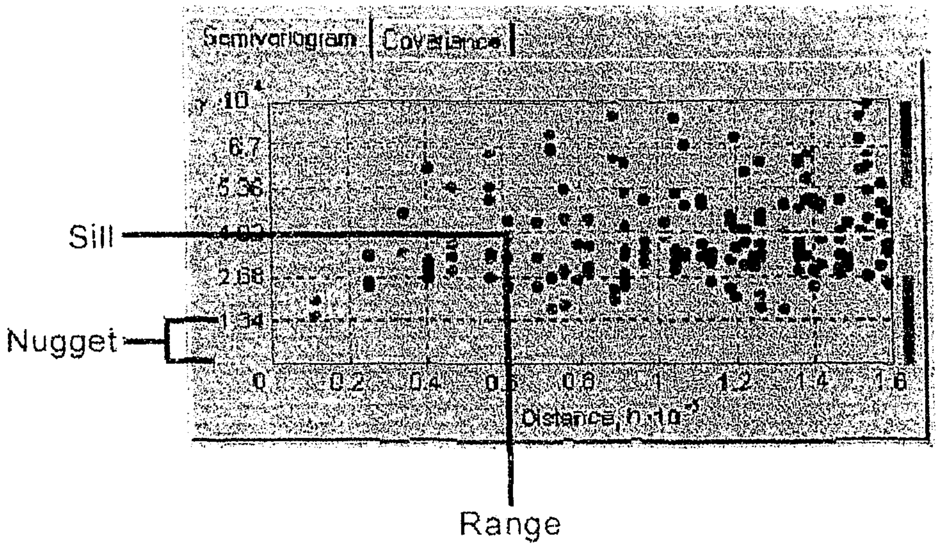


Figure 9. The *range, sill,* and *nugget* characteristic of a semivariogram (Johnston et al., 2001).

Literature regarding rainfall kriging was not extensive. However, there are several sources that suggested promise for interpolating precipitation from observed locations for input into SWMM. For example, in 1997, Kerry and Hawick discuss the distributed and high-performance computing technologies for spatial data interpretation. They observed the techniques for kriging and spline fitting, and the analyses algorithms for implementing these methods on distributed and high-performance computer networks. With their focus on kriging, a number of tests were conducted on comparing rainfall kriging to satellite imagery.

They state that rainfall prediction is an example of meteorological irregularities that make processes like kriging fitting for decision makers who need spatially distributed calculations (e.g. agriculture: likely crop yields based on rainfall distribution). In this case, the rainfall used for this kriging dataset was extracted from satellite imagery. Their results concluded that rainfall kriging is an effective interpolation method for ungauged rainfall area.

Similar to Kerry and Hawick (1997), Mizzell (1999) compared the kriging results of 62 rain gauges operated by the Columbia Airport National Weather Service and Doppler surveillance radar (WSR-88D) data provided by the National Weather Service for seven large rainfall events. Her results found that radar can't (yet) provide the spatial distribution of surface rainfall that is needed for many operational and research applications. This is because of the great variability in the intensity and distribution of precipitation. She recommends that more radar-gauge comparisons should be conducted covering a larger number of storms and that future research is being conducted on these results which include analysis of the radar level II base reflectivity data to determine whether error sources were caused by inaccurate reflectivity values, an incorrect Z-R conversion, or a combination of the two.

4. SWMM and GIS Integration

There is no shortage of literature regarding SWMM and GIS—the same goes for SWMM and GIS integrations. Today, there are many versions OF SWMM with differing user interfaces. However, the trend that can be seen is the protocol of combining SWMM and GIS software or processes. Companies and agencies like Computational Hydraulics International. (CHI), Boss International, DHI Software, XP Software, and the USEPA have taken it upon themselves to bridge the gaps between hydrologic/hydraulic modelling and spatial information. Even the GIS giant ESRI has realized the benefit of liking hydrology/hydraulic modelling and GIS by releasing its ArcHydro software.

The reason why this has become such a phenomenon in the modelling world is because the integration of GIS and SWMM redefines the discreteness of the model. In other words increased detailed in landuse, soil type, rainfall distribution, stream networking, elevation, slope, and much more can now be incorporated into SWMM modelling and hydrologic/hydraulic modelling of all kinds.

For instance, Tri (2002) combined ArcGIS and SWMM in a flood damage analysis for the southwest Louisville, Kentucky. The *Southwest Louisville Flooding Study* was a special challenge because of the large number of structures in the study area (68,000), the size of the study area (82.9 km^2), and the large amount of data being generated by SWMM (combined sewer overflow area with 4,800 sewer manholes). The GIS was used to generate the input for the HEC-Flood Damage Assessment (FDA) model, and to execute the model to obtain the economic impacts for the project conditions. Input data such as assessed property value, year of assessment, first floor elevation, style of structure, property use classification, parcel identifier, and address were generated using the GIS.

A challenging aspect of the study was to develop a method for determining predicted flood depths at each structure, based on the output of the SWMM model. Because the model only provided volumes of surcharge at each node, a method was developed to translate the discharge volumes to a flood elevation for each of the 68,000 structures (Tri, 2002). Because the watershed was flat, the discharge volumes spread across multiple subwatersheds. A custom ArcGIS/Spatial Analyst/VBA application was developed to distribute the volumes of water over the localized subwatersheds until equilibrium existed across the study area.

In another study by Choi and Ball (2002) a GIS was used to delineate the boundaries of the watershed, identify landuse, identify spatial variable controls (e.g. dams) and export the attributes to calibrate the SWMM model. The study set to find the effectiveness GIS would have in parameter estimation for hydrologic models. The study's results suggested that GIS was effective in calibrating their model and better estimating watershed parameters.

With the many interface versions of SWMM (e.g. PCSWMM, MIKE SWMM) a version entitled XP-SWMM was linked to ArcView using Avenue script that consisted of several tools which automated the spatial analysis process of data preparation for XP-SWMM and also displayed XP-SWMM results in the GIS (Hawary, 2000). On a subwatershed basis, a digital elevation model was used where the script extracted parameters for use in the runoff block of XP-SWMM. The results concluded that the interface accurately generated the terrain attributes and the runoff quantities displayed less than 10 percent difference.

Cera et al. (1999) had 280 subwatersheds where none of the subwatersheds had any surface hydraulic connection to one another. Input data for the SWMM model was developed from the soils, land use, and elevation contour map layers. The SWMM model was applied to both present and planned development land use conditions, using a 100-year, 24-hour storm event. The maximum flood elevation within each subwatershed was extracted from the model output using UNIX text processing tools. An ArcInfo AML script was created to take the maximum flood elevation results and assign all grid cells in the elevation grid below that elevation a special code. The new code was used to display the flooded areas in the desired colour. When compared to roads and structures, new flood maps identified the effects of runoff volumes from developing urban areas and identified subwatersheds that may have drainage problems.

Barber et al. (1994) used the GIS simply as a display tool for the spatially referenced data characterizing the drainage watershed. The conveyance system capacities, design flows, and inadequacies were all displayed on the drainage schematic.

In 1994, SWMM was used to simulate the runoff and transport of stormwater through a drainage network for three watersheds in Kansas City, Missouri. In many cases, data preparation for SWMM input parameters (e.g. soil, precipitation, and landuse calculations) is labour intensive. However, GIS was used by Barber et al. (1994) to simplify the management of data files required to run the SWMM model. A stormwater master plan was developed for the three Kansas City watersheds using Intergraph Microstation and an Oracle database. A Microstation Development Language (MDL) application was developed by Black & Veatch to integrate the information from the GIS creating the data files necessary to perform the hydrologic and hydraulic analyses of SWMM.

SWMM and GIS have also been linked to ecological assessments. In this case, sub-estuaries (both natural and conduit channels) draining a mostly urbanized watershed that were contributing to Bayou Chico in Escambia County, Florida, were modelled for event and dry weather flows to determine the contribution of pollution into the bayou. The GIS was used to decipher remotely sensed satellite images and generate surface layers (e.g. slope, drainage). The attribute files were analyzed to develop the database for the SWMM. This approach is similar to the one taken in this study (Schell et al., 2000).

So as you can see, the attempt to link SWMM and GIS is not a new concept, however, there is a lack of a relationship between using GIS, SWMM, and rainfall kriging. Chapter 2 briefly discussed water balance analysis and differing modelling interfaces. The lack of some links provides the guidance for this study where the intention is to explore new concepts, in this case, the link missing in Chapter 2. In Chapter 3, the study area will be described. This will also include the attributes of the input data representing the Reesor Creek watershed.

Chapter 3

Case Study: The Reesor Creek Watershed

This chapter will discuss not only the study area in terms of physical characteristics, but also in terms of the social and political issues that have evolved within it. It will describe the Reesor Creek watershed in two parts: macro scale and micro scale. In this case, the chapter will describe the Duffins Creek watershed (macro scale), which contains the Reesor Creek watershed (micro scale) to give some perspective of space and their social integration. Chapter 3 will also describe the characteristics of the input data used for the modelling.

1. The Reesor Creek Watershed

The Duffins Creek watershed is one of the healthiest watersheds in the GTA and consists of eleven subwatersheds (Figure 10). Located in southern Ontario and bordering the townships of Pickering, Stouffville, Uxbridge, Markham, and Ajax, Duffins Creek drains approximately 285km^2 of land and meanders from the Oak Ridges Moraine to the shoreline of Lake Ontario (Figure 11). The Moraine provides an abundance of groundwater into the watershed and its streams are habitat for speckled trout (TRCA, 2002a).

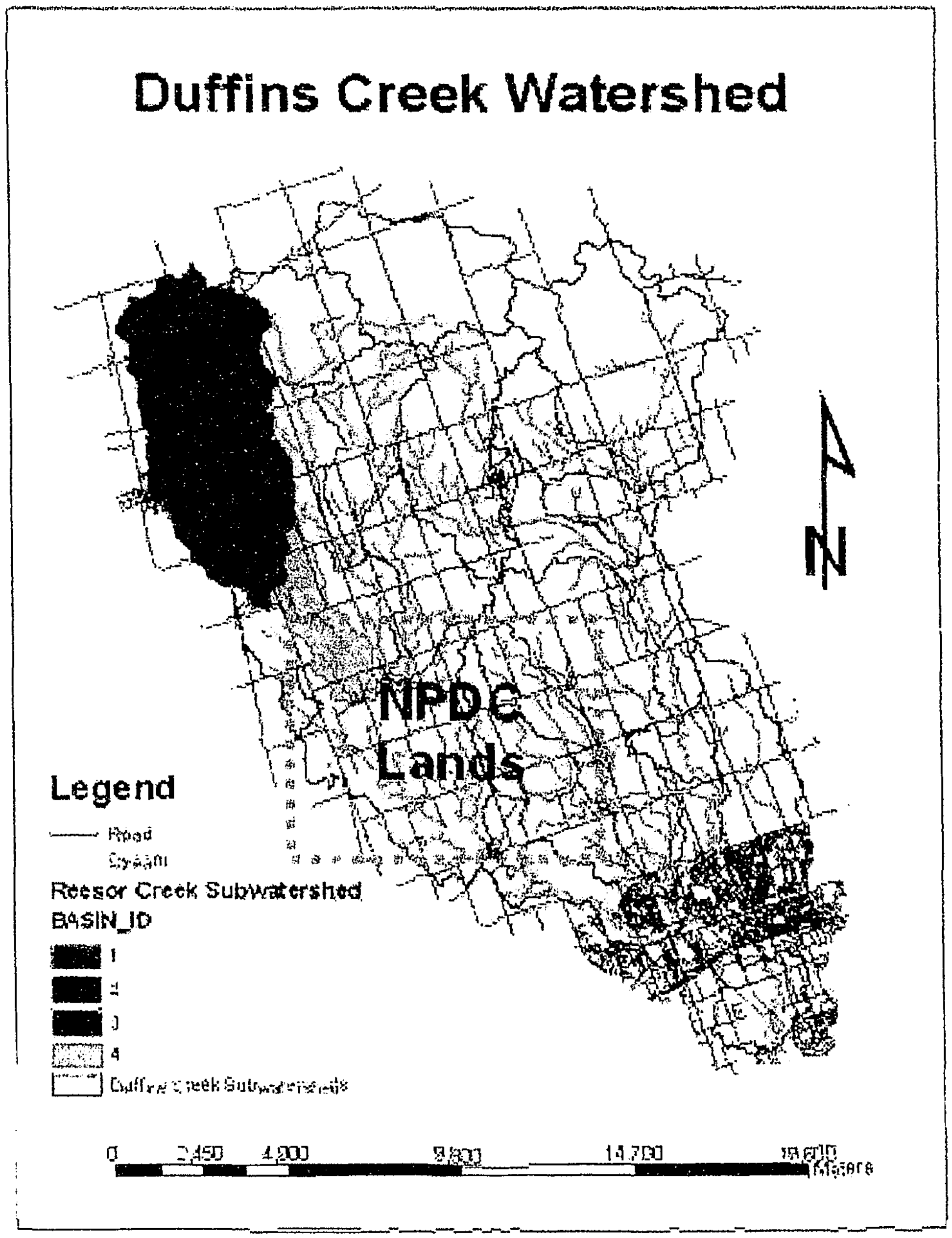


Figure 10. The Duffins Creek watershed and the Reesor Creek subwatershed (TRCA, 2000).

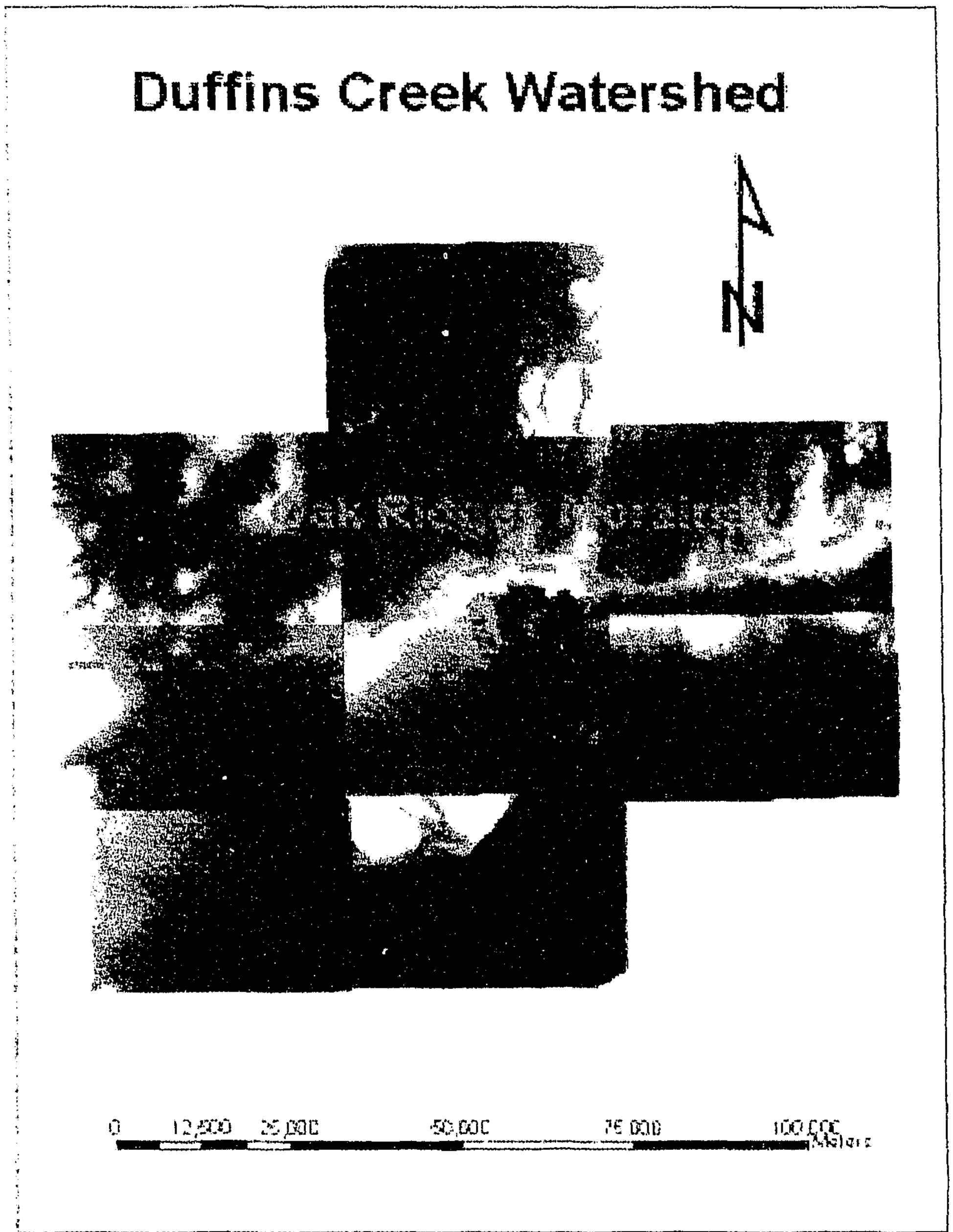


Figure 11. The Oak Ridges Moraine in context with the Duffins Creek watershed. The lowest elevation is black and the highest elevation is white (TRCA, 2000; DMTI, 2002).

Due to economic and development pressures, the TRCA has recommended that a management strategy for the Duffins watershed is needed in order to ensure that its resources are protected and preserved. The following is a list of the issues identified by the TRCA (2002a) that are currently affecting the Duffins Creek watershed:

- Keeping the watershed's healthy while accommodating growth.
- Promoting tourism in the watersheds and protecting the resources upon which public use is based.
- Improving water quality.
- Minimizing flood and erosion risk.
- Conserving the natural environment and biodiversity.
- Conserving heritage and a sense of place.
- Protecting the Oak Ridges Moraine within the headwaters in light of new provincial legislation and its conservation plan.

The GTA has seen several flooding disasters (e.g. Hurricane Hazel—1954). The result has been a stormwater initiative that has heavily monitored GTA watershed's including ongoing measurements of precipitation, stream flow, and snow pack melt. Since 1965, governments and conservation authorities have actively monitored the Duffins Creek watershed in order to characterize the attributes of the Duffins drainage system. The monitoring study's were primarily established to gather background hydrologic data that would guide any development processes, design flood control structures, and predict flooding within the watershed. At least one third of the watershed is developed or is under development and two thirds is rural lands.

In the early 1970s, the Ontario Reality Corporation (ORC) purchased the North Pickering Development Corporation Lands (NPDC) (2850ha) as a development initiative—Seaton Community (Bowen, 1997; TRCA, 1997). It is expected that the residential and commercial development will cause the NPDC lands and other municipality lands to increase in area for the next 25 years as a result of population projections. Table 5 illustrates the municipal population projections for the Duffins Creek watershed. The result will be a significant change in land-use, and affects to its overall water balance.

Table 5. Municipal population projections for the Duffins Creek watershed (TRCA, 2002b).

	1996	2006	2011	2016	2021	2026
Markham	179 100	253 000	281 000	304 000	326 000	384 000
Stouffville	20 500	27 000	31 000	35 000	38 000	41 000
Pickering	81 400				*145 000	
Ajax	66 500				*120 000	
Uxbridge	16 300				*12 500	

*Targets for urban areas only.

In a study by Riemann (1999) the effects of land-use changes on the Dessau watershed in Germany were quantified based on percentage imperviousness. Table 6 summarizes Riemann's results, which supports the TRCA's concern with projected land-use changes on the Duffins Creek watershed.

Table 6. Watershed characteristic changes for the City of Dessau, Germany (Riemann, 1999).

% Impervious	Runoff	Evapo-transpiration	Interflow	Recharge (mm/yr^{-1})	Precipitation
0	26.50	318.00	121.90	63.60	530
5	38.16	313.76	115.54	62.54	530
40	170.13	253.87	63.60	42.40	530
60	257.58	204.58	37.63	30.21	530

% Impervious	Runoff	Evapo-transpiration	Interflow	Recharge (mm/yr^{-1})	Precipitation
80	340.79	159.00	14.84	15.37	530
100	424.00	106.00	0.00	0.00	530

For example, on May 13, 2000, a 50 to 60 mm rainfall event occurred within the Duffins Creek Watershed. Because Duffins Creek is primarily rural, it took approximately 13 hours to peak with flows ranging from 5 to 83m^3/s from the start until peak discharge (TRCA, 2002b). In comparison, an urban watershed such as the Don River (approximately 20km west the Duffins Creek watershed) peaked in approximately 4 to 5 hours with double the flows of Duffins Creek (TRCA, 2002b). It should be noted that both watersheds are similar in both size and shape.

In another example, while the discharge of water may be greater in an urbanized watershed, also affected is the baseflow. For instance, the annual flow of Highland Creek—a predominately urbanized watershed and immediately west—was compared to the Duffins Creek. The Duffins Creek watershed infiltrated precipitation that would eventually become stream flow and displayed a greater stream flow volume, while the Highland Creek watershed exhibited less stream flow, since the watershed is approximately 85 percent impervious. Runoff in this 1991 case is immediate and stream flow is lower because of storm sewer diversions and a lack of infiltrated precipitation of recharge baseflows (TRCA, 2002b).

While the Duffins Creek watershed will not be modelled in this study, the previous discussion identifies some of the critical issues and characteristics that pertain to it—and in turn, to the Reesor Creek watershed.

The Reesor Creek watershed is one of eleven subwatersheds that make up the Duffins Creek watershed. The Reesor Creek watershed is also divided up into four subwatersheds (1 through 4), where each watershed drains to the provincial stream gauging station 02HC039 (Figure 12). When referring to Figure 12, it should be noted that Stouffville Creek also contributes to gauge 02HC039 (subwatersheds 1 and 2). Collectively, all four subwatersheds are commonly known as the Reesor Creek watershed.

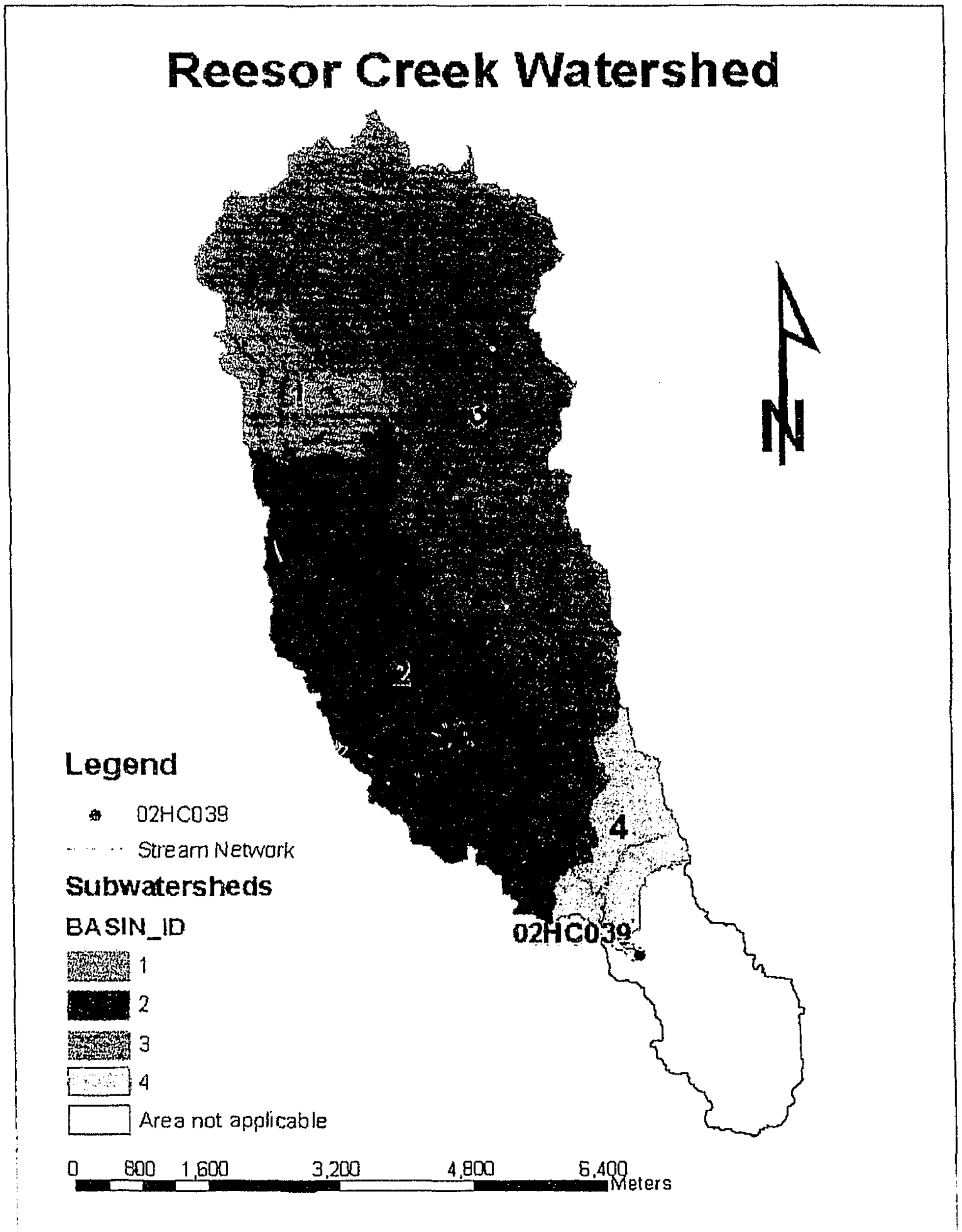


Figure 12. The Reesor Creek subwatersheds 1 through 4 and stream gauging station 02HC039.

The Reesor watershed drains an area of approximately 35 km^2. It is a rural watershed underlain with predominately loam soils, and as a result, the landuse is dominated by agriculture. Approximately, 10.4 percent of the watershed is urban (3.6 km^2) where development (Town of Stouffville) can be found in both subwatersheds 1 and 2 (Figure 13). Other landscape characteristics of the Reesor watershed consist of forest, meadow, wetland, and federal government owned green space. Table 7 summarizes the total area of each landuse.

As stated previously, the Duffins Creek watershed is primarily rural, where less than 1/3 has been developed. While the Reesor Creek watershed is smaller, and has similar landuse, it was considered a good representation of the Duffins Creek drainage network. In terms of calibration, the Reesor watershed has several advantages, for instance, a rain gauge and the stream gauge are located in the watershed. There are also well-defined watershed boundaries and a simplified drainage network.

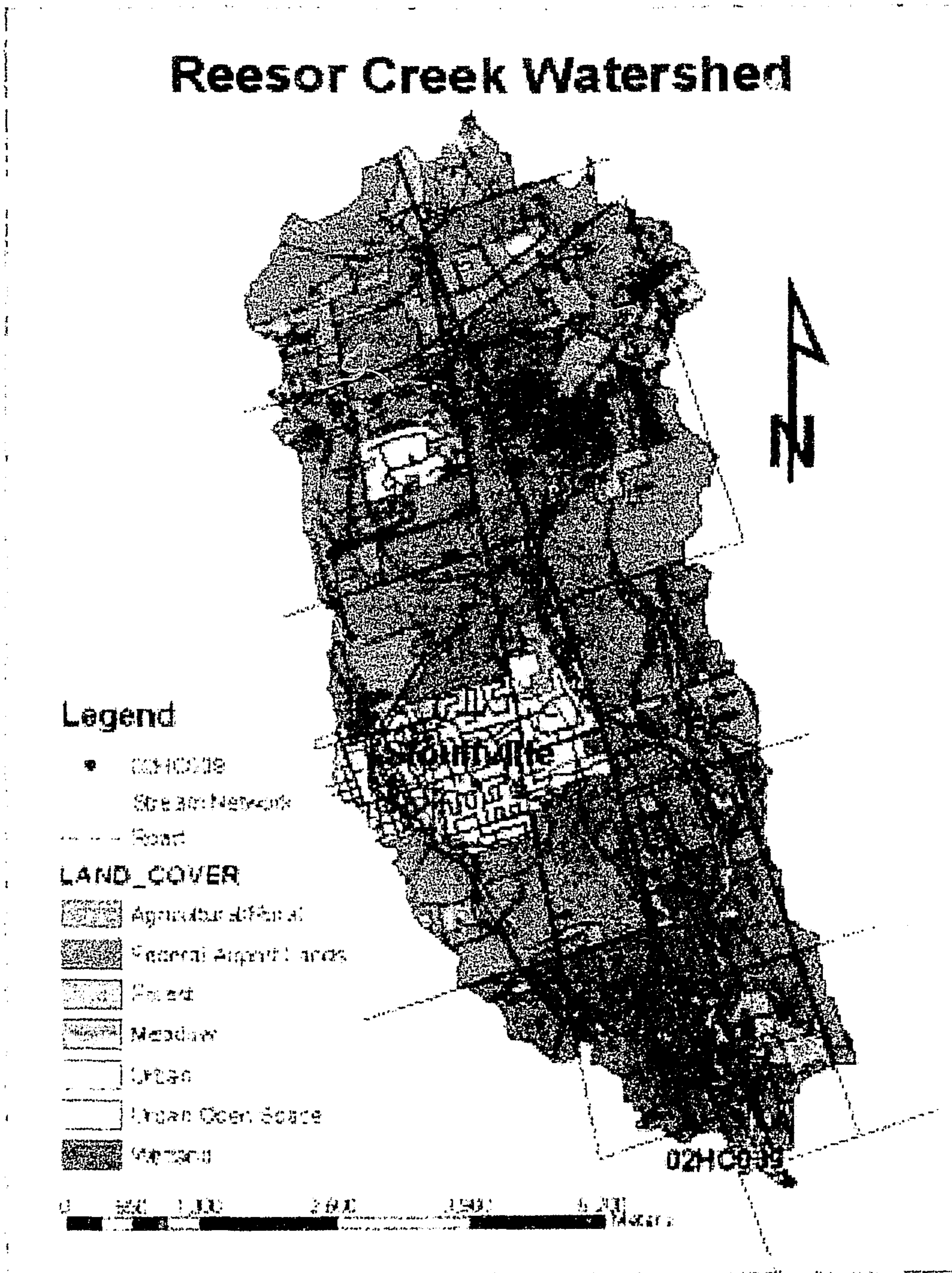


Figure 13. The Reesor Creek watershed landuse.

Table 7. **Landuse area for the Reesor Creek watershed.**

Landuse	Number of Polygons	Average Area (km²)	Maximum Area (km²)	Minimum Area (km²)	Total Area (km²)
Agriculture / Rural	310	0.06	0.88	1.0×10^{-8}	17.4
Federal Green Space	132	0.04	0.45	1.0×10^{-8}	5.1
Forest	526	0.01	0.22	1.0×10^{-8}	4.9
Meadow	271	0.01	0.11	4.0×10^{-8}	2.7
Residential / Urban	73	0.05	0.68	3.4×10^{-7}	3.4
Urban / Residential Open Space	14	0.02	0.05	1.9×10^{-7}	0.2
Wetland	132	0.01	0.28	2.4×10^{-6}	1.3
				Total	**35**

2. The Reesor Creek Watershed Data Characteristics

In many cases, data formats vary between measuring devices. For this study, measured rainfall was converted into similar time-series. In several cases, rainfall was measured in hourly intervals, however, because the majority of the data available was in daily measurements, all hourly data was converted into daily (Table 8).

Table 8. Rain and stream flow gauging station measurement attributes.

Station	Reading Time-step	Units	Converted Units
	Rain Gauge		
Stouffville	Daily	mm/day	NA
Markham	Hourly	mm/hr	mm/day
Bowmanville	Daily	mm/day	NA

Station	Reading Time-step	Units	Converted Units
	Rain Gauge		
Oshawa	Daily	mm/day	NA
Pontypool	Daily	mm/day	NA
Udora	Daily	mm/day	NA
Janetville	Daily	mm/day	NA
Cherrywood	Daily	mm/day	NA
Bedford	Hourly	mm/hr	mm/day
Kimberly	Hourly	mm/hr	mm/day
Buttonville Airport	Hourly	1/10 mm/hr	mm/day
Burketon	Daily	mm/day	NA
Tyrone	Daily	mm/day	NA
	Stream Gauge 02HC039		
02HC039	Hourly	m3/s	NA

In total, thirteen stations were chosen for this study. Three of these stations (Markham, Bedford, and Kimberly) were installed for research purposes (Markham) or owned and maintained for continuous monitoring by the City of Toronto (Bedford and Kimberly). The other ten gauges were owned and operated by Environment Canada's Atmospheric Environment Service (AES). All of the AES stations were recorded in mm/day.

The rain gauges chosen for this study represent approximately 5000 km^2. The area is delineated with Udora in the north, Kimberly in the south, Bedford to the west, and Pontypool in the east (Figure 14). Each station varied significantly in time-series length and dataset completeness. For this study, May to November 1999 was chosen because it was the only time-series that was mostly complete (full data set) at all thirteen stations. It should be noted that Pontypool and Tyrone have significant data gaps in the months of May/June and November respectively (Table 9).

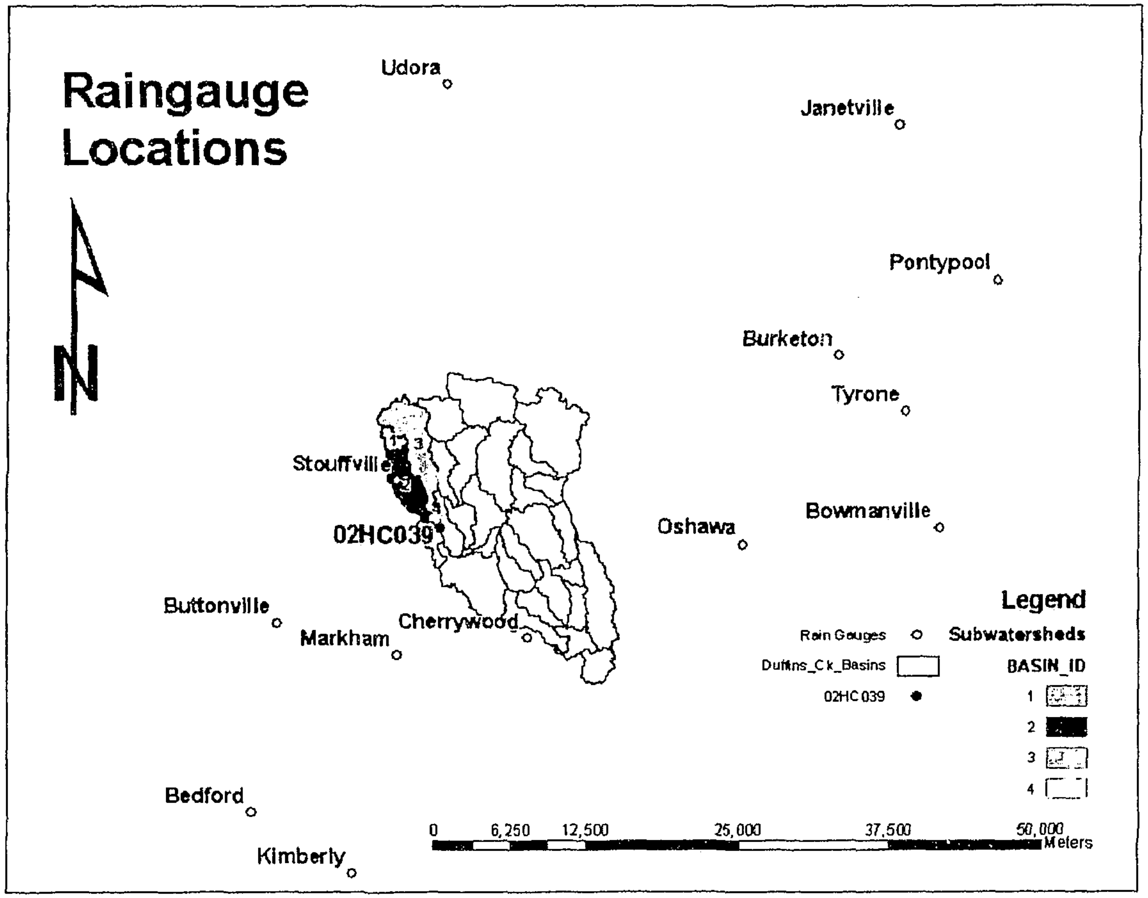


Figure 14. The spatial distribution of rain gauging stations about the Reesor Creek watershed.

Table 9 further depicts some of the characteristics of all thirteen stations. All stations were correlated to the Stouffville gauge since it is the only gauge that is located in the Reesor Creek watershed. Buttonville Airport, Bowmanville, and Kimberly were observed to be the top three highest correlations (0.859, 0.757, and 0.757 respectively) while Cherrywood, Tyrone, and Markham was the lowest three (0.129, 0.438, and 0.457 respectively). Appendix B lists the full precipitation time series for all thirteen gauges.

In summary, this chapter discussed the study area and the characteristics of the input data. In Chapter 4, the methodology for this research will be described the links between GIS, SWMM, and rainfall kriging will be elaborated. It will also review how a hydrologic analysis can discretize a watershed into lumped, clustered and grid modelling.

Table 9. Characteristics of the precipitation gauging stations used in this study.

	Precipitation mm/month									UTM Coordinate		
Gauging Station	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Total**	**R^2**	**Easting**	**Northing**	**Distance to Stouffville Station (km)**
Oshawa	74.5	78.7	62.7	61	147	79.7	85.4	589	0.647	669171	4864705	28.7
Markham	38.3	90.9	13.2	19	113	89.5	99.9	464	0.438	640919	4855378	14.1
Bowmanville	73.8	69.8	51.7	69	143	76.2	104	587	0.757	685257	4865922	44.8
Buttonville Airport	48	89.2	60.4	70	83.4	77	80.9	509	0.859	631051	4858217	15.3
Stouffville	**58.2**	**77**	**60.8**	**63**	**117**	**83.5**	**101**	**560**	**1***	**640784**	**4869977**	**0**
Cherrywood	46.2	69	52.8	21	48.2	24.2	24.2	286	0.129	651327	4857270	17
Bedford	53.5	92.8	38.5	82	50.3	60	107	484	0.606	658897	4842807	29.9
Kimberly	43.4	61.8	24.6	67	110	54	59	420	0.757	637134	4838075	32.5
Udora	79.8	135	106	63	131	77.8	101	693	0.512	644839	4901879	31.9
Burketon	84	68.4	55.2	60	120	106	100	595	0.713	676741	4880115	37.6
Janetville	67.2	69.6	120	62	137	95.8	107	659	0.632	681742	4898635	50.2
Pontypool			108	62	120	93.1	108	491	0.663	690258	4885793	51.6
Tyrone	63.4	48	70	67	117	25.8		392	0.457	682553	4875519	42.4
Average	**60.9**	**79.2**	**63.4**	**59**	**111**	**72.5**	**89.7**	**517**				

**Note: All gauges were correlated to the Stouffville gauge.

Chapter 4

Methodology

This chapter will discuss the methodology of this research. The chapter is sectioned into several parts: the software used, data requirements and characteristics, data preparation, the GIS component, the PCSWMM component, and the flow duration curves for results observation.

1. Software

Several software programs from differing companies were used in this study. The software includes: Computational Hydraulics International (CHI) PCSWMM GIS 2002, Environmental Science Research Institute (ESRI) ArcGIS 8.3, Microsoft Excel, and the United States Army Corps of Engineers HEC-Geo HMS. Figure 15 depicts how the software will be linked for this study.

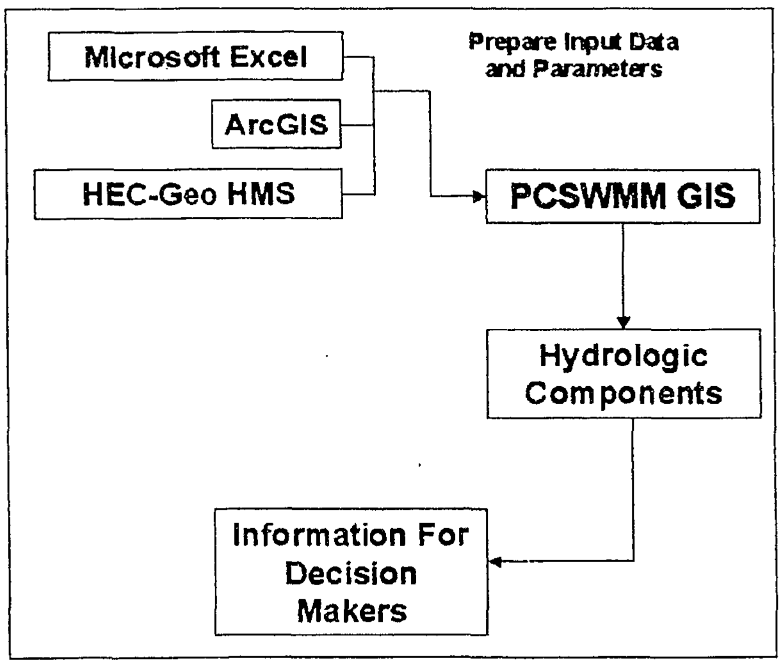


Figure 15. A flow chart depicting software links.

Microsoft Excel, ArcGIS, and HEC-Geo HMS were used to prepare the database for PCSWMM GIS, which in turn, generated the hydrologic components that represented the watershed.

1.1. PCSWMM 2002 GIS

The USEPA's SWMM was developed between 1969 and 1971 and has seen many amendments since then (Table 3, Chapter 2) (James and James, 2000). In 1993, the CHI redesigned the SWMM program as a Windows based program to be used on personal computers (PC) by hydrologic modellers—hence the name PCSWMM. Today, SWMM is the most widely used stormwater modelling program and its Windows based interface as PCSWMM, makes it a very user-friendly application. Recently, the release of PCSWMM 5 by the USEPA is also Windows based, however, it was not available during this study. PCSWMM was used to model the hydrologic components of the Reesor Creek watershed.

The stand-alone GIS provided in PCSWMM accommodates basic GIS needs, but it lacks the advanced analysis tools and overlay capabilities that ArcGIS provides. This is why PCSWMM is being used as a hydrologic modeller and file exporter for this study. In other words, the GIS application in PCSWMM GIS 2002 was not used because it did not provide the functionality needed for this study.

1.2. ArcGIS

ArcGIS can be accessed using three software blocks entitled ArcView, ArcEditor, and ArcInfo—each with differing functionality. Simply put, ArcView offers basic mapping, editing, analysis, and geoprocessing tools, while ArcEditor includes ArcView with advanced editing and geoprocessing capabilities. ArcInfo encompasses both have the previous blocks with several more advanced analysis and editing packages (e.g. ArcPLOT) (ESRI, 2001).

Appendix C depicts in greater detail the functionality of ArcView, ArcEditor, and ArcInfo. For this study, the ArcInfo block is used which a suite of specialized application tools has entitled ArcMap, ArcCatalog, and ArcToolbox--all three of these applications were used for this research.

ArcMap is the foremost ESRI GIS desktop software that allows the user to visualize, create, solve, present, and develop geospatial information in context with any type of geodatabase (e.g. populations trend, military strategies, or watershed planning) (Minami, 2000). ArcMap has a Windows based interface that displays toolbars overhead, a legend (layer) window, and a viewing window . The applications itself can be customized by adding differing ESRI analysis tool extensions such as *geostatistical analyst* and *spatial analyst*.

The *Geostatistical Analyst* (GA) extension was designed to bridge the gap between GIS mapping and geospatial statistics. It is used as an advanced analysis tool within the ArcMap environment to develop statistically generated surfaces (layers) that can be applied to typical mapping layers (e.g. landuse) (Johnston et al., 2001).

The GA uses sample points taken within the area under study (landscape) and generates layers by conducting a series of statistical calculations (e.g. kriging) that predict a particular phenomenon at sites where it has not been directly measured. The GA has two groups of interpolations techniques: deterministic and geostatistical. Deterministic techniques use mathematical functions for interpolation, while the geostatistical technique uses both mathematical and statistical functions for analysis (Johnston et al., 2001).

The *Spatial Analyst* (SA) extension enables the user to solve spatial problems with a wide range of tools. For instance, the functionality of SA can be divided as follows, the user can:

- derive spatial information such as landuse, calculate slope, determine distances, etc.;
- identify spatial relationships between differing datasets (e.g. outbreaks of Ecoli sickness in relation to the water treatment plant location);
- find suitable locations by querying map attributes (e.g. landfill locations); and
- perform least cost pathway analysis for calculating the minimal expense of traveling from one area to another (McCoy and Johnston, 2001).

ArcToolBox is designed to integrate and access over 100 of ArcInfo's geoprocessing and analysis tools (Tucker, 2000). ArcToolBox was used to convert ASCII format spatial data into coverage such as raster grids. The four main tools of ArcToolBox includes: data management, conversion, analysis, and personalized toolsets that give the user the ability to join, split, combine, and clip advanced coverage sheets (Tucker, 2000). For this study, the conversion option was used.

Finally, ArcCatalog is a powerful data management tool that allows the user to connect and access geospatial data in shared folders and databases stored on networks or Internet map services (Vienneau, 2001). ArcCatalog was used for map browsing, data exploration, metadata viewing and creation, searching, managing data sources, and linking both ArcMap and ArcToolbox through file swapping capabilities.

1.3. HEC-Geo HMS Extension

As stated previously, ArcMap has the capability to integrate software extensions to be made available with the ArcView platform. The United States Army Corps of Engineers developed a geospatial hydrologic modelling extension that is a public domain extension to the ArcView GIS and SA extensions (Doan, 2000). It should be noted that ArcView GIS is the predecessor to ArcGIS's ArcMap.

HEC-Geo HMS was designed to discretize lumped modelling approaches. With the ever-growing use of thorough radar, rainfall, and spatial databases (e.g. GIS and remote sensing), hydrologic modelling has evolved into detailed grid level analysis of watersheds.

The HEC-Geo HMS model can be summarized in three parts:

- A background file that delineates stream alignments and watershed boundaries.
- A lumped watershed model containing hydrologic elements and their connectivity (e.g. water movement throughout drainage system).
- If the input data (e.g. hydrographs and precipitation) reflects that of a distributed model, then HEC-Geo HMS can produce a grid-cell parameter file that is used in conjunction with the distributed watershed model to depict discrete grid-cell (sized) watershed attributes. In other words, HEC-Geo HMS can not only produce a lumped parameter model, but produce a distributed (subwatershed) model that is reflects the precision of the input data (Doan, 2000).

The HEC-Geo HMS is intended to process the terrain and spatial data and generate hydrologic inputs such as gauged precipitation, stream and watershed characteristics, and stream flow. The user has the ability to edit the connectivity of watershed attributes to better represent the model. One frequently used feature is the flow path delineation option where the user can choose a point within the watershed and based on the terrain layer; delineate the drainage area to the chosen point. For this study, this was the only option in HECGeo-HMS, which was used to define the drainage area of Reesor Creek that flowed past gauge 02HC039. The drainage area was simply overlaid on the subwatershed layer and clipped to the Reesor Creek subwatershed boundaries (See Chapter 3 Figure 12). This was done in order to remove the down stream polygon from 02HC039, which otherwise would have been included erroneously in area calculations later on.

2. Recommended Input Data

Below is a list of the necessary input data needed in order to complete this study:

- Measured precipitation
- Measured stream or channel flow
- Location of gauging stations
- Data layers for GIS

  –Landuse
  –Soil type
  –Stream network
  –Watershed/subwatershed boundaries
  –Gauging station locations
  –User defined grid (i. e. grid cell 1 km^2)
  –Digital Elevation Model of area

3. Baseflow Separation

The stream flow data was provided by the TRCA. It was confirmed that the station was calibrated every two months during the study period by correlating gauge 02HC039 with other portable gauges. The data was delivered in monthly data sets of flow and depth measurements. The flow data was organized into a continuous data set using spreadsheets.

This study used the hourly data instead of daily averages (to reflect rainfall values) because PCSMM is able to export runoff results in hourly time-steps. A comparison of hourly and daily average stream flow measurements can be observed in Appendix D. A 0.16 per cent difference between the daily average and hourly flows was calculated.

Runoff was extracted using a revised version of a baseflow separation technique used by Clarifica Inc. (2002). While there are many techniques described by several authors (Pilgrim and Cordery, 1993; Viessman et al., 1989) the Clarifica approach was chosen because it was used on the Duffins Creek watershed in 2002 and generated good results acceptable to the TRCA. It should be noted that flow measurements at least one week before and after the start and end of the study period must be included in the data set. The techniques can be described as follows:

- The stream flow was organized into a continuous time series.
- The minimum stream flow measurement starting twelve hours before and thirty-six hour after the measurement (2 day range) was extracted.
- An *IF* statement was prepared where if the current measured value is less then the average of the extracted minimum values, then return the

current measurement, if not, return the minimum average. The range of the minimum average was the same as step 2. These values are considered baseflow.

- The baseflow was then subtracted from the stream flow (Figure 16).

Several variations of this formula were attempted where the minimum was exaggerated over 3, 5, and 9 days, as well as, 12 and 24 hours. The two-day minimum and average used for this study produced the best results (Appendix E).

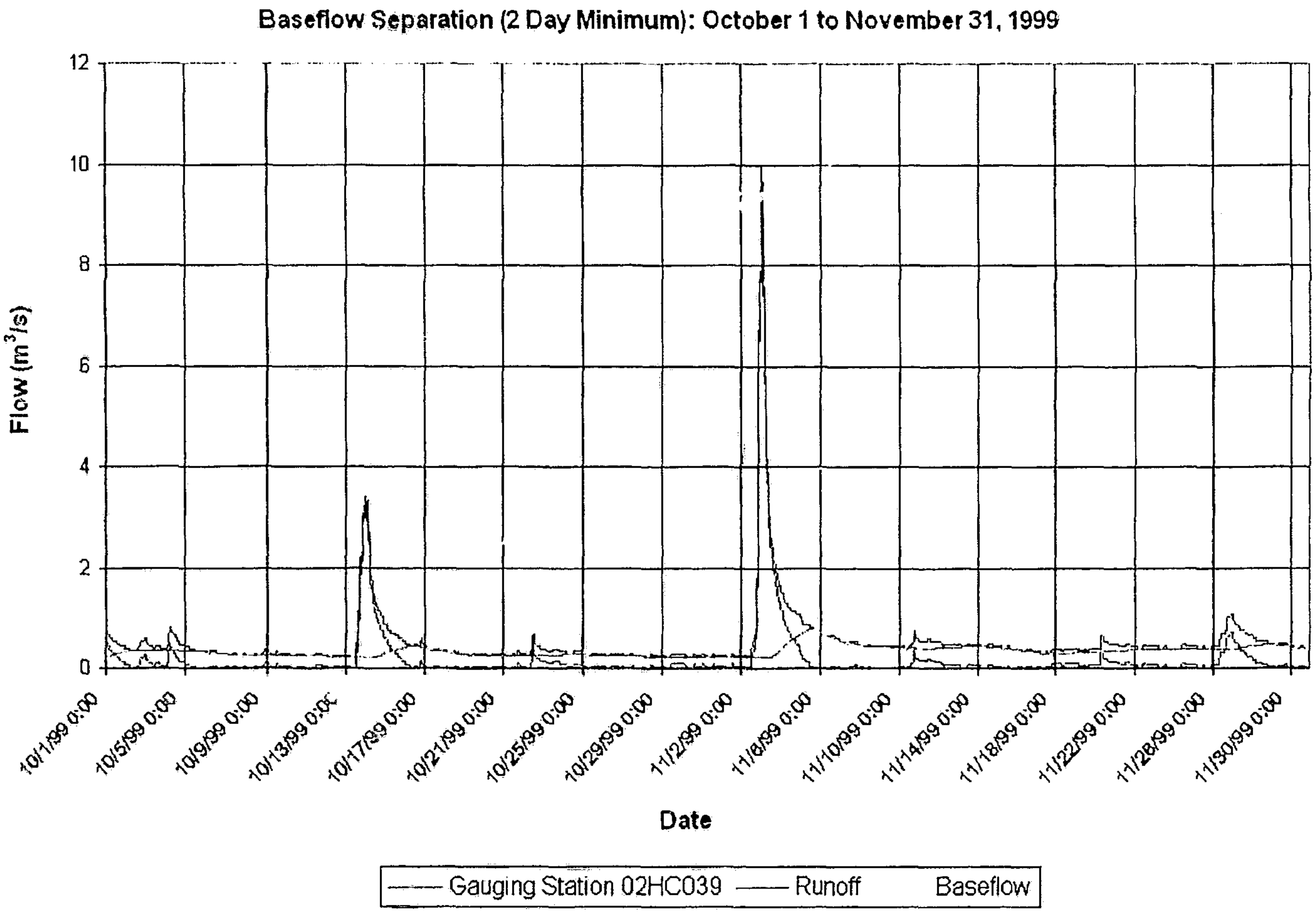


Figure 16. Baseflow separation of gauging station 02HC039.

PCSWMM is precipitation driven in order to generate runoff. During dry weather, runoff is not modelled. Unfortunately, the baseflow separation technique used did not consistently produce zero runoff during dry weather. Therefore, prior to correlating the modelled flow, an *IF* statement was written in order to remove the zero values from the 02HC039 flow. Table 10 and Figure 17 are examples of this scenario.

Table 10. Second generation baseflow separation was done using an *IF* statement. This table is only an example.

Time	Rainfall (mm)	*PCSWMM Generated Flow (m^3/s)	02HC039 Measured Flow (m^3/s)	IF statement	*New Flow 02HC039 (m^3/s)
00:00	0.1	0	2.0	*IF* generated flow = 0 remove flow from 02HC039	0
01:00	0.1	0	1.9	"	0
02:00	0.2	0	2.1	"	0
03:00	0	1.9	2.1	"	2.1
04:00	0	1.8	2.2	"	2.2
05:00	0	1.8	2.1	"	2.1
06:00	0	1.7	2.2	"	2.2
Etc.	0	0	2.1	"	2.1

*Note: conducted on all generated flows by each rain gauge in order to correlate total volumes.

Table 11 depicts the percentage of time removed from each time series for each model.

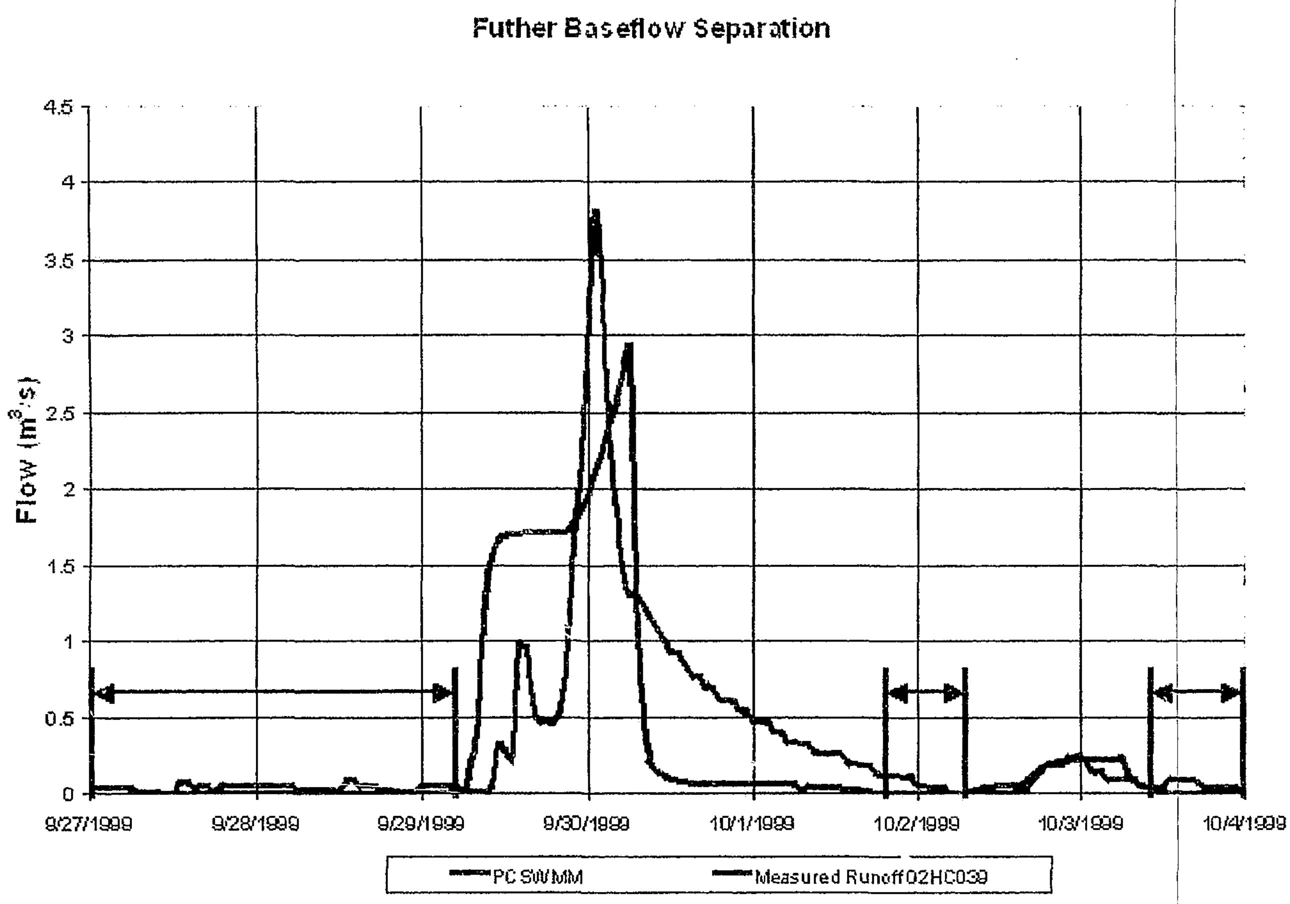


Figure 17. Second generation baseflow separation of gauging station 02HC039. The arrows indicate periods of measured flow at 02HC039, which occurred during periods of no-flow generated by PCSWMM.

Table 11. **Percentage of time series removed from station 02HC039.**

Lumped	Lumped Summer	Lumped Fall
64.6	36.8	27.1
Clustered	**Clustered Summer**	**Clustered Fall**
65.6	37.4	27.5

4. GIS Data Layer Development

The base GIS data layers used in this study were developed by the TRCA and DMTI Spatial and were available through Ryerson University's Geography Department. ASCII digital elevation model layers in 30-metre resolution and UTM coordinates were prepared by DMTI Spatial, while all other layers pertaining to the Duffins Creek watershed were prepared by the TRCA. Flow charts are used in this section in order to summarize and clarify the steps taken to develop the layers and data needed for this study.

All layers and data frames used in ArcMap were set to the following coordinate system: UTM NAD 1983 zone 17N. The following is a list of the map sheets/DEM layers used in this study below; the orientation of these sheets can be seen in Figure 11 (see Chapter 3).

31D/6	**31D/4**	**31D/3**
31D/2	**30M/13**	**30M/14**
30M/15	**30M/12**	**30M/11**

The ArcToolBox application was used to convert the ASCII text DEM's prepared by DMTI into ArcGrid format (raster layers) using the conversion tool. The input ASCII file location was chosen and the output file was given a file name. It should be noted that the DEM needs to be exported in integer format, or there will be calculation errors using the *geostatistical analyst*.

Unlike the DEM layers, the Duffins Creek watershed layer was simply given the appropriate coordinate system and legend identifiers (e.g. colour categorized land use). From the Duffins Creek data set, this study used the landuse, soil type, road network, river and stream network, subwatersheds, and stream gauging station layers.

The Reesor Creek watershed is located in the northwest corner of the Duffins Creek watershed. The layers for Reesor Creek needed to be mechanically extracted from the Duffins Creek layers. Using the Duffins Creek subwatershed layer, the appropriate subwatersheds draining Reesor Creek were selected. The selected subwatersheds were labelled 1, 2, 3, and 4 (Figure 18).

As stated previously, part of subwatershed 4 was down stream of the gauging station 02HC039 and did not contribute any flow. This area was removed in order to correctly calculate the area of polygons. The delineation of the Reesor Creek drainage system was determined using the HEC-Geo HMS extension.

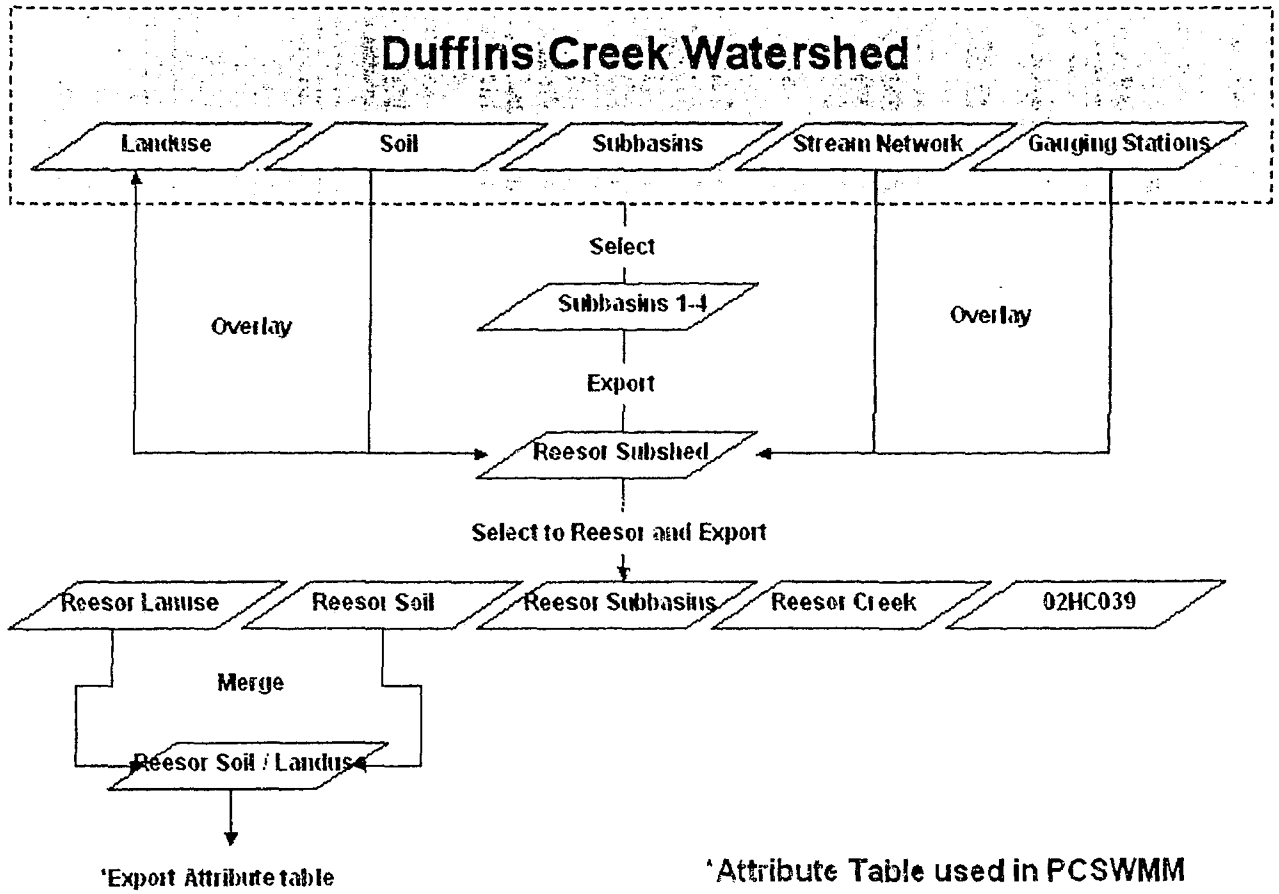


Figure 18. The Duffins Creek watershed database was used to develop the Reesor watershed layers.

During the time of this study, Darren Sutton, a graduate student of the Ryerson University Geography Department had prepared the input data of the Duffins Creek watershed for use in the HEC-Geo HMS model. Simply put, elevations, watershed boundaries, and the stream network were properly formatted for use. The HEC-Geo HMS extension provided a watershed delineation tool, which was used to select a point in a watershed, and the extension delineated the total area that drains to the point. In this case, station 02HC039 was the outlet point for the Reesor Creek watershed and the HEC-Geo HMS delineated the total area that drained to this gauge.

The area was then exported as a layer file, and overlaid on the Reesor Creek subwatershed layer and the subwatershed layer was clipped to the shape of the HEC-Geo HMS delineation layer. Other layer attributes such as landuse, roads, stream network, and soil type were also clipped to the boundaries of the new Reesor Creek subwatershed boundaries (Figure 18).

At this point, a layer depicting the location of the rain gauges needed to be developed. This process was simply done by using the *spatial analyst* extension of ArcMap. The raster layers were converted into point feature layers where each pixel of the raster layer was converted into a point (Figure 19).

With the new point layers developed, the approximate area of the rain gauges was determined using their UTM coordinates to select the closest point. The selected point was then saved as a layer file and given the station name. This process was conducted for all 13 stations.

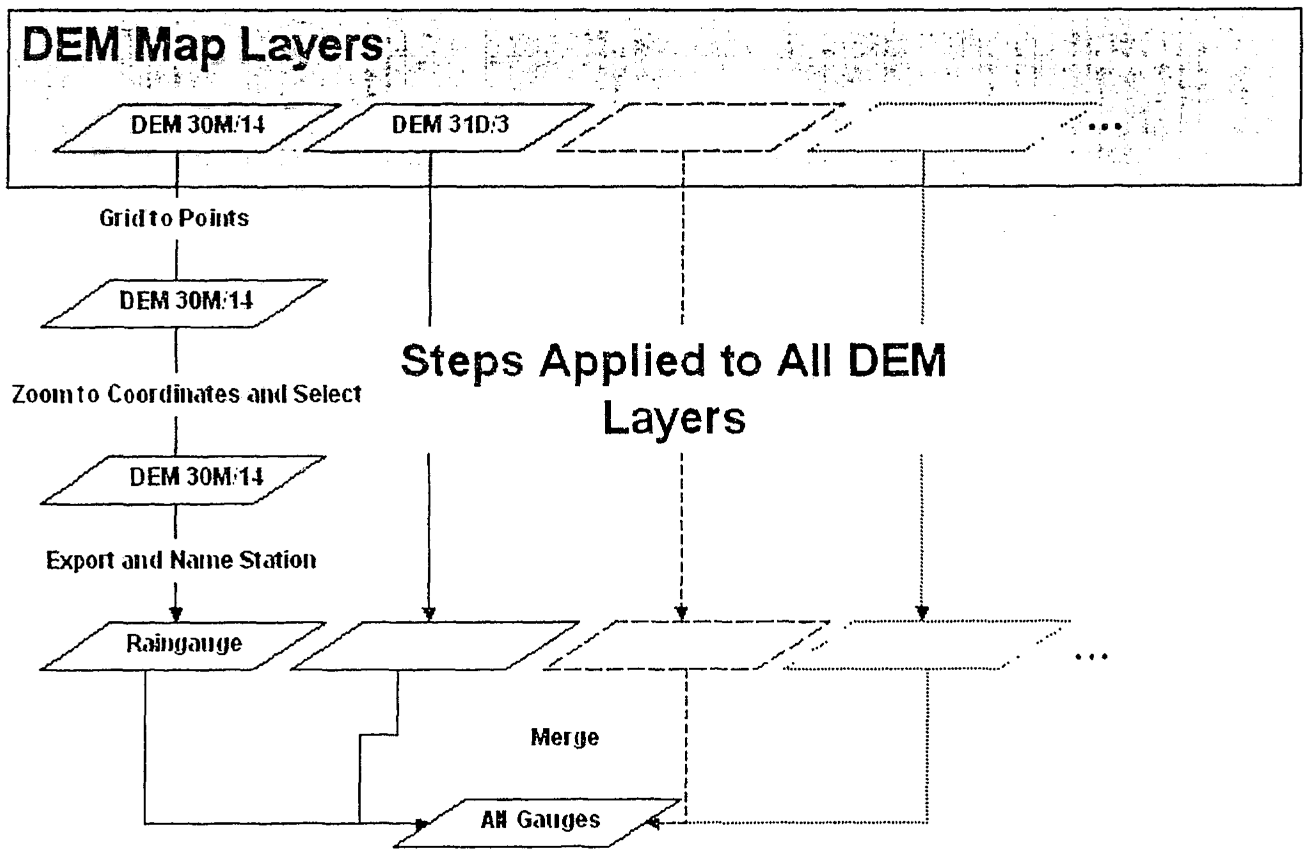


Figure 19. Flow chart depicting the rain gauge location layer.

Using ArcMap's *geoprocessing wizard* tool all of the rain gauges were merged together to produce a single layer of all the rain gauge locations. The output is a single layer depicting the spatial distribution of the rain gauge network (Figure 19 and Figure 14 Chapter 3).

With the rain gauge distribution layer complete, several fields were added to its attribute table. The fields included the UTM coordinates, rainfall, and station identifier. A blank rain gauge layer was saved for use as a template where rainfall values were added to the template for each day rainfall occurred within the time period being studied. Each layer was exported and was named the date in which precipitation occurrence (e.g. rainfall September 6—the file name will be September 6) (Figure 20). For the next step, a hard copy of the storm events was available for reference.

At this point, the ArcGIS editor extension was activated and an editing session was conducted on the newly exported daily rain gauge layers. The attribute layer was revised and using the hard copy rainfall time-series where the applicable rainfall values were added to the rainfall column for the appropriate rain gauge. Data entry was done for all applicable rainfall layers.

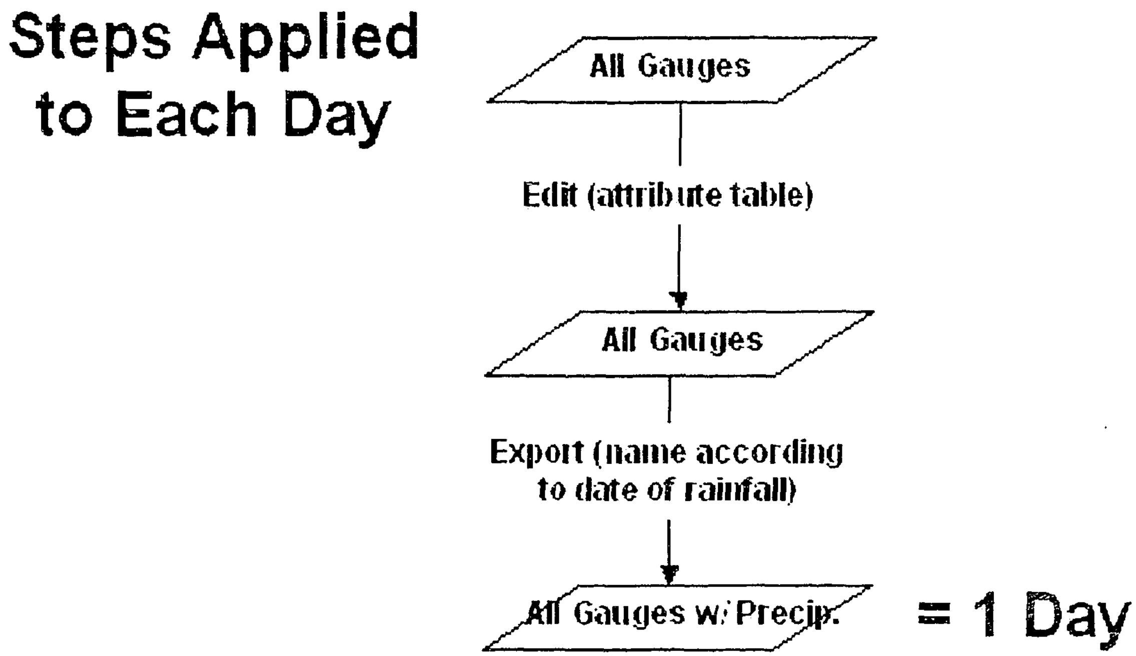


Figure 20. Development of daily rain gauge layers. A layer was generated for each day rainfall occurred during September, 1999.

As stated previously, the *geostatistical analyst* (GA) in ArcMap uses sample points and generates layers by conducting a series of statistical calculations (e.g. kriging) to predict a particular phenomenon. For this study, each daily rain gauge layer was used to develop a kriging layer based on its rainfall attribute. The following outlines how each kriged layer was produced. Figure 21 depict the several steps taken by this study.

The first step of the GA wizard needed to identify the input layer, the attribute to krig (e.g. rainfall), the option of using NODATA, and the methodology of analysis (kriging). It should be noted that the NODATA option value will specifies missing values in the input data file. NODATA values will be ignored during data analysis. If activated, the default missing value was 0.0 (because some applications use 0.0 for empty records). There is the option to enter a different value to represent NODATA, but for this study, the NODATA option was not used.

All other parameters offered at this point were left defaulted. At this point, the type of ordinary kriging model is defined. Users have the option of generating three separate models and using spatial delimiters such as circular, spherical, exponential, etc. as well as use a semivariogram or a covariance view. There is also an option to use anisotropy. For this study, a semivariogram was used and a single spherical model with no anisotropy was applied. All other parameters were left as default.

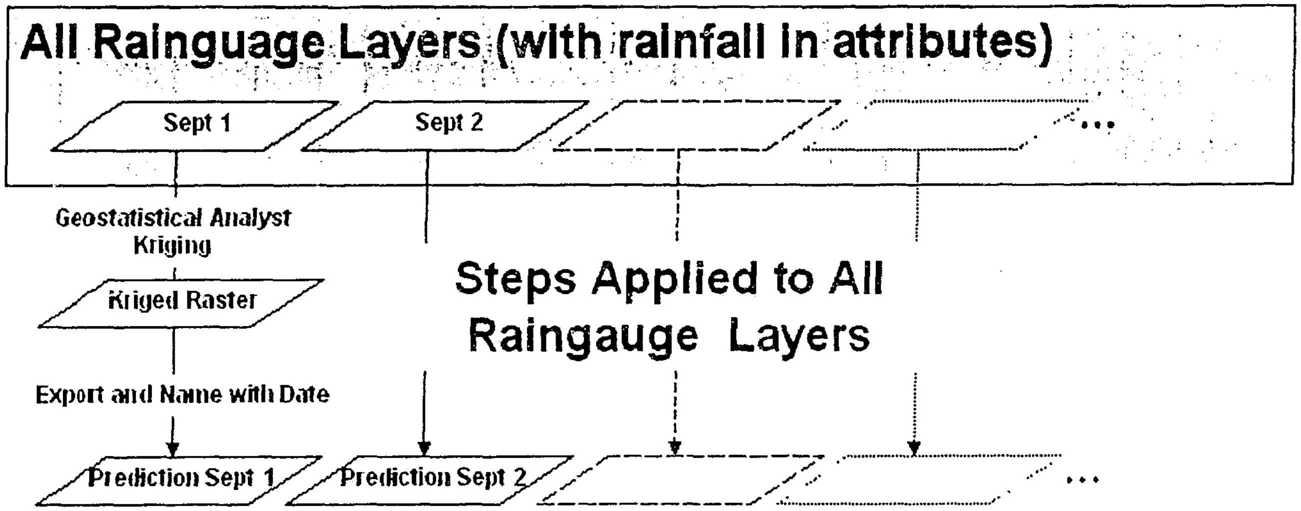


Figure 21. ArcMap's *geostatistical analyst* was used to generate prediction layers for each day precipitation occurred

The next step identifies the analysis neighbourhood of all data points of the rain gauge locations. There is an option of changing and orientating the coverage area, as well as, splitting the area into 1/4, 1/8, or 1/16 sectors. The coverage area for this study was left on the default 1/4 angular sector orientated to the compass points northeast, northwest, southeast, and southwest.

The final step in the GA wizard was a cross validation of the kriged layer. There are four viewing tabs: predicted, error, standardized error, and Qplot. While editing the data set is possible, the default plots for this study were used and no adjustments were made. A window prompting the layer output information was reviewed.

The result was a raster coverage layer that predicted precipitation values for each pixel within the grid. It should be kept in mind that the rainfall produced in this layer is only representative of one day. Similar layers were produced for each day when rainfall was measured at any of the gauging stations. Figure 22 depicts a kriged prediction layer produced using the protocol listed above. The layer was not used in this study, it was developed to demonstrate the production and output of the kriged prediction.

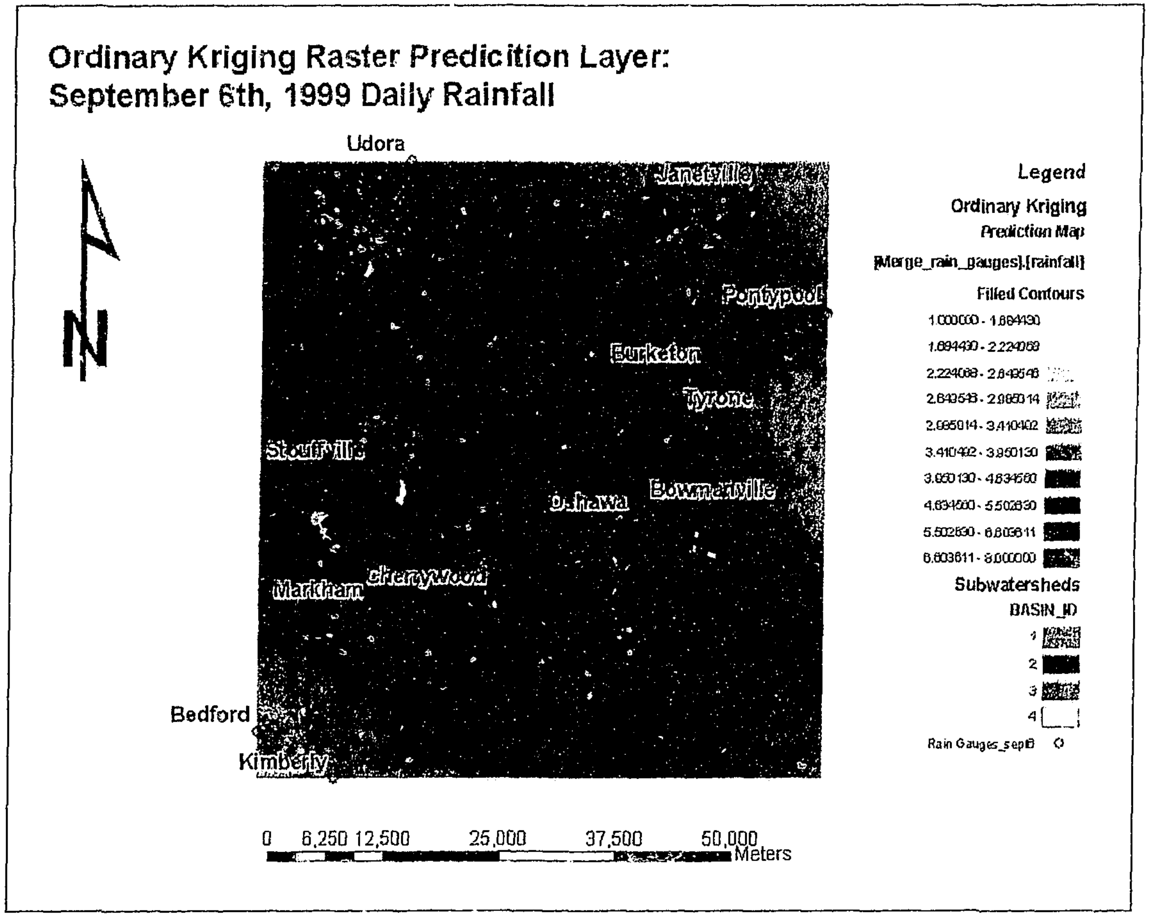


Figure 22. A raster ordinary kriging coverage layer predicting rainfall about the Reesor Creek watershed.

It was decided that a 1 km^2 grid would overlay the watershed and the centroid of each grid cell would be determined instead. The result was fifty-four virtual rain gauges (Figure 23), each gauge being characteristic of its applicable cell. It should be noted that the size of the grid is user defined. For this study, the 1 km^2 grid was chosen because of its compatibility with the ArcMap project layer coordinates and because the extent of the watershed was small (approximately 35 km^2).

With assistance from Michael MacDonald—a GIS specialist at Ryerson University, the grid was designed to cover approximately 1700 km^2—far greater than the area of both the Reesor and Duffins Creek watersheds. Once the grid was orientated above the Reesor watershed, the centroids were calculated using the VB script. The script termed *get_centroid* was applied using ArcMap's macro option (Figure 24). The script was retrieved from the ESRI support downloads where minor customization revisions were made (www.esri.com). The VB script can be viewed in Appendix F.

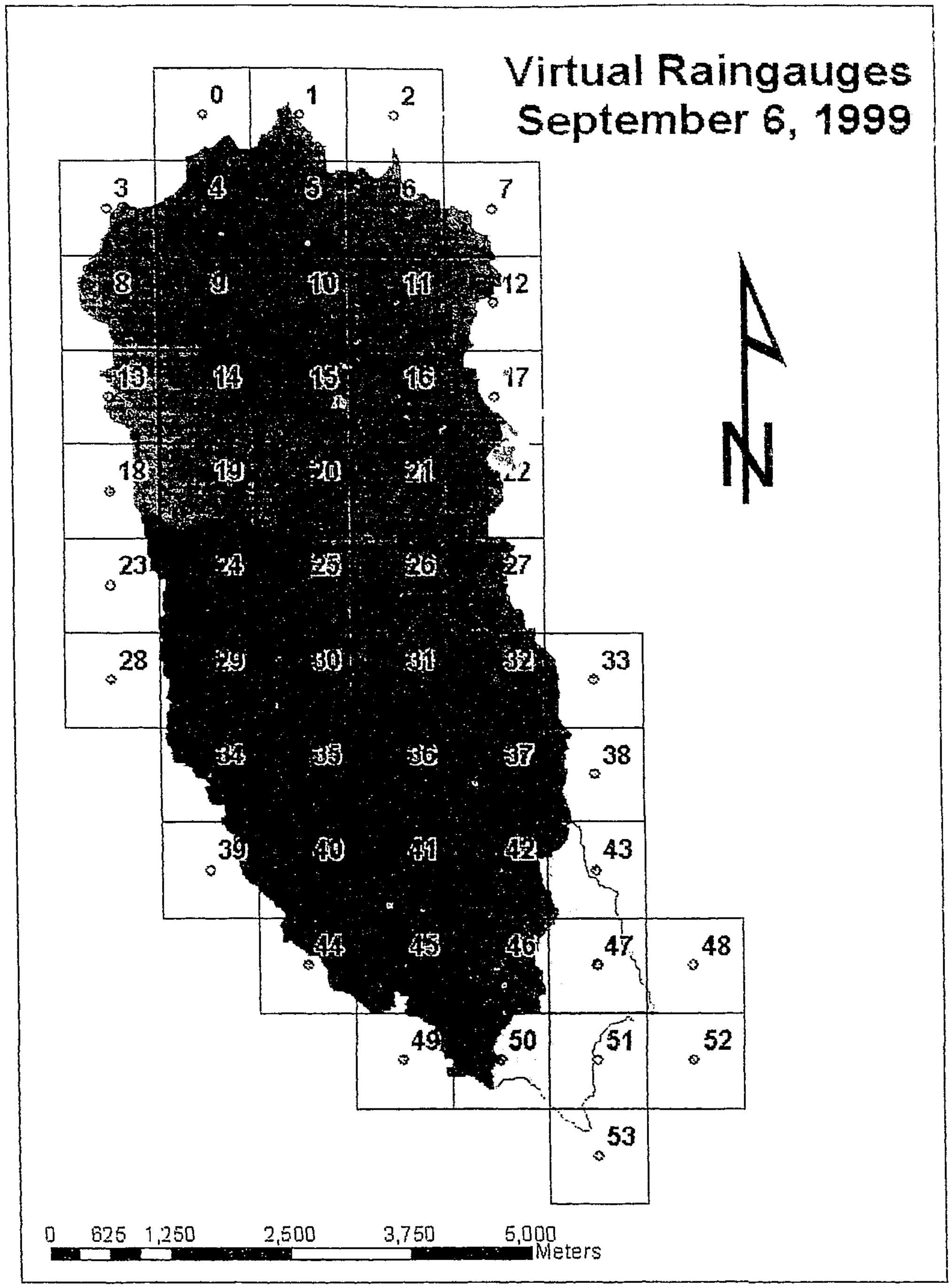


Figure 23. Each 1 km² centroid represented a virtual rain gauge.

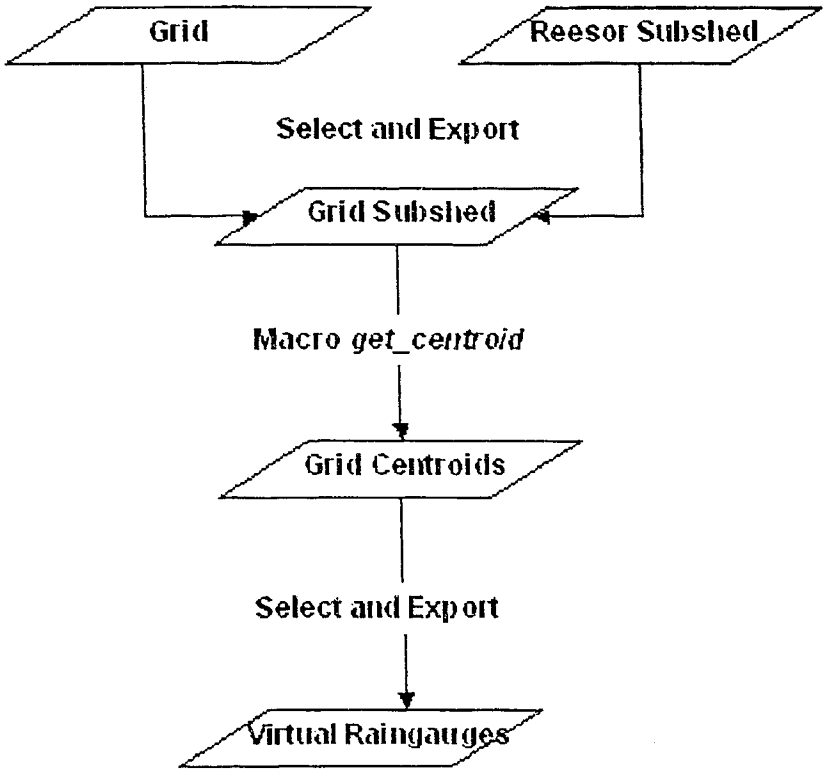


Figure 24. A macro was used to calculate the centroid of each grid cell and the centroids were exported to be used as a *virtual rain gauge* layer.

Before the macro can be run, it must be properly set up in the table of contents view. In this case, the grid must be positioned as the first layer in the table of contents, immediately after the grid layer, a point layer (e.g. one of the rain gauge layers) needs to be positioned underneath. When the macro is run, the point layer is used as a reference layer for the grid centroid calculations. Unfortunately, once the centroids have been tabulated, the new layer will also include the reference points. These points can be removed easily by using the selection tool via an editing session and directly from the attribute table.

All non-applicable grid cells and centroids needed to be removed that did not intersect the Reesor Creek watershed boundaries in order to calculate new polygon areas and new rainfall values. This was done by using the *select by location* tool to select the grid cells that intersect the Reesor Creek watershed boundaries and the centroids that intersect the new grid. In each case, a new layer was created from the selected features respectively. It was necessary to select the centroids in context with the new grid layer because several rain gauges are not contained by the Reesor Creek watershed boundaries.

It is imperative that the centroids not in the Reesor Creek watershed boundaries be selected based on the new grid layer (centroids located just outside the watershed). This is because some of the virtual gauges contribute rainfall values to only small parcels of the watershed (e.g. grid cell 53) (Appendix G).

A macro termed *raster_join* was used to assign a predicted rainfall value to the new gauges (Figure 25). Similar to the previous VB script, the original script was downloaded from the ESRI support site and customization was contributed by Ryerson's GIS specialist. The script can be seen in Appendix F.

Similar to the *get_centroid* macro, the *raster_join* macro must have the gauge layer at the top of the ArcMap table of contents and immediately below it, a kriged rainfall layer. It should also be noted that the virtual rain gauge layer should not have a rainfall column in the attribute table—the macro will create one. Once the appropriate layers are organized, the *raster_join* macro was run. When complete, the new layer should be exported and named the applicable date of rainfall (e.g. Sept_6_grid_rain). This process was completed for each day which rainfall occurred—or better still—for each kriged rainfall raster layer. In order to confirm that the macro worked, the virtual rain gauge attribute table was left open at all times to observe the addition of a rainfall column. This is necessary, because immediately after each layer export the rainfall column in the original virtual rain gauge layer needs to be deleted. As stated above, every time the *raster_join* macro is run, a new rainfall column with the new rainfall values is created (Appendix H). In the end, each virtual rainfall layer was exported and organized in to a time series that was used in PCSWMM.

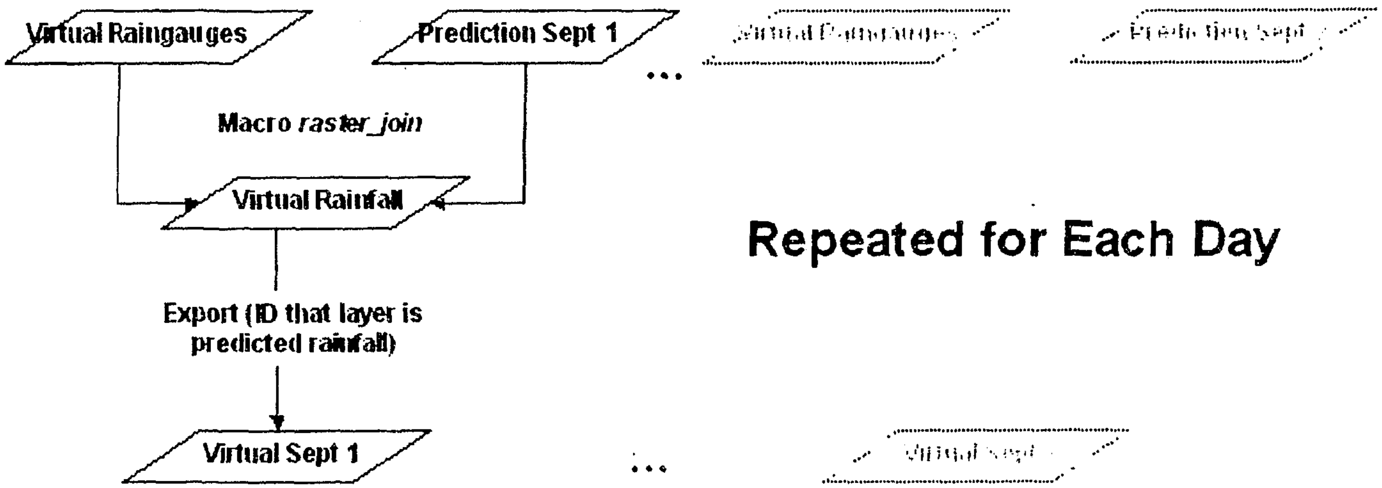


Figure 25. Using a macro, the virtual rain gauges were combined with the kriged prediction layer.

At this point, once all of the layers have been developed and a single layer was created depicting the soil type, landuse, and the virtual rain gauges. ArcMap's *geoprocessing wizard*, the grid layer needs to be intersected with the landuse/soil type layer. This intersection was necessary in order to remove all of the grid cell lines that occur outside of the Reesor Creek watershed boundaries, which in turn, is necessary for area calculations discussed later in this section.

Joining the layers combined all of the attributes in the previous layers and created one layer that has a cell/gauge identifier attached to it. This was done by using the *join* tool found in the table of contents of ArcMap. The join included the following: 1) the virtual rain gauge layer (use template, no rainfall values) to join to the landuse/soil type/grid layer, 2) join points to polygons, where each polygon was all the attribute of the point that is closest to the polygon boundary, and 3) the layer was given a unique identifier (*final_landuse*).

The join process combined with the intersection of the landuse/soil type/grid layer simply gave each polygon in each grid cell a cell and virtual rain gauge value. The cell/gauge identifier is necessary for running PCSWMM in order to run the characteristics of each cell separately.

Confirmation if the join was successful was simply done by opening the attribute table and selecting similar gauge attributes. This was done by using the *select by attributes* tool and choosing only one cell/gauge attribute (e.g. cell 10) (Figure 26).

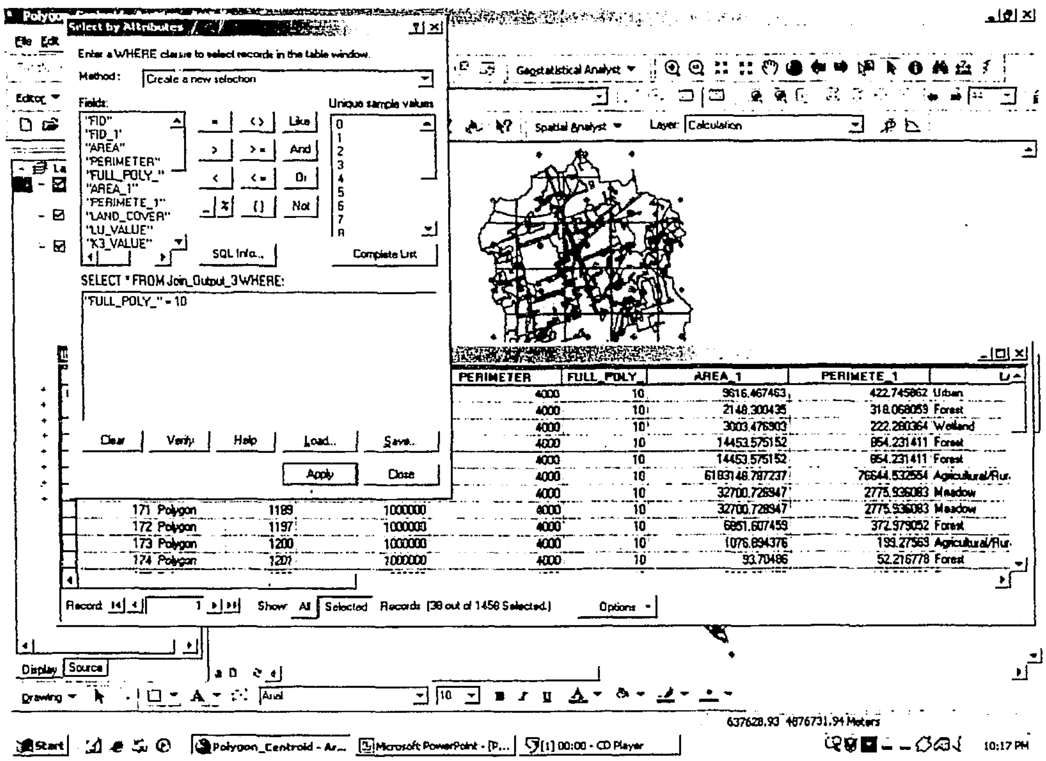


Figure 26. Confirmation if the virtual rain gauge and landuse/soil type/grid *join* was successful.

Finally, the area of the *final_landuse* layer polygons was updated. This was done by using the *field calculator* tool and a VB script from the ArcMap help file. Optionally, an editing session was started, where if any calculation mistakes are made, they can be undone. With the editor off, any calculation errors are permanent. By opening the attribute table and the field calculator tool of the *final_landuse* layer, the following script was entered:

```
Dim dblArea as double
Dim pArea as Iarea
Set pArea = [shape]
DblArea = pArea.area
```

The *advanced* option was activated because the variable *dblArea* needed to be entered directly into the advanced text box.

At this point, all of the following attribute tables (data layers) were exported for use in PCSWMM:

- all kriged rainfall, where each export was saved with the applicable date of rainfall (e.g. sept_6).
- the *final_landuse* layer, where the layer includes the landuse, soil type, grid/gauge number, area of polygons, and several other attributes already included in the original data set from the TRCA (e.g. percentage imperviousness).

5. **Calibration**

Figure 27 depicts how each model was calibrated. The purpose here is to apply a traditional calibration method throughout the development of the model, which in turn, keeps the model consistent.

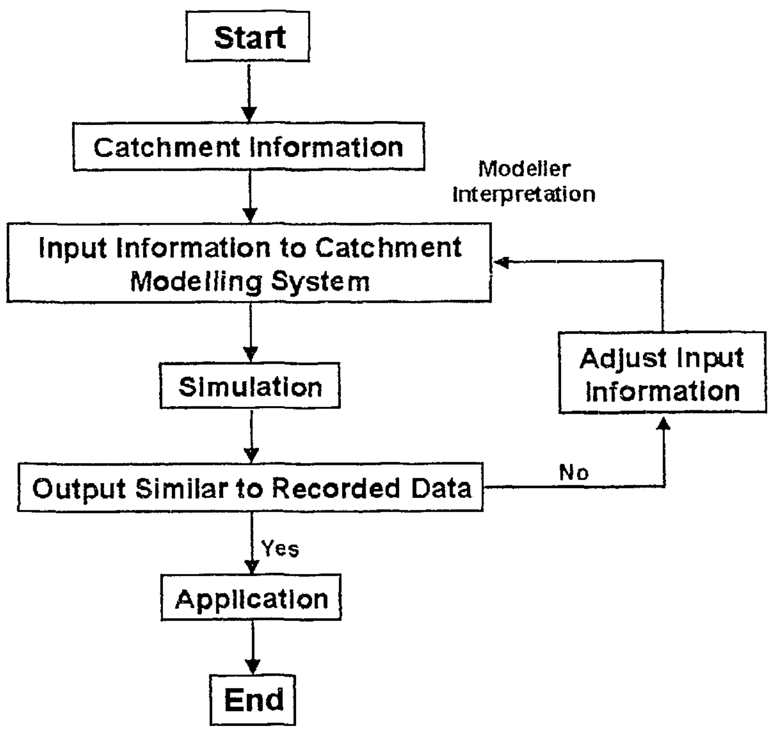


Figure 27. A flow chart depicting the calibration process of each model data based on Choi and Ball (2002).

The parameters used in each model were calibrated in context with the Stouffville rain gauge. The Stouffville gauge was chosen because it best represented precipitation falling on the Reesor watershed and it was located approximately 5000 metres from the stream gauging station 02HC039. The hydrograph depicted in Figure 28 plots flow for the both station 02HC039 and generated runoff by PCSWMM using Stouffville gauge, as well as, the measured rainfall at Stouffville.

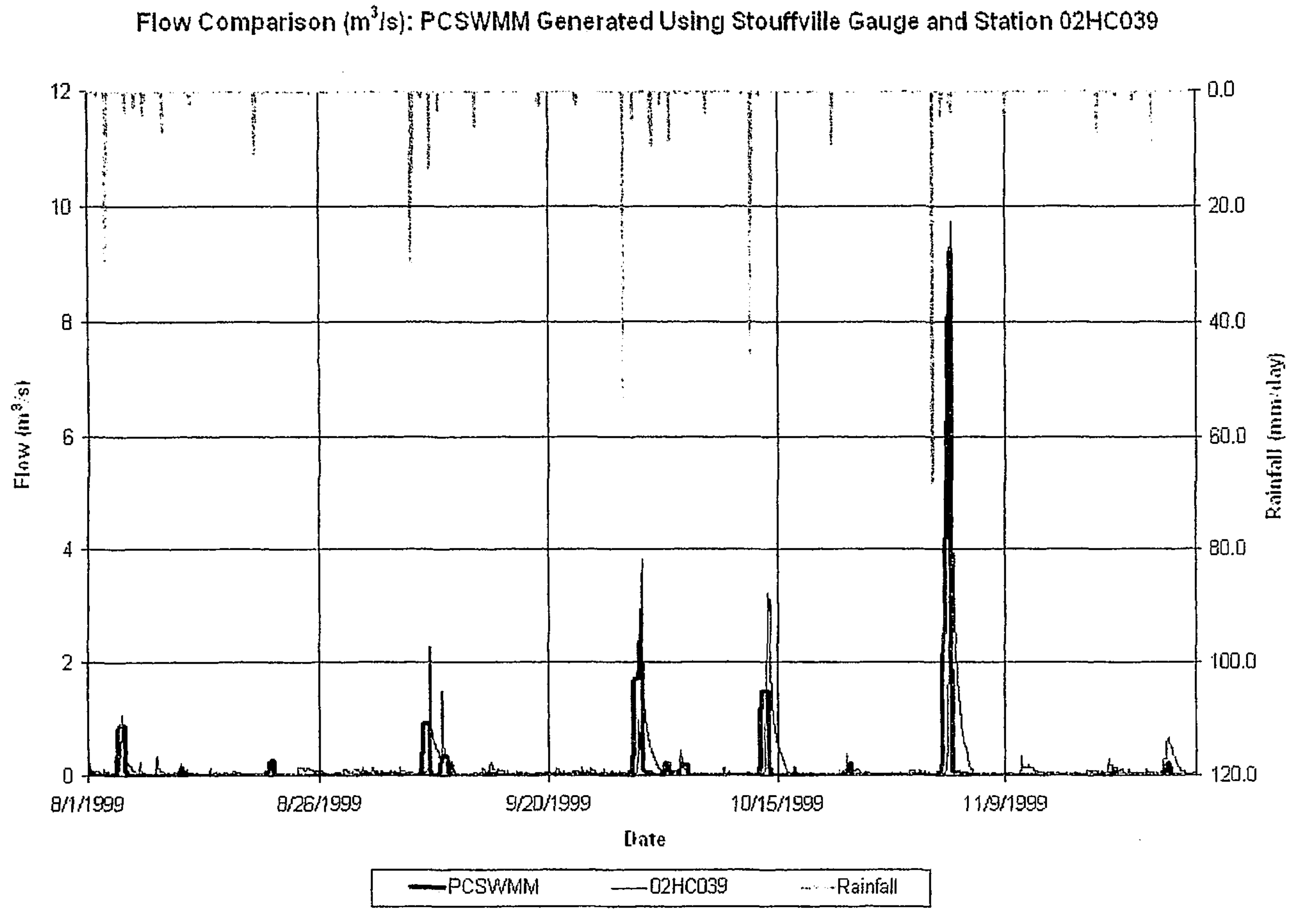


Figure 28. Runoff flows measured at station 02HC039 and generated by PCSWMM using the Stouffville rain gauge.

6. PCSWMM Parameter Development

As stated in Table 3 (Chapter 2), over the years SWMM has had several versions that have improved the SWMM program. In PCSWMM, each version is available for modelling. For this study, the SWMM engine 4.4h was used. Prior to starting the PCSWMM modelling, ArcMap was used to develop an attribute table (previously discussed) of the Reesor watershed representing the soil type, landuse, imperviousness, and area. The data was used to determine many of the parameters of the PCSWMM input files. Table 12 lists some of the run, print, and precipitation controls that were used in all three models. It should be noted that Table 12 does not represent a complete and working input file for PCSWMM. Complete input files can be observed in Appendix I.

Table 12. PCSWMM parameters that was common in all three models.

Run Control			Precipitation Data			Print Control		
Parameter	Value	Description	Parameter	Value	Description	Parameter	Value	Description
B1			D1			M1		
METRIC	1	metric units	ROPT	0	precipitation data source (E line)	NPRNT	1	number of inlet time series to be printed in output
ISNOW	0	no snow simulated				INTERV	0	printing interval for inlet hyetographs (statistical summary)
NRGAG	13	number of rain gauges	E1					
INFILM	0	Horton's infiltration	KTYPE	2	precipitation type (date, time columns)	M2		
KWALTY	0	no water quality simulated	KINC	1	data points per line	NDET	1	print complete simulation period
IVAP	0	default evaporation rate (3 mm/day)	KPRINT	0	print all precipitation input	STARTP1	0	start of simulation period (0 = start date line B1)
NHR	23	hour of day for simulation start	KTHIS	0	precipitation time-step variability (NA)	STOPPR1	0	end of simulation period (0 = end date line B1)
NMN	45	minute of hour for simulation start	KTIME	1	precipitation time units (hours)			
NDAY	1	day of months for simulation start	KPREP	1	precipitation units (mm)	M3		
IYRSTR	1999	year of simulation	THISTO	24	time interval between precipitation values	IPRNT	100	"dummy" pipe to be printed

Run Control			Precipitation Data			Print Control		
Parameter	Value	Description	Parameter	Value	Description	Parameter	Value	Description
IVCHAN	0	allow channel evaporation	TZRAIN	0	initial time of day of start of precipitation (offset)		200	"dummy" pipe to be printed
							1300	"dummy" pipe to be printed
B2								
IPRN1	0	print all input data						
IPRN2	1	do not plot all graphs (ASCII plots)						
IPRN3	0	do not print totals (print summaries)						
IRPNGW	0	do not print error messages (ground water)						
	0	print headers						
	1	include percents (land use summaries)						
B3								
WET	3600	wet time-step (sec)						
WETDRY	7200	wet/dry time-step (sec)						
DRY	86400	dry time-step (sec)						
LUNIT	3	units for length of simulation (day)						

Run Control			*Precipitation Data*			*Print Control*		
Parameter	Value	Description	Parameter	Value	Description	Parameter	Value	Description
B4								
PCTZER	25	percent impervious with zero detention (default %)						
REGEN	0.1	infiltration regeneration (default)						

There are several key parameters used in the PCSWMM input files that should be discussed as to why they were chosen for this study. These parameters include ISNOW, INFILM, KWALTY, IVAP, and IVCHAN.

ISNOW—This parameter simulates snowmelt. ISNOW was not used since the precipitation data occurred during non-winter months from May 1st to November 30th, 1999.

INFILM—This parameter recognizes the type of infiltration simulation that will be used in the runoff model. This study used *Horton's Infiltration* equation--it is expressed:

$$f_p = f_c + (f_o - f_c)\, e^{-kt} \qquad 7.0$$

Where (f_p) is the infiltration capacity into soil, mm/sec; (f_c) is the minimum or ultimate value of f_p (WLMIN) in mm/sec; (f_o) is the maximum or initial value of (f_p) (WLMAX), mm/sec; (t) is the time from beginning of storm in seconds; and (k) is the decay coefficient (DECAY) in sec-1. The equation was originally developed to depict the reduction of a watersheds infiltration capacity in the presence of surface moisture. The Horton equation was chosen for several reasons, the first is because it is the most well know and accepted of several infiltration equations (Huber and Dickinson, 1992; James and James, 2000; Viessman et al., 1989; Elliot and Ward, 1995; and Kim et al., 1999). The second reason was because PCSWMM used an integrated form of the equation that compensates for the reduced loss of soil infiltration capacity when a light rainfall occurs (Nix, 1994).

KWALTY—This parameter is used to model water quality. This parameter was not used because the study was intending to model runoff flow and volume.

IVAP—All PCSWMM engines included evaporation modelling. This parameter identifies how evaporation will be included in the model. For example, if measured data is available, it can be entered as units per day or month. While lake evaporation data for Lake Ontario was available, it was not representative of the Reesor watershed. Therefore, the PCSWMM default rate of 3 millimetres per day was used for this study.

IVCHAN—This parameter omits or includes channel evaporation. IVCHAN was included because the entire Reesor Creek network is open.

For all PCSWMM models, the input file E and H lines were created on a spreadsheet. The input file was then exported as a text file and pasted into PCSWMM.

7. Lumped Model

The lumped model run in PCSWMM consisted of all four subwatersheds of the Reesor Creek watershed combined into one large watershed. Parameters were based on majority characteristics of the watershed. For instance, Table 13 summarizes total area of soil type, land use, and percentage imperviousness in context with the total area of the watershed.

Table 13. **Total area of soil type, land use, and percentage imperviousness for the Reesor Creek watershed.**

Soil type	Area (m^2)	Landuse	Area (m^2)
Sand	1137758	Agricultural / Rural	17366991
Sandy Loam	188177	Forest	4928007
Loam	27177705	Meadow	2724043
Clay Loam	527275	Wetland	1294946
Clay	2578781	Urban	3422962
Organic	1020384	Urban Open	215868
Variable	2409116	Federal Green Space	5097619
Total	**35039196***		**35050436**

Percent Impervious	Area (m^2)	Percent of Watershed
0	31627477	90
15	974167	3
40	2117962	6
75	330832	1

*** Several soil polygons did not have an identifier, resulting in slightly differing areas.**

The data in Table 13 used to determine several parameters in the PCSWMM input file— Table 14 lists these controls.

Table 14. The following parameters were determined in context with Table 13. Listed are the recommended values.

		Lumped	Subwatershed				Recommended*
Parameter	Description		1	2	3	4	
WW(1)	Average Width of Watershed (m)	3200	1678	3294	4357	1545	
WAREA	Area of Watershed (ha)	3505	282	1085	1898	239	
WLMAX	Maximum Infiltration Rate (mm/hr)	7.620	7.620	7.620	7.620	7.620	7.620
WLMIN	Minimum Infiltration Rate (mm/hr)	1.572	1.572	1.572	1.572	1.572	3.81 - 7.62
DECAY	Rate of Decay of Infiltration (1/sec)	0.00115	0.00115	0.00115	0.00115	0.00115	0.00115
WW(3)	Percent Impervious (%)	8.41	10	15	2	2	
WW(5)	Manning's (n) Impervious	0.011	0.011	0.011	0.011	0.011	0.01 - 0.013
WW(6)	Manning's (n) Pervious	0.035	0.035	0.035	0.035	0.035	0.03 - 0.04
WSTORE1	Impervious Depression Storage (mm)	3.413	3.413	3.413	3.413	3.413	3.8
WSTORE2	Pervious Depression Storage (mm)	6.810	6.810	6.810	6.810	6.810	1.6 - 6.4

*Note: recommended values were suggested by the USEPA manual for SWMM 4.0 (1992), James and James (2000), and Viessman (1989).

By running all 13 gauges from the E line in the runoff module, the each gauge was given a number (1 to 13) to be read in the JK field (gauge number) of the H lines. Table 15 below identifies the gauge and corresponding identifier.

Table 15. PCSWMM rain gauge identifier.

PCSWMM Gauge ID	Rain gauge
1	Oshawa
2	Markham
3	Bowmanville
4	Buttonville Airport
5	Stouffville
6	Cherrywood
7	Bedford
8	Kimberly
9	Udora
10	Burketon
11	Janetville
12	Pontypool
13	Tyrone

The identifiers need to be in place in order for PCSWMM to read each gauges individually. A *dummy pipe* system was used to act as the outlet of the lumped watershed. The pipes were numbered 100 to 1300 reflecting the gauge identifiers. The total volume measured at the pipe outlet is the runoff produced by the applicable rain gauge.

7.1. Lumped Seasonal

A seasonal model was run on the lumped model. The model was developed for the summer and fall months May 1 to August 31, 1999 and September 1 to November 31, 1999 respectively. Other than adjusting the rainfall time series, all other parameters were not changed.

8. Clustered Model

The subwatershed model was divided into the four subwatersheds—one through four. Only the parameters for area, average width, and percentage imperviousness were adjusted to characterize the. Similar to the lumped model, a dummy pipe network was developed to combine all the runoff flows from each subwatershed. The rain gauge identifiers were also left the same.

8.1. Clustered Seasonal

A seasonal model was run on the subwatershed model. The model was also developed for the summer and fall months May 1 to August 31, 1999 and September 1 to November 31, 1999 respectively. Other than adjusting the rainfall time series, all other parameters were not changed.

9. Grid Model

Unlike the other three models, the grid model produced a large database that was organized differently than the previous two models. In this case, each grid cell had the total area of landuse and soil type calculated using ArcMap. The attribute file was exported to a spreadsheet and filters were used to determine the area and soil type values (Appendix J). The virtual rain gauge values were also exported to spreadsheet and each file was merged into a single time series for each day in September (Appendix K).

Also at this point, the virtual rain gauge identifiers needed to be adjusted--because PCSWMM dislikes using 0's as a label and one of the gauges was labelled 0. The result was a shuffle of all the station numbers. In this case, the original dataset from ArcMap exported the gauges with the numbers 0 through 53, with the adjustment for PCSWMM, the gauges were renumbered 1 through 54 respectively.

Three runoff modules were created for each landuse type using gauges 1 to 23, 24 to 46, and 46 to 54 respectively. This was only done in order to lessen the size of the input file and the run time. Similar to the previous, a dummy pipe network was created. However, PCSWMM can only compensate for six dummy pipe connections, therefore, the gauges were then directed to contribute to six pipes at a time (e.g. gauges 1 to 6, all contribute to pipe 100; gauges 7 to 12, all contribute to pipe 200; etc.). Table 16 summarizes the gauge and dummy pipe network.

Table 16. Summary of the gauge and dummy pipe network setup in PCSWMM.

Grid Cell and Virtual Rain Gauge Number	Dummy Pipe Number
1 to 6	100
7 to 12	200
13 to 18	300
19 to 24	400
25 to 30	500
31 to 36	600
37 to 42	700

Grid Cell and Virtual Rain Gauge Number	Dummy Pipe Number
43 to 48	800
49 to 54	900

10. Flow Duration Curve

A flow duration curve plots the cumulative frequency of discharge, that is, discharge as a function of the percentage of the time that the discharge is exceeded. It is not considered a probability curve, because the discharge is correlated between successive time intervals and discharge characteristics are dependent on season of year (Ward and Robinson, 1990).

The flow duration curve is useful is predicting the availability and variability of sustained flows and identify the effects of imperviousness on a watershed (Viessman et al., 1989)

To hydrologists, FDC's are commonly used in modelling like hydrographs and mass curves (Yu and Yang, 1996). While widely know and used, there is little resources regarding their study (Cigizoglu and Bayazit, 2000).

Smakhtin, et al. (1998) used FDC's to study the characterize a stream's low-flow regime in South Africa, where observed stream flow records were insufficient, and low-flow characteristics were needed to estimate from simulated daily stream flow time-series. The model conceptualized low-flow generation mechanisms and surface-subsurface interactions adequately where the ability of the model to simulate low-flow regimes was assessed by means of various low-flow analysis techniques.

On the other hand, Smakhtin and Masse (2000) used flow duration curves to generate continuous daily stream-flow time-series from observed daily rainfall data in a watershed also in South Africa. The curves were used to convert the *daily rainfall information from source rain gauges into a continuous daily* hydrograph at a point in the river. Each source rain gauge a time-series of rainfall related *current precipitation index* CPI was generated and its duration curve is established. The CPI reflected the current watershed wetness and is defined as a continuous function of precipitation, which accumulates on rainy days and exponentially decays during the periods of no rainfall.

The process of rainfall-to-runoff conversion was based on the assumption that daily CPI values at rainfall site(s) in a watershed and the river flows corresponded to similar probabilities on their respective duration curves. The method was designed primarily for application at ungauged sites in data-poor regions where the use of more complex and information consuming techniques of data generation may not be possible.

A review of the literature seemed to uncover that the much of the study's used FDC's to predict flow at ungauged sites (Young et al.; 2000 and Smakhtin, 1999; Studley, 1998; and above). However, there are still many study's that use FDC's for phenomenon like flood prediction, sediment yield, and ecological risk assessment (Cordova and Gonzales, 1997; Bovee and Scott, 2002; Jehng-Jung and Bau, 1995; and Petts et al., 1999 respectively). For this study, FDC's will be used to observe the relationship of both generated and measured flows, as well as to demonstrate their use in observing the affects of imperviousness on the watershed.

In summary, this chapter discussed the methodology used to complete this research. The link between PCSWMM, GIS, and rainfall kriging and the hydrologic components were outlined. They were applied to Reesor Creek watershed, which in turn, give way to Chapter 5 where the results are discussed.

Chapter 5
Discussion of Results

This section discusses the results from the four models that were generated using PCSWMM. These models include the lumped, clustered, seasonal, and grid models. The models were observed in terms of total volume and percentage difference in order to discuss the effects of spatial distribution on rainfall. All percentage differences were referenced against the Stouffville gauge results. Flow duration curve results are also mentioned.

1. Lumped Model

The lumped model used spatially aggregated parameters to represent the Reesor Creek watershed. In PCSWMM, each rain gauge was run using the Reesor watershed parameters and a percentage difference was generated. Parameter calibration for the model was conducted using the Stouffville gauge. Calibration results generated a percentage difference of 0.8 between the measured and generated volumes (Table 16).

Gauges at Janetville and Pontypool generated the lowest percentage differences of –3.1 and –5.5 respectively. All other gauges generated a large percentage difference which suggests there may be spatial variability in rainfall measurements.

Table 16. Summary of the total runoff volume generated by PCSWMM and the measured volume at station 02HC039 for the lumped watershed model.

Gauging Station	Gauge #	Dummy Pipe	Lumped Volume (m³)	02HC039 Volume (m³)	% difference
Oshawa	1	100	1082659	1289609	-16.0
Markham	2	200	962800	1289609	-25.3
Bowmanville	3	300	1091106	1289609	[illegible]
Buttonville Airport	4	400	926433.4	1289609	[illegible]
Stouffville	**5**	**500**	**1300474**	**1289609**	**0.8**
Cherrywood	6	600	327554	1289609	-74.6
Bedford	7	700	1079298	1289609	-16.3
Kimberly	8	800	713111.8	1289609	-44.7
Udora	9	900	1804451	1289609	39.9
Burketon	10	1000	1051117	1289609	-18.5
Janetville	11	1100	1249605	1289609	-3.1
Pontypool	12	1200	1218675	1289609	-5.5
Tyrone	13	1300	635670.5	1289609	-50.7

Unfortunately, the reason for the lack of measurements cannot be confirmed as to why they were 0. There was also a very significant difference with the Cherrywood gauge (–74.6 percentage difference). The Cherrywood gauge is located approximately 17 km from Stouffville and one would assume that there would be a strong correlation between the two. It wasn't until the completion of the study was it discovered that the Cherrywood gauge was poorly maintained. While many of the rainfall measurement dates (in terms of occurrences) are similar to Stouffville, the measured volume at the Cherrywood gauge is much less than the Stouffville gauge. This would cause PCSWMM to generate less runoff volume and thus, increase the percentage difference.

2. Clustered Model

The subwatershed model was similar to the lumped model in terms of percentage difference (Table 17). In most cases the percentage difference increased between the lumped model and the subwatershed model. This is most likely because of the discretization of the lumped watershed into four subwatersheds (1 to 4). However, percentage differences at Markham and Pontypool decreased. For this model, the parameters for area, imperviousness, and average width were adjusted accordingly for each subwatershed. The result was a 3.2 percentage increase in percentage difference from the lumped Stouffville calibration model. While minor adjustments in all three parameters could have been done, it was preferred not to do so in order to keep the model consistent with the lumped model. In other words, the percentage imperviousness and area calculations were similar in both models, suggesting that discretization can introduce volume differences.

Table 17. The total runoff volume generated by PCSWMM and the measured volume at station 02HC039 for the clustered models.

Gauging Station	Gauge #	Dummy Pipe	Clustered Volume (m^3)	02HC039 Volume (m^3)	% difference
Oshawa	1	100	876178.4	1234248.5	-29.0
Markham	2	200	940569.3	1234248.5	-23.8
Bowmanville	3	300	928004.7	1234248.5	-24.8
Buttonville Airport	4	400	811876.9	1234248.5	-34.2
Stouffville	**5**	**500**	**1283343**	**1234248.5**	**4.0**
Cherrywood	6	600	266590.6	1234248.5	-78.4
Bedford	7	700	1033694	1234248.5	-16.2
Kimberly	8	800	574026.1	1234248.5	-53.5
Udora	9	900	1777742	1234248.5	44.0
Burketon	10	1000	856729.2	1234248.5	-30.6
Janetville	11	1100	1083847	1234248.5	-12.2
Pontypool	12	1200	1212959	1234248.5	-1.7
Tyrone	13	1300	512848	1234248.5	-58.4

3. Seasonal Model

Unlike the lumped and subwatershed models, significant volume differences were observed by dividing the rainfall time-series into summer and fall seasons (Table 18 and 19). Generally, the summer lumped and summer subwatershed models generated flow greater than 02HC039. On the other hand, the results that were generated during the fall months did lower the range of percentage difference; however, PCSWMM generally underestimated flows.

Table 18. Summary of the total runoff volume generated by PCSWMM for the summer and fall lumped model and the measured volume at station 02HC039.

Gauging Station	Gauge #	Dummy Pipe	Summer Lumped Volume (m^3)	02HC039 Volume (m^3)	% difference	Fall Lumped Volume (m^3)	02HC039 Volume (m^3)	% difference
Oshawa	1	100	469827.4	303580.6	54.8	612831.9	986028.7	-37.8
Markham	2	200	217951.2	303580.6	-28.2	744848.7	986028.7	-24.5
Bowmanville	3	300	428273.7	303580.6	41.1	662831.9	986028.7	-32.8
Buttonville Airport	4	400	433829.4	303580.6	42.9	492604	986028.7	-50.0
Stouffville	**5**	**500**	**399135.2**	**303580.6**	**31.5**	**901339.2**	**986028.7**	**-8.6**
Cherrywood	6	600	256792.9	303580.6	-15.4	70761.1	986028.7	-92.8
Bedford	7	700	460274.9	303580.6	51.6	619023.3	986028.7	-37.2
Kimberly	8	800	299477	303580.6	-1.4	413634.7	986028.7	-58.1
Udora	9	900	856891.2	303580.6	182.3	947560.2	986028.7	-3.9
Burketon	10	1000	424556	303580.6	39.8	626786.2	986028.7	-36.4
Janetville	11	1100	557415.1	303580.6	83.6	692189.6	986028.7	-29.8
Pontypool	12	1200	622604.3	303580.6	105.1	596071	986028.7	-39.5
Tyrone	13	1300	373182.6	303580.6	22.9	262488	986028.7	-73.4

Table 19. Summary of the total runoff volume generated by PCSWMM for the summer and fall clustered model and the measured volume at station 02HC039.

Gauging Station	Gauge #	Dummy Pipe	Summer Clustered Volume (m^3)	02HC039 Volume (m^3))	% difference	Fall Clustered Volume (m^3)	02HC039 Volume (m^3)	% difference
Oshawa	1	100	379788.8	285297.2	33.1	496389.6	948951.3	-47.7
Markham	2	200	176728	285297.2	-38.1	763841.4	948951.3	-19.5
Bowmanville	3	300	346520.6	285297.2	21.5	581484.2	948951.3	-38.7
Buttonville Airport	4	400	350452.2	285297.2	22.8	461424.7	948951.3	-51.4
Stouffville	**5**	**500**	**323033.6**	**285297.2**	**13.2**	**960309.3**	**948951.3**	**1.2**
Cherrywood	6	600	208873	285297.2	-26.8	57717.6	948951.3	-93.9
Bedford	7	700	370913.8	285297.2	30.0	662780.2	948951.3	-30.2
Kimberly	8	800	242940.1	285297.2	-14.8	331086	948951.3	-65.1
Udora	9	900	783132.3	285297.2	174.5	994610.1	948951.3	4.8
Burketon	10	1000	343912.1	285297.2	20.5	512817.1	948951.3	-46.0
Janetville	11	1100	449355.2	285297.2	57.5	634491.3	948951.3	-33.1
Pontypool	12	1200	726238.8	285297.2	154.6	486719.9	948951.3	-48.7
Tyrone	13	1300	302001.1	285297.2	5.9	210846.8	948951.3	-77.8

4. Grid Model

A summary of the association of the virtual rain gauges, the inlet dummy pipe, the landuse, and the total runoff from each pipe can be viewed in Table 20. Tables 21 and 22 summarize the total runoff volume generated by PCSWMM for the lumped, subwatershed, and the grid models for the month of September 1999. The tables have two parts; the first is a comparison of the PCSWMM runoff generated by each rain gauge and the 02HC039 runoff for the month of September, 1999. The second part is a comparison of the 02HC039 volume and the PCSWMM generated volume for the grid. A comparison of the grid model with 02HC039 is made in Table 21 and 22.

There are several key characteristics that were noticed in the results. The first is the change in percentage difference for the Stouffville measurements. In both the lumped and subwatershed models, the difference generally increased. In several cases the percentage difference improved. This is most likely because of the increase in discretization, where, the improved differences may be largely a direct result of the kriging.

The second observation was the average percentage difference between all of the gauges. In both cases (the lumped and subwatersheds), the average percentage difference for all of the gauges improved. This is because many of the erroneous volumes produced by the individual gauge runs that were in poor correlation in terms of rainfall volume (e.g. Cherrywood, Bowmanville, Oshawa) were vastly improved using the grid approach. On the other hand, some of the better matches using the true rainfall values from the original 13 gauges (e.g. Markham) became worse using the grid method.

Table 20. Summary of the virtual rain gauge, the associated dummy pipe, landuse, and total runoff (m^3).

Grid Cell and Virtual Rain Gauge Number	Dummy Pipe Number	Federal Airport Lands	Forest	Meadow	Urban Open Area	Urban	Agriculture / Rural	Wetland	Total
1 to 6	100	0.0	41.7	8325.0	0.0	2959.0	3559.0	31.1	14915.8
7 to 12	200	0.0	585.8	455.6	0.0	598.8	3883.0	636.9	6160.1
13 to 18	300	0.0	519.3	174.9	0.0	2825.0	2566.0	5778.0	11863.2
19 to 24	400	2.4	343.3	19.5	0.0	1641.0	3823.2	591.7	6421.1
25 to 30	500	17650.0	470.5	4948.0	279.7	12500.0	3435.0	508.3	39791.5
31 to 36	600	2669.0	8578.0	174.8	405.1	78480.0	2071.0	45.3	92423.2
37 to 42	700	6669.0	544.5	72.4	0.0	3757.0	4071.0	22.1	15136.0
43 to 48	800	41040.0	982.2	2077.1	0.0	0.0	282.4	640.7	45022.4
49 to 54	900	5425.0	272.5	33.2	0.0	0.0	0.0	83.6	5814.3
	Total Runoff	**73455.4**	**12337.8**	**16280.5**	**684.8**	**102760.8**	**23690.6**	**8337.6**	**237547.4**

Table 21. Summary of the total runoff volume generated by PCSWMM for the lumped and the grid models for September 1999.

Gauging Station	Gauge #	Dummy Pipe	Lumped Volume (m³)	02HC039 Volume (m³)	% difference	Lumped Volume (m³)	Grid Volume (m³)	% difference
Oshawa	1	100	334375.6	258728.6	29.2	334375.6	237220.5	41.0
Markham	2	200	254909.1	258728.6	-1.5	254909.1	237220.5	7.5
Bowmanville	3	300	337648.5	258728.6	30.5	337648.5	237220.5	42.3
Buttonville Airport	4	400	206156.2	258728.6	-20.3	206156.2	237220.5	-13.1
Stouffville	**5**	**500**	**267773.4**	**258728.6**	**3.5**	**267773.4**	**237220.5**	**12.9**
Cherrywood	6	600	41960.1	258728.6	-83.8	41960.1	237220.5	-82.3
Bedford	7	700	85860.2	258728.6	-66.8	85860.2	237220.5	-63.8
Kimberly	8	800	226022.9	258728.6	-12.6	226022.9	237220.5	-4.7
Udora	9	900	286383	258728.6	10.7	286383	237220.5	20.7
Burketon	10	1000	245206.5	258728.6	-5.2	245206.5	237220.5	3.4
Janetville	11	1100	286757.7	258728.6	10.8	286757.7	237220.5	20.9
Pontypool	12	1200	244798.8	258728.6	-5.4	244798.8	237220.5	3.2
Tyrone	13	1300	242170.8	258728.6	-6.4	242170.8	237220.5	2.1

Table 22. Summary of the total runoff volume generated by PCSWMM for the clustered and the grid models for September 1999.

Gauging Station	Gauge #	Dummy Pipe	Clustered Volume (m^3)	02HC039 Volume (m^3)	% difference	Clustered Volume (m^3)	Grid Volume (m^3)	% difference
Oshawa	1	100	272174	250753.4	8.5	272174	237220.5	14.7
Markham	2	200	245586.8	250753.4	-2.1	245586.8	237220.5	3.5
Bowmanville	3	300	308761.9	250753.4	23.1	308761.9	237220.5	30.2
Buttonville Airport	4	400	230645.2	250753.4	-8.0	230645.2	237220.5	-2.8
Stouffville	**5**	**500**	**248266**	**250753.4**	**-1.0**	**248266**	**237220.5**	**4.7**
Cherrywood	6	600	33968.5	250753.4	-86.5	33968.5	237220.5	-85.7
Bedford	7	700	69266	250753.4	-72.4	69266	237220.5	-70.8
Kimberly	8	800	180486.8	250753.4	-28.0	180486.8	237220.5	-23.9
Udora	9	900	229183.1	250753.4	-8.6	229183.1	237220.5	-3.4
Burketon	10	1000	196344.2	250753.4	-21.7	196344.2	237220.5	-17.2
Janetville	11	1100	228919	250753.4	-8.7	228919	237220.5	-3.5
Pontypool	12	1200	196263.2	250753.4	-21.7	196263.2	237220.5	-17.3
Tyrone	13	1300	193923.3	250753.4	-22.7	193923.3	237220.5	-18.3

Table 23 summarizes the results from the four models using flow generated by the Stouffville rain gauge. The table clearly depicts an increase in difference as the watershed was discretized. For instance, in the September models where the generated volumes were compared to the measured volumes the percentage difference increased from 3.5 to –5.4 to –8.3 for the lumped, clustered, and grid models. While the same increase occurred when both the generated models were compared (lumped against grid and clustered against grid), in this case 3.5 to 12.9 and –1.0 to 4.7 respectively.

Table 23. Results for the lumped, clustered, seasonal, and grid models generated by the Stouffville rain gauge.

	Generated Volume (m^3)	02HC039 Volume (m^3)	% difference
May to November, 1999			
Lumped	1300474.4	1289609.4	0.8
lumped summer	399135.2	303580.6	31.5
lumped fall	901339.2	986028.7	-8.6
Clustered	1283342.8	1234248.5	4.0
clustered summer	323033.6	285297.2	13.2
clustered fall	960309.3	948951.3	1.2
September, 1999			
Lumped	267773.4	258728.6	3.5
Clustered	248266	250753.4	-1.0
grid (lumped)	237220.5	258728.6	-8.3
grid (clustered)	237220.5	250753.4	-5.4
Generated (Sept, 1999)	**Grid Volume (m^3))**	**Lumped/Clustered Volume (m^3)**	**% difference**
lumped vs. grid	267773.4	237220.5	12.9
clustered vs. grid	248266	237220.5	4.7

5. Flow Duration Curve

FDC's were generated for all of the models in this study. The common trend noticed was that all plots depicted a flow exceedance no greater than 2 m^3/s where the probability of exceedance a low 20 percentage (Figure 29). Figure 30 depicts what would happen if the percentage impervious for the lumped model was increased from 8 to 50 percent. The result is a larger flow exceedance, but the probability changed very little.

Flow duration curves for all rain gauging stations and the grid results can be observed in Appendix L.

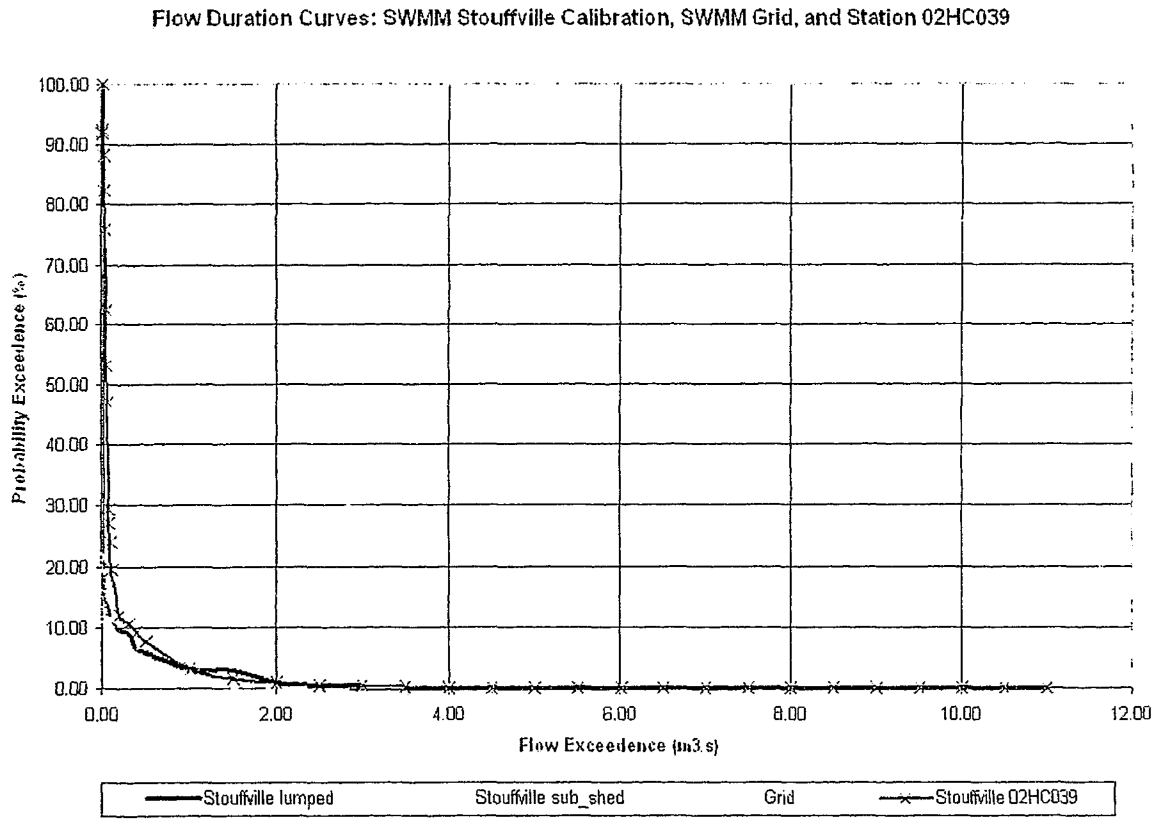


Figure 29. A flow duration curve depicting the flow calculated by PCSWMM using the Stouffville rain gauge for the lumped and subwatersheds, the PCSWMM grid generated rainfall model using the virtual rain gauges, and the measured stream flow at station 02HC039.

Chapter 6

Evaluation and Discussion

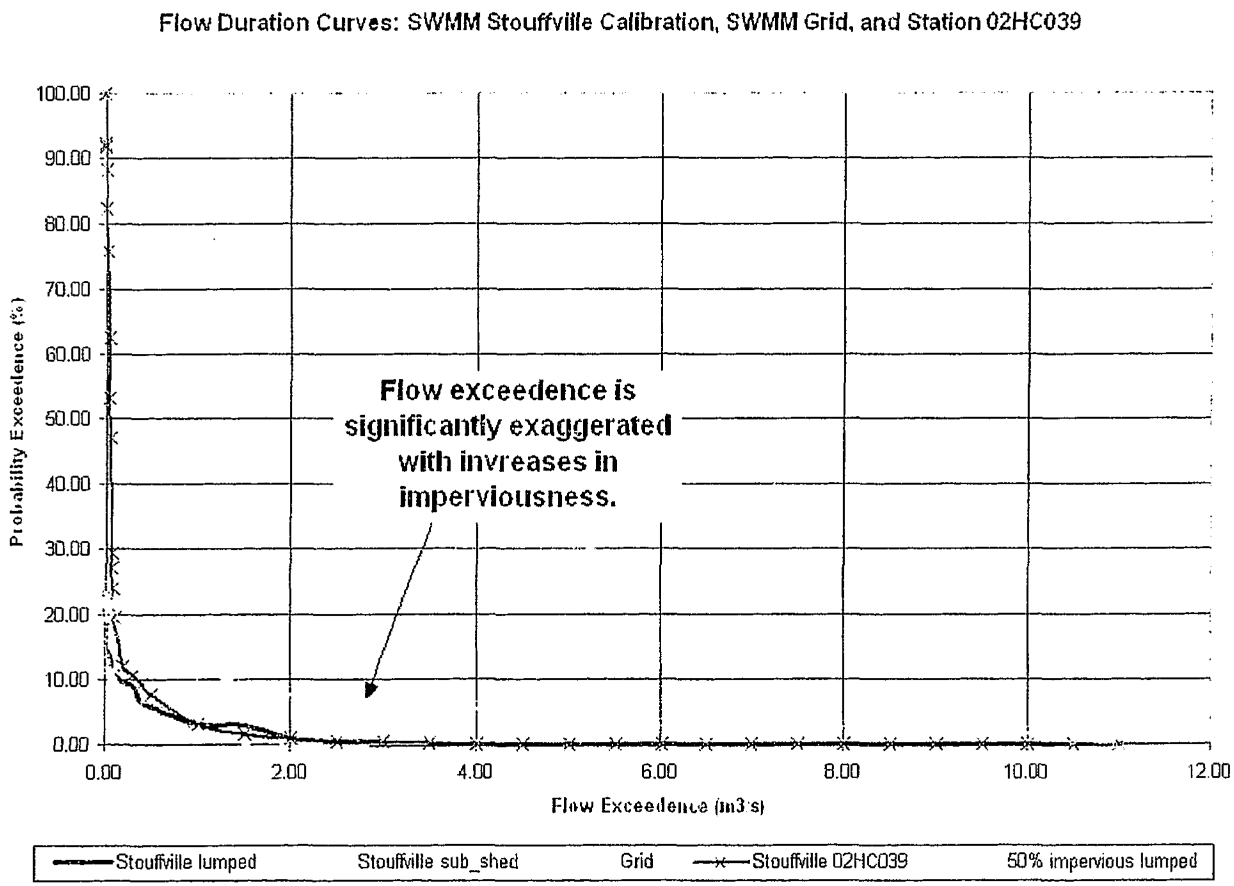


Figure 30. Flow duration curve depicting an increase in flow exceedance with increased percentage imperviousness.

In Chapter 5, the results from the lumped, clustered,, and grid modelling was described. In this chapter, the results are discussed in depth with elaboration and emphasis on significant observations.

1. Lumped Model

In Table 16, it was noticed that the Cherrywood station had the highest percentage difference, despite it being the closest rain gauge to Stouffville (17 km). One would assume that the sets of modelled results would be similar because of their location to one another; however the difference may have been a result of measurement error, improper maintenance, and natural / structural influence (e.g. elevated topography). Generally, most of the gauges correlated with the Stouffville gauge from average to well (0.6 to 0.9 respectively). Two of the stations (Pontypool and Tyrone) had gaps in the data set (Table 9). In both cases, the Pontypool and Tyrone measured significantly less rainfall (greater than 100mm) than the Stouffville gauge. The lower rainfall volume generated far less runoff in the PCSWMM environment. This is why both Pontypool and Tyrone generated smaller flows than the measured flow at 02HC039.

In most cases (except Janetville and Pontypool), the percentage difference was greater than 15 percent. Several of these gauges had a reasonably good correlation with the rainfall measured at the Stouffville station. However, despite a moderate correlation between some gauges, it is the volume differences that contributed to most of the differences. For example, since PCSWMM is precipitation driven, the larger or smaller a measured value is in context with the Stouffville measurements, the runoff volume generated by PCSWMM will reflect the volume of the measured rainfall. This response is further discussed in Section 6 of this Chapter using Buttonville as an example.

It was observed that there was no relationship between the spatial distribution of the rain gauge network and its correlation with the Stouffville (Figure 35, Section 6).

2. Clustered Model

The observations and discussion in the clustered model are very similar to the lumped model (Figure 31). However, the trend observed was that the clustered model generally increased the percentage difference with the discretization of the Reesor Creek watershed. While the rainfall used in the clustered model was the same as the rainfall used in the lumped model, the difference here was the parameter adjustments used to represent subwatersheds 1, 2, 3, and 4. The differing parameters can be viewed in Table 14 (Chapter 4). In this case area, average width, and percentage impervious were calculated, and unlike the lumped model where each parameter represented the total area (e.g. percentage impervious). For example, the percent imperviousness for the lumped watershed was 8.41%, while the clustered model was 10, 15, 2 and 2 percent for subwatersheds 1, 2, 3, and 4 respectively. Changes in imperviousness contribute significantly in the generation of runoff in PCSWMM since the SWMM engine is very sensitive to changes in this parameter (Section 6, Figure 37).

The changes in catchment area and width are also sensitive parameters in the SWMM engine that can increase or decrease the volume of runoff generated by PCSWMM (Figure 32). Nonetheless, for this study the square root of the subwatershed was used to represent the average width, and the percentage difference may have been improved if changes in the average area during the calibration runs was conducted.

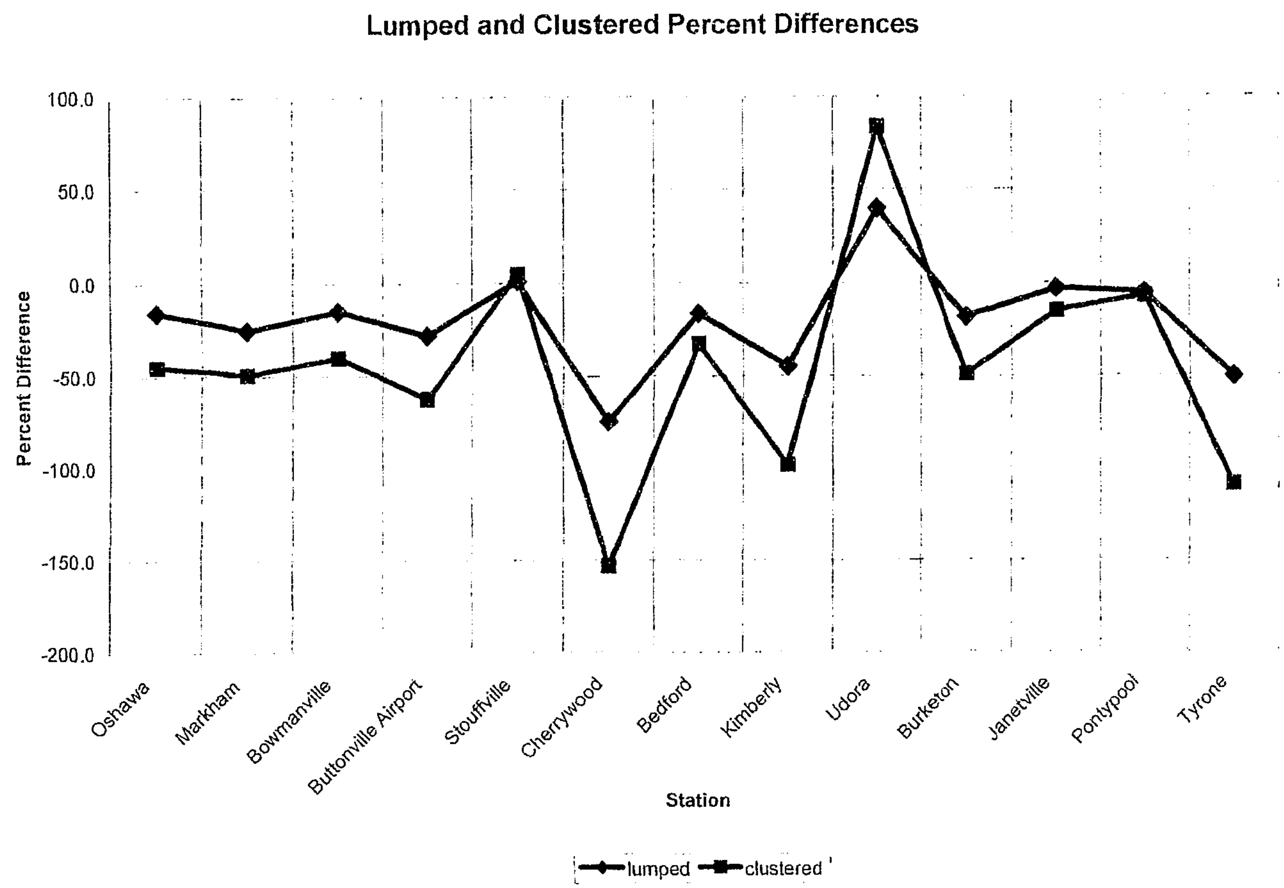
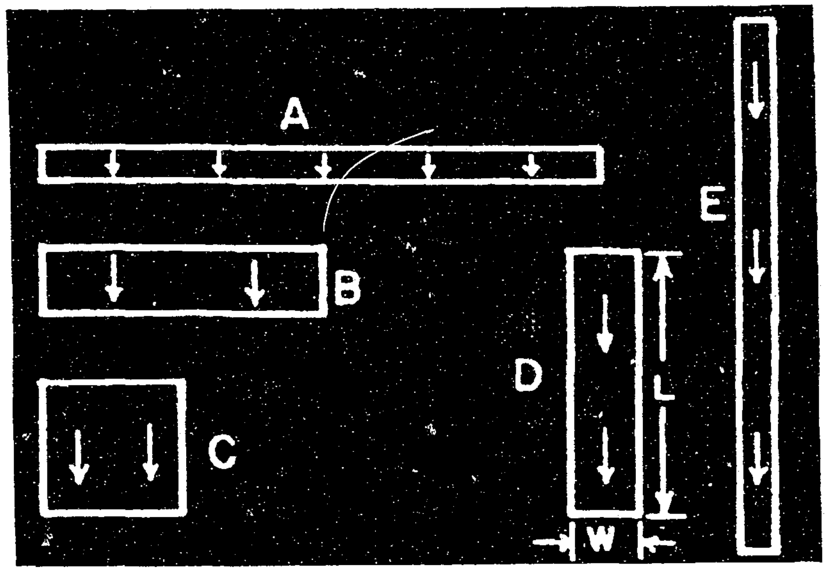


Figure 31. Percentage difference for both the lumped and clustered models.



Slope = 0.01
Imperviousness = 100%
Depression Storage = 0
n = 0.02
Equilibrium outflow = i*A = 0.926 cfs

DELT = 5 min = 300 sec
i* = Rainfall = 1.0 in./hr = 0.000023148 ft/sec

Shape	A (ft^2)	W (ft)	L (ft)	t_c[a] (min)	WBCON[b] (ft-sec units)
A	40,000	800	50	3.7	-0.149
B	40,000	400	100	5.7	-0.0745
C	40,000	200	200	8.6	-0.03725
D	40,000	100	400	13.0	-0.018625
E	40,000	50	800	19.7	-0.0093125

Figure 32. Changes in catchment width will change he rate and volume of runoff (Huber and Dickinson, 1992).

3. Grid Model

The grid model discretized the Reesor Creek watershed into 1km^2 grid cells. Observations concluded that the grid model when compared to the lumped, clustered, and gauge 02HC039 increased the percentage difference. Similar to the discussion for the clustered model above, the discretization of the watershed and changes in the PCSWMM parameters of percent imperviousness, area, and average width are what contributed to the differences. While this is not necessarily incorrect, since one would assume that the more discrete a model and its database is the more, so to should its percentage difference. This observation can be seen in Figure 33.

4. Seasonal Model

The outstanding observation for this model was the drastic increase in percentage difference in the summer model. Because PCSWMM is best suited for urban watersheds, the rural landscape of Reesor Creek may be the reason for the differences. During the dry summer months the soil will dry out and increase soil moisture storage, therefore, during a storm event, rainfall is used up as soil recharge and retained as pervious depressions storage and not immediate runoff.

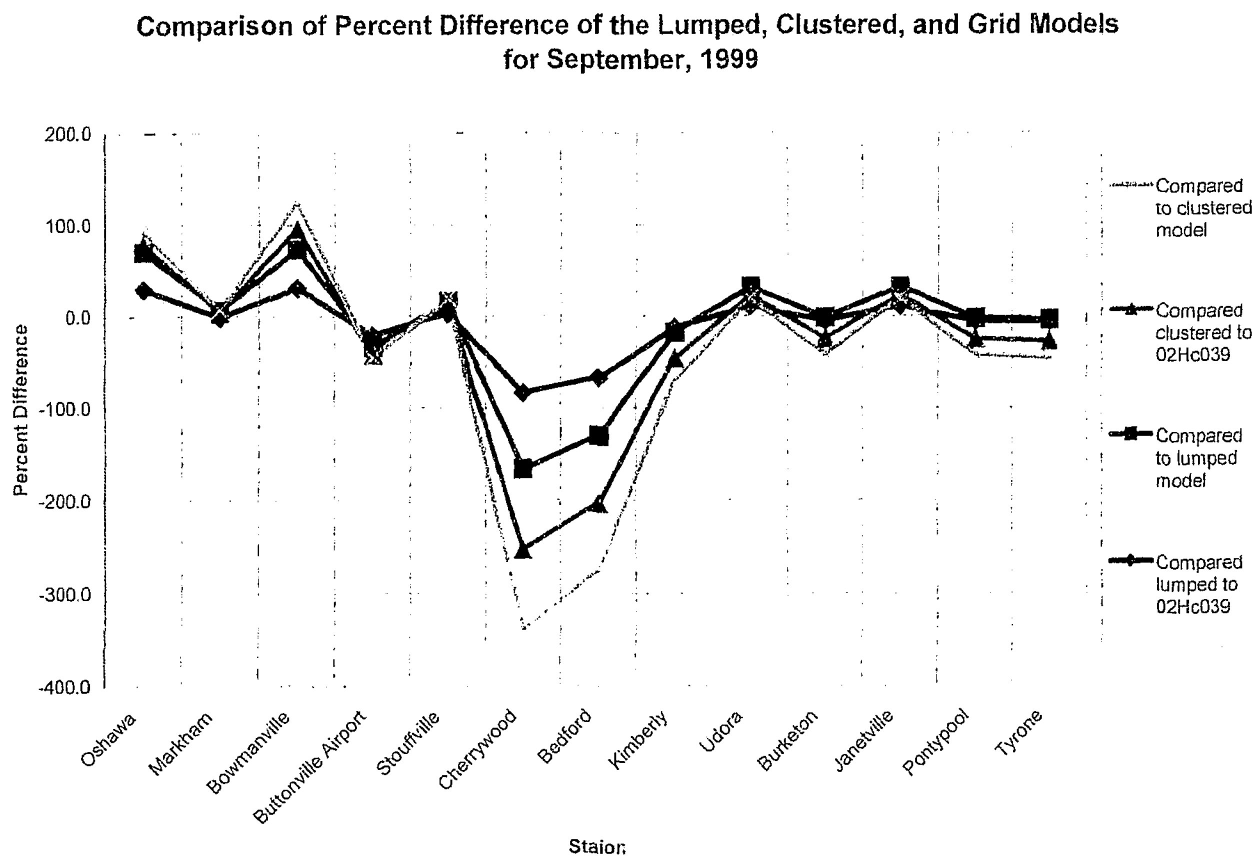


Figure 33. A Comparison of the percentage differences of the lumped, clustered, and grid models.

As stated in Chapter 5, the fall model generally underestimated flows. This may be because the fall is generally a wet time of year with frequent rainfall events. With the soil recharged, little infiltration will occur. The result can be overland flow that directly discharges to Reesor Creek as runoff—thus, increasing runoff volumes. The condition of the watershed in the fall was similar to pavement or impermeable surfaces. Nonetheless, PCSWMM still underestimates the true measured volume because the percent impervious runoff is much less than the contributions of the entire watershed as groundwater flow and overland runoff.

5. Flow Duration Curve

As depicted in Figure 29 (Chapter 5) the common trend noticed was that all plots depicted a flow exceedence no greater than 2 m^3/s where the probability of exceedence is a low 20 percent. This suggests that even during heavy storm events, there is significant risk of exceeding this low flow rate. This is most likely because the rural environment (low imperviousness) combined with the loam soils may result in less runoff because of infiltration and watershed groundwater recharge.

Also, Figure 30 (Chapter 5) changes in percent impervious for the lumped model was increased from 8 to 50 percent. The result is a larger flow exceedence, but there was very little change of probability. This would suggest that increases in development to the Reesor Creek watershed would drastically affect runoff quantity and increase stream volumes. Surge or flash effects on the natural watercourse can flood downstream if the flow exceedence volume is greater than the bank full discharge. Just to recall one of the concerns of the TRCA (stated in Chapter 3), was the proposed development for Duffins Creek and in turn Reesor Creek could generate flooding and changes to natural baseflows and watercourses if development follows through.

6. Model Evaluation

One would assume that a strong correlation between measured rainfall volumes would generate similar runoff volumes in PCSWMM. It was observed that this was not the case. For example, Figure 34 is an example of a strong correlation of rainfall generating a large volumetric difference in PCSWMM. In this case, the Buttonville Airport and the Stouffville rain gauge had a correlation of 0.868. However, the percentage difference in volume was –28.2 percent.

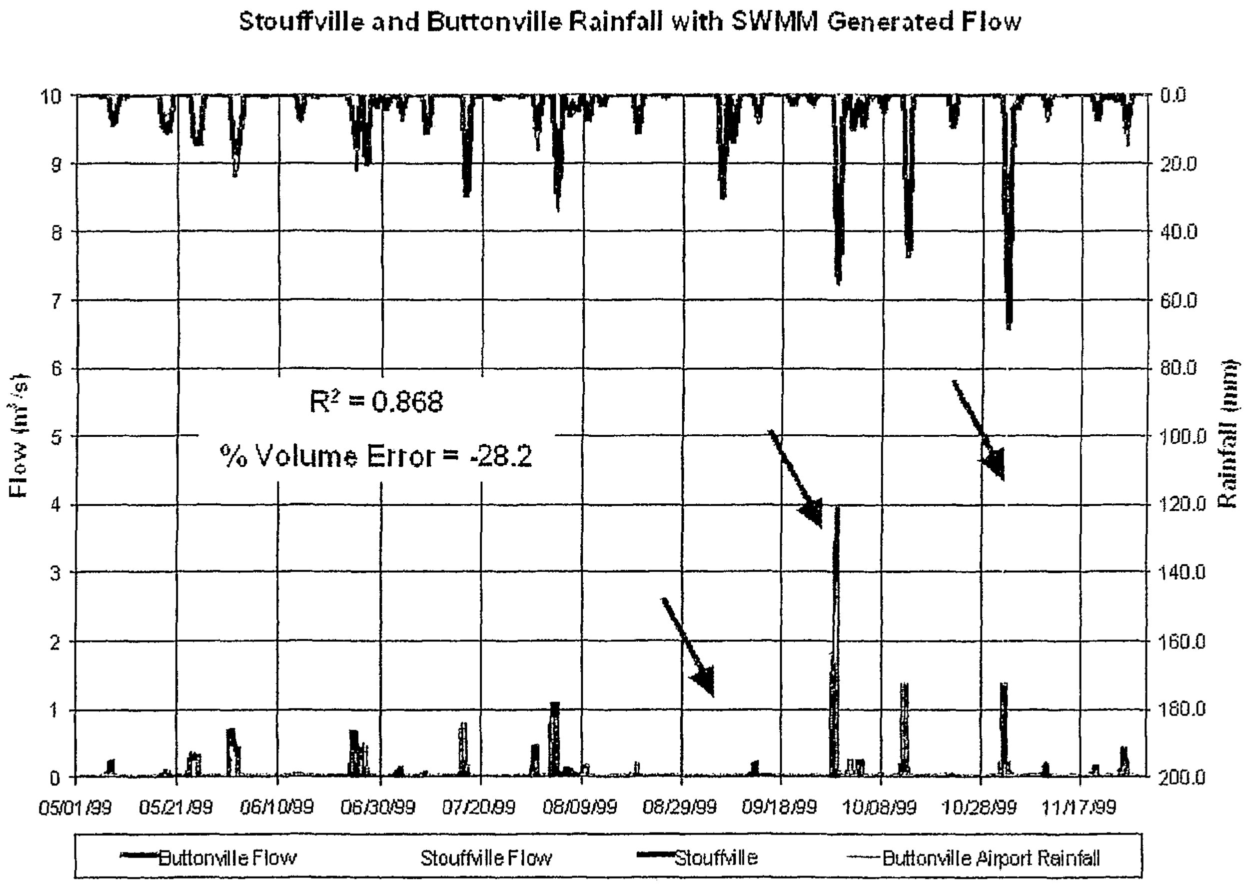


Figure 34. Volume differences in PCSWMM generated flow despite strong rainfall correlations. The red arrows identify peak differences.

This was because during several storm events, the Stouffville gauge measured a larger precipitation value. A larger flow generated by PCSWMM. This observation is significant because it identifies two things: 1) rainfall is spatially variable, and 2) decision making models generated using rain gauges from outside the watershed boundaries or a single gauge for a large watersheds on their own, may not truly represent runoff using SWMM as a prediction tool.

The first point is further supported when the correlation values are plotted against the distance from the Stouffville gauge (Figure 35). In this case, observations suggested that there is no relationship between the strength of the correlation with the calibration gauge (Stouffville) and the distance from it. This poor relationship may also be a direct result of the poor rainfall measurements, lack of maintenance on the rain gauge, or lost data. It is recommended that future studies confirm rainfall data accuracy before this assumption can be made.

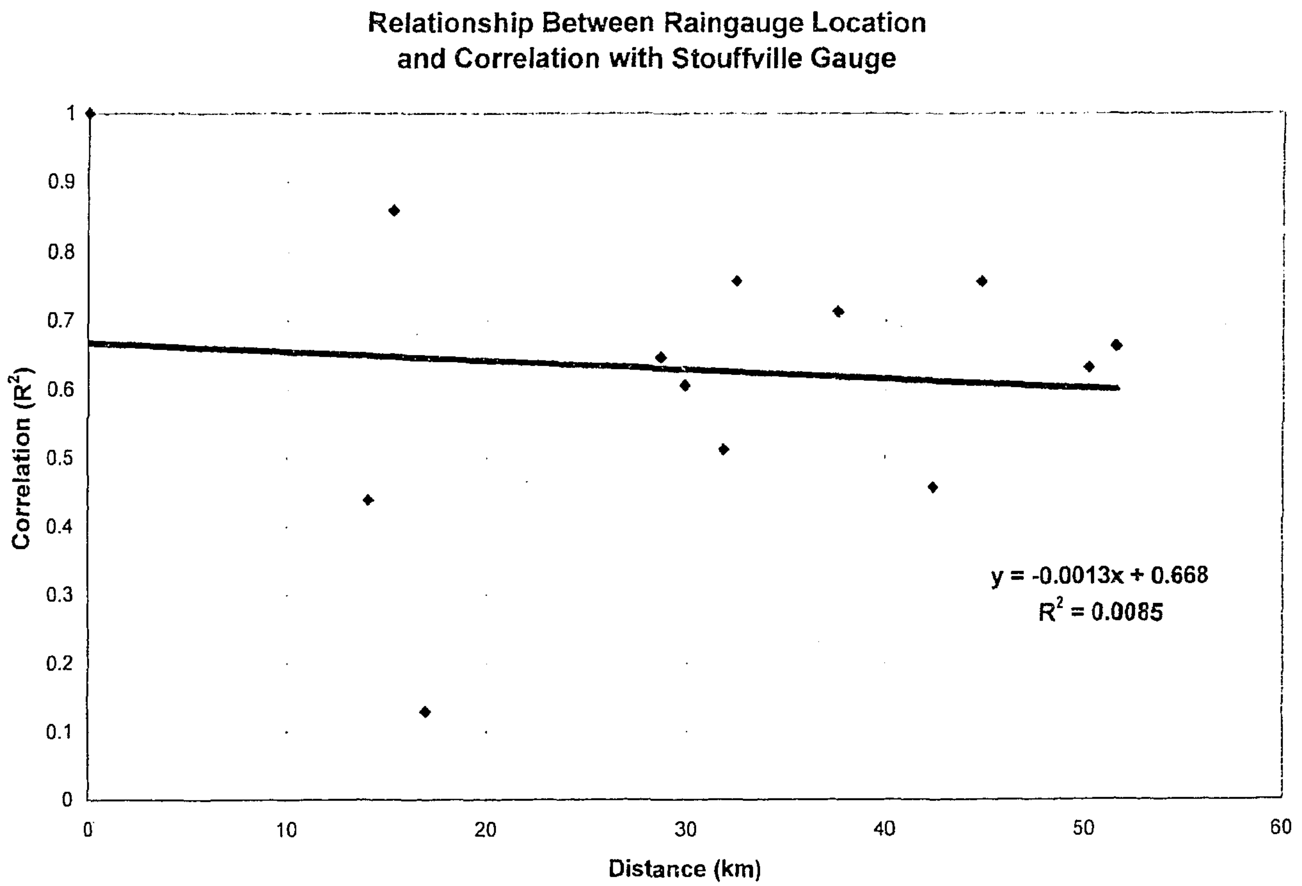


Figure 35. Spatial variability was observed with rainfall measurements.

The regression values for all of the virtual rain gauge correlated to the Stouffville gauge. The high values (average 0.9694) are a direct result of the kriging. This is because the values were weighted using the Stouffville gauge during the kriging process. The closeness of the virtual rain gauges to the Stouffville gauge generated the strong correlation (Table 24).

This observation is significant since it suggests that all of the rainfall that occurred in the Reesor Creek watershed boundaries is uniformly distributed and that rainfall values only "taper off" gradually with distance. This is not always the case in reality. For instance, Figure 36 depicts a hypothetical scenario where rainfall values bordering a watershed have a high correlation. However, a single measurement taken in the middle of the area is much lower. The result would be a predicted layer that is reflective of all the measurements and includes the middle values. This is inferred to the relationship between the Stouffville gauge and the Cherrywood gauge (poor correlation 0.128) (Figure 36).

Conversely, if the middle value was not measured or if the topography had a high elevation, then the prediction would be significantly different. In this case, the predicted value would be reflective of the gauges bordering it. This observation would also contribute significant percentage differences in generated SWMM runoff.

Table 24. Regression values for the virtual rain gauges correlated to the Stouffville gauge.

Average R^2	0.9694		
Station #	R^2	Station #	R^2
0	0.962	27	0.9671
1	0.9577	28	0.9698
2	0.9561	29	0.963
3	0.9637	30	0.9625
4	0.9629	31	0.9694
5	0.9621	32	0.9719
6	0.9578	33	0.9634
7	0.9625	34	0.9874
8	0.9647	35	0.967
9	0.9635	36	0.9711
10	0.9675	37	0.9738
11	0.9668	38	0.9752
12	0.9639	39	0.9734
13	0.9661	40	0.973
14	0.9684	41	0.9746
15	0.9676	42	0.9764
16	0.9664	43	0.9772
17	0.9663	44	0.9777
18	0.9687	45	0.9783
19	0.9666	46	0.979
20	0.9659	47	0.9789
21	0.9665	48	0.9772
22	0.9676	49	0.9805
23	0.9675	50	0.9805
24	0.9647	51	0.9797
25	0.9642	52	0.9773
26	0.9656	53	0.9794

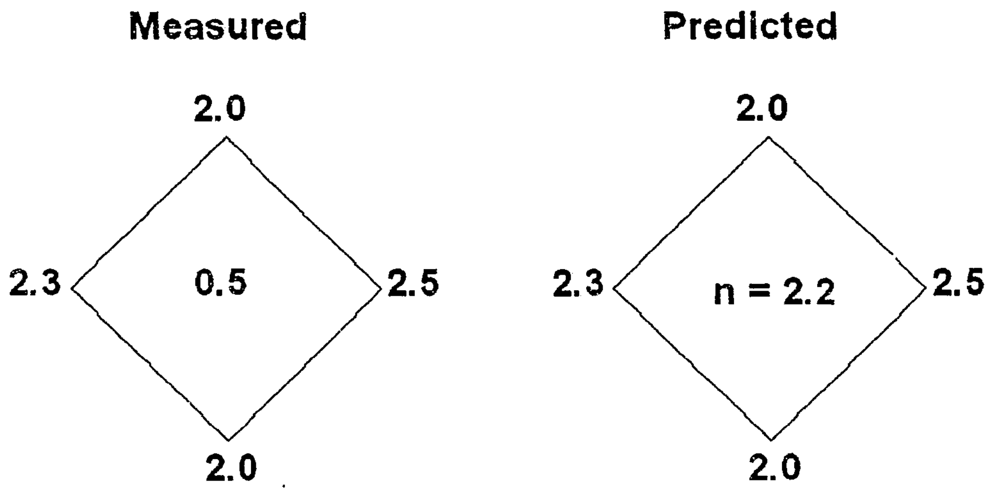


Figure 36. A hypothetical scenario depicting measured against predicted (kriged) rainfall.

The hypothetical scenario described previously was tested on several poorly to average correlated rain gauges (Table 25). For this test, the kriged rainfall was generated without the gauges Cherrywood, Markham, Janetville, and Tyrone. The kriging was then re-run with the gauges removed and measurements from the predicted layer were taken at the point at which they originally were. The new values were then correlated to the Stouffville gauge and in all cases, the predicted values were observed to have a better correlation. However, the new values were not reflective of the originally measured values. This suggest that there is a need for many more rain gauges to be used in this type of modelling to best represent the watershed and avoid "exaggerated" predictions.

Table 25. A comparison of measured and predicted rainfall correlations for the Reesor Creek watershed.

Station	Measured with Stouffville	Predicted with Stouffville	Predicted with Measured
	R^2	R^2	R^2
Cherrywood	0.129	0.852	0.606
Markham	0.438	0.888	0.006*
Janetville	0.632	0.847	0.901
Tyrone	0.457	0.811	0.949

*Value low because of non-measured value and high predicted value in data.

As stated previously, Vieux (2001) stated that considering the attributes of parameters and precipitation controlling hydrologic processes, it is not surprising that GIS have become an integral part of hydrologic studies. In the past, the difficulties in managing and efficiently using spatial information have prompted hydrologists to resort to lumped models to develop technology for managing the data.

Because of the vast amount of data that is generated with a clustered or grid models, the model can be discretized to observe the effects of development change (e.g. paving and construction). Figure 37 depicts the above by changing the percentage imperviousness of the watershed for the lumped and subwatershed models. In both cases, runoff volume increased.

Chapter 7

Conclusions and Recommendations

1. Conclusions

Below is a list of the key conclusions made for this research. A short discussion follows to elaborate several of these points.

- GIS was useful in generating the landuse, soil type, and rainfall attributes for use in PCSWMM.
- Kriging rainfall does accurately predict rainfall at ungauged (virtual) sites only under the following conditions: 1) All neighbouring stations must have a good correlation, and 2) stations measuring lower values than neighbouring stations should be confirmed for errors in measurements or other systematic influence.
- The methodology outlined in this study does contribute to understanding the effect of spatial distribution on rainfall.
- Rainfall variance is independent of distance. Rainfall variability does occur with spatial location.
- A strong correlation between measured rainfall values does not confirm a strong relationship with generated runoff.
- Changes in percentage imperviousness of a watershed will affect modelled runoff.
- Disaggregating a watershed does induce differences, however, calibration of some watershed modelling parameters can limit this (e.g. watershed width).
- Seasonal variability does affect hydrologic modelling results.

As a methodological protocol, this study is uniquely applicable to rainfall-runoff analysis using PCSWMM and ArcGIS software. Integration of data file exchange was a critical link for this study. In this case, attribute tables for soil, landuse, and virtual rainfall were generated by ArcMap and analyzed to develop the parameters for the input files for PCSWMM.

PCSWMM and ArcGIS were chosen because of their relative popularity with most professionals. The steps outlined in this study can be customized and applied by others to not only generate discretized runoff volume, but to improve upon the variability of spatially distributed rainfall measurements.

This study also observed the effects of disaggregating a watershed based on lumped, subwatershed, seasonal, and grid models. Three of the four models did generate a reasonable water balance over the full time-series; however, a longer time-series would most likely generate a better representation of the watershed. For instance, results found in this study did not generate a good water balance for the summer months (-1.4 to 182.3 percentage difference lumped model). This is because PCSWMM generates flow usually with short lag time, characteristic of an urban watershed. In urban environments, runoff has a shorter lag time, and PCSWMM takes this into consideration when generating flow. However, since most of Reesor Creek is pervious, during the dry summer months the soil will dry out and increase soil moisture storage. The result during storm events is a soil moisture recharge (first) and not runoff.

On the other hand, the results that were generated during the fall months did lower the range of percentage difference (-8.6 to -92.8 lumped model), however, PCSWMM in all cases underestimated flow. This might be because fall is generally a wet time of year with frequent rainfall events. With the soil being recharged, infiltration rates are lowered. The result can be overland flow that directly discharges to Reesor Creek as runoff—far with little or no depression storage in the pervious area (which is the majority).

However, PCSWMM is better suited for a watershed in this condition because saturated soils are similar to pavement or impermeable surfaces. Nonetheless, PCSWMM still underestimated the true measured volume because the percentage impervious runoff is much less than the contributions of the entire watershed as groundwater flow and overland runoff.

It would appear that the discretization of the watershed did introduce volumetric differences into the models. The increase in data and parameters from lumped to grid scale modelling most likely became more representative of reality and less like a single parameter model. When the generated flows using the Stouffville gauge (calibration gauge) are compared, the percentage difference form lumped to grid ranged from –8.3 to 0.8 percent., all of which are still good results in terms of a water balance (less than 10 percent difference).

The third objective guided observations to reflect the effects of spatial distribution on rainfall. In all cases, flow generated by PCSWMM did differ when using different gauges outside of the watershed. Using the Stouffville gauge to calibrate the Reesor watershed parameters of all four models, the remaining 12 gauges were run in PCSWMM, and in each case, differences were introduced. Because PCSWMM is precipitation driven, if there is no rainfall, no flow is generated. The inverse will occur if it does rain. Using kriging to improve the rainfall values to generate virtual rain gauges improved the rainfall measurements within the watershed. The virtual rainfall and rain gauges are more representative of the precipitation falling on the Reesor watershed. The kriged rainfall approach, while slightly time consuming to generate, lowered the percentage difference between spatially distributed rainfalls. It should be noted that even if the model is left as a lumped parameter model, and only the virtual rainfall was generated, the difference results still improved.

This study observed the effects of lumped, clustered, and gird modelling. It also reviewed the influence that spatial distribution has on rainfall. Together, the key objective was completed—to demonstrate a new modelling technique using GIS and hydrologic modelling in a water balance. The new technique was to use the GIS to discretize both the rainfall and watershed attributes using kriging and a grid layer analysis. Results suggest that the introduction of GIS to the modelling did introduce differences; however, it was only because the model became more like reality, and less like a lumped model. While this study is simply a protocol for further research, is does answer the question how do space and time affected modelling?

2. Recommendations

The following outlines some of the key recommendations that would improve future GIS-based hydrological analysis and serve as a guide for further research.

- In terms of a water balance, a longer time series for both stream flow and rainfall would have been preferred. A time series of approximately 1-year minimum would improve the observed effects of winter snowmelt and antecedent conditions.

- Rainfall kriging should be conducted for a longer time-series (e.g. 6 months to 1 year) and it would be preferred to observe if the grid analysis becomes erroneous with time.

- To complete all analysis within the ArcGIS environment and limit the exporting of attribute tables. Removing the Excel spreadsheet medium could improve errors (if applicable).

- To develop a script and look–up tables that could be used by PCSWMM to read the attribute tables developed by ArcMap, which in turn, would adjust the parameters in the PCSWMM accordingly.

- To confirm data accuracy prior to analysis (e.g. rain gauge maintenance schedules, interviews, etc.).

- To demonstrate the effectiveness of differing surface interpolation methods (e.g. Inverse Distance Weighting and other kriging options) on rainfall.

- To apply the kriging model to a minimum of 50 gauges to improve the values generated by the prediction layers.

- To assess the importance of using only localized rainfall measurements for PCSWMM models. The percentage differences generated depict the significant differences in a models prediction.

- To incorporate measured evaporation and temperature data into PCSWMM rather than default parameters (e.g. evaporation 3 millimetres per day).

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Appendix A

Appendix A. Differing Kriging models were statistically compared on three rainfall layers (September 6, 7, and 9, 1999) to determine any significant differences. All model approaches were similar.

September 6, 1999	Circular	Spherical	Tetral	Pental	Expo	Gaussian	Rational Quad	Hole	K-Bessel	J-Bessel	Stable
Mean:	-0.3232	-0.3266	-0.3398	-0.3407	-0.2264	-0.3457	-0.2763	0.1316	-0.5062	1.869	-0.6268
Root-Mean-Square:	10.59	10.67	10.7	10.73	11.12	10.75	11.17	9.471	10.66	8.816	10.68
Average Standard Error:	10.28	10.34	10.35	10.37	10.55	10.35	10.52	9.853	10.23	9.581	10.07
Mean Standardized:	-0.01168	-0.01239	-0.0136	-0.01378	-0.006108	-0.01361	-0.009775	0.01886	-0.02594	0.1701	-0.03488
Root-Mean-Square Standardized:	1.02	1.024	1.026	1.028	1.056	1.029	1.063	0.9414	1.035	0.8658	1.055

September 7, 1999	Circular	Spherical	Tetral	Pental	Expo	Gaussian	Rational Quad	Hole	K-Bessel	J-Bessel	Stable
Mean:	-0.2415	-0.1206	0.1049	0.2356	0.3686	-0.1461	-0.1719	0.37	-0.1362	0.5075	-0.1178
Root-Mean-Square:	9.736	9.767	9.788	10.04	10.16	9.766	10.08	9.773	9.873	9.449	9.849
Average Standard Error:	10.21	10.46	10.54	10.59	11.27	10.49	10.76	9.969	10.15	9.704	10.18
Mean Standardized:	-0.007693	0.00502	0.02484	0.03848	0.04369	0.004271	0.006166	0.05529	0.009093	0.06467	0.01066
Root-Mean-Square Standardized:	0.9931	0.9544	0.9463	0.963	0.9009	0.9448	0.9391	1.044	1.004	1.066	0.9985

September 9, 1999	Circular	Spherical	Tetral	Pental	Expo	Gaussian	Rational Quad	Hole	K-Bessel	J-Bessel	Stable
Mean:	0.02531	0.01628	-0.008472	-0.008131	0.006275	-0.004519	-0.02227	-0.0553	0.03628	-0.03811	0.02767
Root-Mean-Square:	1.769	1.803	1.836	1.843	1.86	1.832	1.917	1.862	1.916	1.835	1.907
Average Standard Error:	1.871	1.886	1.893	1.898	1.972	1.948	1.953	1.92	1.869	1.899	1.865
Mean Standardized:	-0.001474	-0.006344	-0.019	-0.01882	-0.007908	-0.01258	-0.02175	-0.0388	0.002358	-0.02901	-0.002831
Root-Mean-Square Standardized:	0.9128	0.9238	0.9377	0.939	0.9208	0.9163	0.9577	0.9473	0.9895	0.9423	0.9862

Appendix B

Appendix B. Rainfall measurements for all gauging stations.

Date	Oshawa	Mark	Bowman	Button	Stouff	Cherry	Bedford	Kim	Udora	Burke	Janet	Ponty	Tyrone
5/1/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
5/2/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
5/3/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
5/4/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
5/5/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
5/6/1999	0.2	0.0	0.2	0.8	0.4	0.0	1.0	0.0	0.0	0.0	0.0		0.4
5/7/1999	0.6	0.0	2.4	0.0	0.1	0.0	0.3	0.2	0.0	1.0	1.4		1.0
5/8/1999	13.6	6.5	15.4	9.4	7.8	0.2	10.0	7.2	14.6	16.4	11.4		14.8
5/9/1999	0.0	1.8	0.0	0.6	2.8	0.0	0.3	1.2	0.0	0.0	0.0		0.0
5/10/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
5/11/1999	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0		0.0
5/12/1999	0.0	0.0	0.0	0.0	0.0	6.2	0.0	0.0	0.0	0.0	0.0		0.0
5/13/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
5/14/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
5/15/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
5/16/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
5/17/1999	0.2	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.0		0.0
5/18/1999	12.5	7.8	11.4	5.4	9.2	2.2	10.8	9.2	18.0	15.0	0.0		13.4
5/19/1999	0.0	2.7	0.0	5.2	10.4	11.8	5.3	1.8	0.0	0.2	0.0		0.0
5/20/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
5/21/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
5/22/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
5/23/1999	4.8	0.0	5.8	0.0	0.0	0.0	0.0	0.0	5.0	3.0	7.4		3.2

Date	Oshawa	Mark	Bowman	Button	Stouff	Cherry	Bedford	Kim	Udora	Burke	Janet	Ponty	Tyrone
5/24/1999	26.1	10.3	20.2	12.6	13.0	14.2	13.8	15.2	16.8	15.6	22.8		7.4
5/25/1999	10.0	9.0	11.0	12.2	13.9	7.4	11.8	8.4	13.8	14.8	12.2		7.8
5/26/1999	0.5	0.2	0.2	0.8	0.3	3.6	0.5	0.2	0.0	1.2	1.4		0.4
5/27/1999	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0		0.0
5/28/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
5/29/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
5/30/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
5/31/1999	6.0	0.0	7.2	1.0	0.0	0.0	0.0	0.0	11.6	16.8	10.6		15.0
6/1/1999	19.7	18.4	21.6	23.4	16.5	0.0	18.0	14.4	32.0	22.0	13.6		16.6
6/2/1999	5.0	6.5	11.8	15.4	11.0	0.4	9.3	5.6	39.4	7.2	10.2		4.8
6/3/1999	0.0	0.0	0.0	0.0	0.0	3.4	0.0	0.0	0.0	0.2	0.0		0.0
6/4/1999	0.0	0.0	0.0	0.0	0.0	4.6	0.0	0.0	0.0	0.0	0.0		0.0
6/5/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
6/6/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
6/7/1999	14.8	14.8	7.0	1.0	0.3	0.0	3.5	10.0	3.0	0.4	0.0		0.4
6/8/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
6/9/1999	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0		0.0
6/10/1999	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0		0.0
6/11/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
6/12/1999	0.0	0.0	0.0	0.0	0.0	6.6	0.0	0.0	0.0	0.0	0.0		0.0
6/13/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
6/14/1999	10.2	7.4	7.0	6.4	6.8	8.8	15.0	6.8	8.4	12.8	11.2		6.0
6/15/1999	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
6/16/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
6/17/1999	1.4	0.0	1.8	0.0	0.7	0.0	0.0	0.0	0.0	0.4	0.0		0.0

Date	Oshawa	Mark	Bowman	Button	Stouff	Cherry	Bedford	Kim	Udora	Burke	Janet	Ponty	Tyrone
6/18/1999	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0		0.0
6/19/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
6/20/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
6/21/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
6/22/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
6/23/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
6/24/1999	26.4	1.1	19.0	1.6	3.5	0.0	0.0	0.0	34.2	22.8	19.6		18.8
6/25/1999	0.0	34.0	0.0	22.2	14.7	38.4	35.5	22.4	0.0	0.0	0.0		0.0
6/26/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
6/27/1999	0.0	6.7	0.0	16.0	20.1	4.2	9.0	1.6	16.2	1.6	13.2		0.6
6/28/1999	1.2	0.0	1.4	0.0	0.3	0.8	0.5	0.0	2.0	1.0	1.4		0.8
6/29/1999	0.0	2.0	0.0	3.2	3.0	1.4	2.0	1.0	0.0	0.0	0.4		0.0
6/30/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
7/1/1999	3.2	2.2	1.6	2.2	3.4	0.0	2.3	1.4	2.6	5.4	8.0	3.2	1.6
7/2/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7/3/1999	1.8	0.0	1.6	1.2	0.1	0.0	4.0	3.6	58.2	3.6	46.8	5.1	2.8
7/4/1999	0.0	5.6	0.0	7.8	5.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7/5/1999	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7/6/1999	0.0	0.0	0.4	0.0	0.0	13.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7/7/1999	1.0	0.0	0.0	0.0	0.0	0.2	0.0	0.6	0.0	0.8	4.6	0.0	0.4
7/8/1999	4.0	0.0	4.4	0.0	0.0	0.0	0.0	0.0	9.2	6.0	8.8	10.0	5.8
7/9/1999	12.6	4.0	6.2	6.8	11.1	12.8	2.0	0.4	1.2	2.0	3.6	0.2	2.6
7/10/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.4	0.0	0.0
7/11/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7/12/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Date	Oshawa	Mark	Bowman	Button	Stouff	Cherry	Bedford	Kim	Udora	Burke	Janet	Ponty	Tyrone
7/13/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7/14/1999	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7/15/1999	0.0	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7/16/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7/17/1999	34.0	0.0	29.8	25.2	29.3	17.8	3.8	0.0	0.0	16.0	22.2	70.0	19.6
7/18/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	9.0
7/19/1999	0.0	0.0	0.0	0.6	0.3	0.2	0.3	0.2	0.0	0.0	0.8	0.4	0.4
7/20/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7/21/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7/22/1999	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7/23/1999	0.4	0.0	0.6	0.0	1.0	0.0	0.0	0.0	0.0	0.0	1.8	1.3	1.6
7/24/1999	0.0	0.0	2.0	0.0	0.2	0.0	0.0	0.0	14.0	7.8	2.6	9.6	15.0
7/25/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	1.4	0.0	0.0
7/26/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7/27/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7/28/1999	0.0	0.0	0.0	0.2	0.7	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.4
7/29/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7/30/1999	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7/31/1999	5.7	0.0	5.1	16.4	9.5	6.8	26.0	18.4	19.6	13.2	17.4	8.6	10.8
8/1/1999	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8/2/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8/3/1999	14.0	0.0	14.6	0.4	0.7	0.0	1.3	1.2	9.0	6.6	9.8	4.3	8.6
8/4/1999	14.4	0.0	14.6	34.5	29.4	2.2	27.3	33.4	8.0	14.0	8.4	12.8	14.4
8/5/1999	0.0	0.0	0.0	0.0	0.1	9.4	0.3	0.0	0.0	0.0	0.0	0.0	0.4
8/6/1999	3.2	0.0	2.8	6.4	3.9	0.0	1.5	0.6	3.2	0.0	2.6	1.7	3.0

Date	Oshawa	Mark	Bowman	Button	Stouff	Cherry	Bedford	Kim	Udora	Burke	Janet	Ponty	Tyrone
8/7/1999	10.2	0.0	11.6	5.8	2.8	0.2	3.0	2.8	15.8	14.0	18.0	17.6	15.6
8/8/1999	0.0	0.0	0.0	3.4	4.3	0.0	5.5	3.2	0.0	0.8	0.6	0.0	0.0
8/9/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8/10/1999	8.2	6.6	9.8	7.6	7.1	1.0	5.5	5.4	1.6	5.4	1.6	3.2	6.2
8/11/1999	0.0	0.0	0.2	0.0	0.1	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0
8/12/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	1.0	0.4	0.0	0.0
8/13/1999	2.2	2.5	1.8	3.0	2.9	0.6	2.5	1.4	2.0	2.0	1.2	1.6	1.4
8/14/1999	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8/15/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8/16/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.8	0.0	0.0
8/17/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8/18/1999	0.0	0.0	0.0	0.0	0.0	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8/19/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0
8/20/1999	8.2	9.8	12.6	8.0	10.7	3.8	31.8	16.2	13.2	12.0	13.8	19.2	13.4
8/21/1999	0.2	0.0	0.0	0.0	0.5	0.6	0.0	0.0	8.2	1.6	0.0	0.0	1.0
8/22/1999	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8/23/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8/24/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0
8/25/1999	0.0	0.3	0.6	0.6	0.2	0.0	0.8	0.2	0.0	1.4	4.0	1.4	1.0
8/26/1999	0.0	0.0	0.0	0.0	0.2	0.2	2.3	2.4	0.0	0.0	0.4	0.0	0.0
8/27/1999	0.2	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	2.0
8/28/1999	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0
8/29/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8/30/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8/31/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Date	Oshawa	Mark	Bowman	Button	Stouff	Cherry	Bedford	Kim	Udora	Burke	Janet	Ponty	Tyrone
9/1/1999	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9/2/1999	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9/3/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9/4/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9/5/1999	2.0	0.0	8.0	0.0	0.0	2.6	0.0	0.0	2.6	4.8	14.2	18.8	7.2
9/6/1999	26.6	18.9	31.0	3.4	30.2	0.0	24.3	32.4	34.8	17.0	39.2	14.2	23.8
9/7/1999	41.2	8.2	21.6	0.2	1.0	6.0	2.3	2.6	13.6	17.4	10.6	4.4	7.0
9/8/1999	3.8	5.7	4.1	1.6	13.4	0.0	0.8	4.8	13.0	8.4	3.8	1.0	5.8
9/9/1999	9.0	6.6	6.6	5.0	3.3	7.0	8.3	9.8	0.0	5.2	3.8	7.8	7.6
9/10/1999	0.0	0.0	0.0	0.0	0.0	3.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9/11/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9/12/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9/13/1999	9.2	11.0	11.2	8.6	6.1	6.4	13.8	7.2	17.4	16.0	14.0	19.6	13.6
9/14/1999	0.0	1.3	0.0	0.0	0.1	0.4	0.8	0.0	0.4	0.0	0.0	0.0	0.0
9/15/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0
9/16/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9/17/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9/18/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9/19/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9/20/1999	2.4	2.5	2.8	3.0	2.5	0.2	0.0	1.6	3.4	5.4	4.4	5.2	3.8
9/21/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9/22/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9/23/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.2	1.6	2.4	0.2	0.6
9/24/1999	2.6	53.8	3.0	3.6	2.4	1.6	0.0	2.2	0.6	0.0	2.0	1.8	0.4
9/25/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

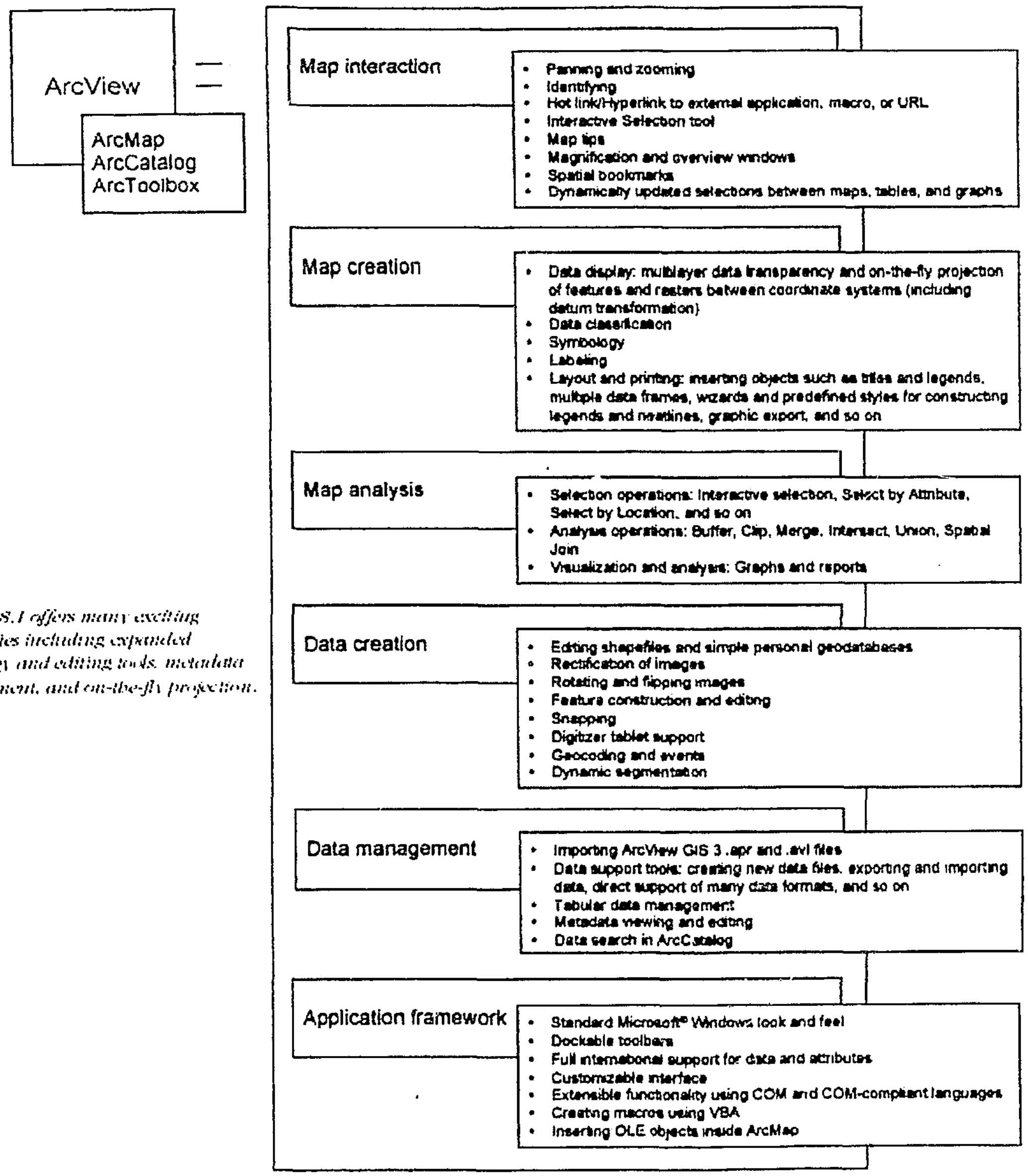
Date	Oshawa	Mark	Bowman	Button	Stouff	Cherry	Bedford	Kim	Udora	Burke	Janet	Ponty	Tyrone
9/26/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9/27/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9/28/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9/29/1999	50.0	0.0	53.6	55.8	53.2	15.6	0.0	45.8	42.6	44.0	41.2	46.6	47.2
9/30/1999	0.2	4.7	1.3	2.2	4.8	4.6	0.0	3.6	0.0	0.2	1.4	0.2	0.4
10/1/1999	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.4	0.3	0.0
10/2/1999	3.0	9.8	2.4	10.0	9.6	0.0	0.0	2.6	12.0	8.2	7.8	6.7	7.2
10/3/1999	9.8	0.6	7.0	1.2	2.2	0.0	0.0	1.0	9.0	11.4	9.2	6.0	7.6
10/4/1999	0.0	10.7	0.0	9.5	8.8	0.0	0.0	6.8	3.0	1.4	1.4	1.8	0.0
10/5/1999	0.6	0.0	0.8	0.0	0.2	0.0	0.0	0.2	0.0	0.0	1.6	2.2	0.8
10/6/1999	0.0	0.3	0.0	0.4	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0
10/7/1999	0.0	0.0	0.0	0.0	0.0	3.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10/8/1999	6.2	6.6	8.6	6.0	3.9	4.8	7.8	5.0	3.2	9.6	5.6	9.6	7.0
10/9/1999	0.3	0.0	0.0	0.0	0.2	0.0	0.3	0.0	0.0	0.4	0.0	0.5	0.4
10/10/1999	0.4	0.0	0.0	0.0	0.0	0.0	0.3	0.4	1.4	0.6	6.2	1.0	1.0
10/11/1999	0.0	0.0	0.0	0.0	0.0	7.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10/12/1999	0.4	0.0	0.4	0.2	0.5	3.6	0.0	0.0	2.6	2.4	3.8	2.4	1.8
10/13/1999	45.6	50.7	42.2	42.2	47.0	0.2	41.5	32.2	32.6	49.0	44.8	41.2	0.0
10/14/1999	0.0	2.2	0.0	0.0	0.9	0.0	0.5	2.4	0.0	0.0	0.0	0.0	0.0
10/15/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0	0.0	0.0
10/16/1999	0.4	0.0	1.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0
10/17/1999	2.2	0.0	4.1	0.2	0.0	0.0	0.3	0.2	0.0	2.4	1.6	0.0	0.0
10/18/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10/19/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.8	0.0
10/20/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	0.0	0.0

Date	Oshawa	Mark	Bowman	Button	Stouff	Cherry	Bedford	Kim	Udora	Burke	Janet	Ponty	Tyrone
10/21/1999	1.4	0.0	1.0	0.0	0.0	0.0	0.0	0.0	2.2	3.4	1.8	0.0	0.0
10/22/1999	7.0	7.2	6.5	6.5	9.1	4.2	9.0	2.6	5.0	7.6	3.4	0.0	0.0
10/23/1999	0.0	0.0	0.0	0.0	0.1	0.0	0.3	0.0	2.0	6.4	2.8	14.4	0.0
10/24/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.0	1.0	0.0
10/25/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10/26/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0
10/27/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10/28/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0
10/29/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10/30/1999	2.4	0.0	2.2	0.0	0.0	0.0	0.0	0.0	3.0	1.6	4.2	2.0	0.0
10/31/1999	0.0	1.3	0.0	0.8	0.3	1.0	0.3	0.6	0.0	0.0	0.0	0.0	0.0
11/1/1999	1.0	0.0	0.2	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.6	0.0	
11/2/1999	43.2	59.9	50.8	42.4	68.0	0.0	64.3	33.4	71.0	50.4	57.0	50.4	
11/3/1999	2.4	2.5	1.4	4.4	4.4	0.0	8.3	2.4	0.0	0.0	0.0	0.0	
11/4/1999	0.0	0.0	0.0	0.6	3.9	0.2	0.0	0.0	0.0	0.0	0.0	0.0	
11/5/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
11/6/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
11/7/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
11/8/1999	0.0	0.0	0.0	0.0	0.0	2.6	0.0	0.0	0.0	0.0	0.0	0.0	
11/9/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	
11/10/1999	8.6	8.2	14.2	8.0	4.5	0.0	8.3	3.8	9.2	13.6	11.2	12.0	
11/11/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
11/12/1999	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	1.0	0.0	1.8	1.0	
11/13/1999	0.0	0.0	0.0	0.0	0.1	0.0	0.3	0.0	0.0	0.0	0.6	0.0	
11/14/1999	0.0	0.6	2.2	1.0	0.0	0.2	0.5	0.0	0.0	1.4	0.0	0.8	

Date	Oshawa	Mark	Bowman	Button	Stouff	Cherry	Bedford	Kim	Udora	Burke	Janet	Ponty	Tyrone
11/15/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
11/16/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
11/17/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
11/18/1999	0.0	0.0	0.0	0.0	0.0	0.0	3.8	0.0	0.0	0.0	0.0	0.0	
11/19/1999	8.8	0.0	12.6	0.0	0.0	0.0	1.0	0.0	5.0	10.2	7.2	9.0	
11/20/1999	2.9	8.8	1.6	7.7	7.3	6.4	9.0	5.0	1.0	2.0	2.6	4.3	
11/21/1999	1.5	0.0	0.6	0.0	0.1	0.0	0.0	0.0	0.2	1.6	1.4	5.0	
11/22/1999	0.0	0.3	0.0	0.2	0.9	0.4	0.0	0.2	0.0	0.0	0.6	6.0	
11/23/1999	1.6	0.0	2.0	0.0	0.0	0.0	0.0	0.0	2.0	2.2	2.0	2.8	
11/24/1999	0.0	1.9	0.0	1.6	1.7	1.0	0.5	0.4	0.0	0.0	0.4	0.0	
11/25/1999	4.2	0.0	4.6	0.0	0.0	0.0	0.0	0.0	10.8	5.8	6.2	4.4	
11/26/1999	11.2	17.6	12.8	15.0	9.5	12.2	10.8	13.8	1.2	12.8	11.6	11.8	
11/27/1999	0.0	0.0	0.0	0.0	0.1	1.2	0.0	0.0	0.0	0.0	2.4	0.0	
11/28/1999	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	0.0	
11/29/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
11/30/1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	

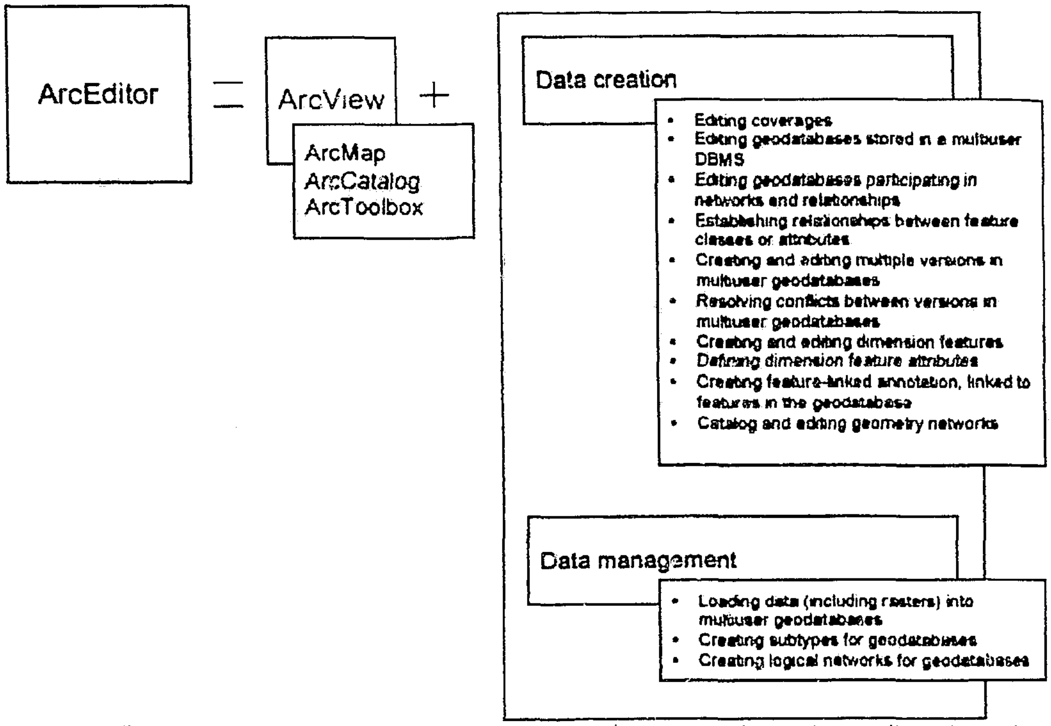
Appendix C

Appendix C-1. Functionality of the ArcView block (ESRI, 2001).



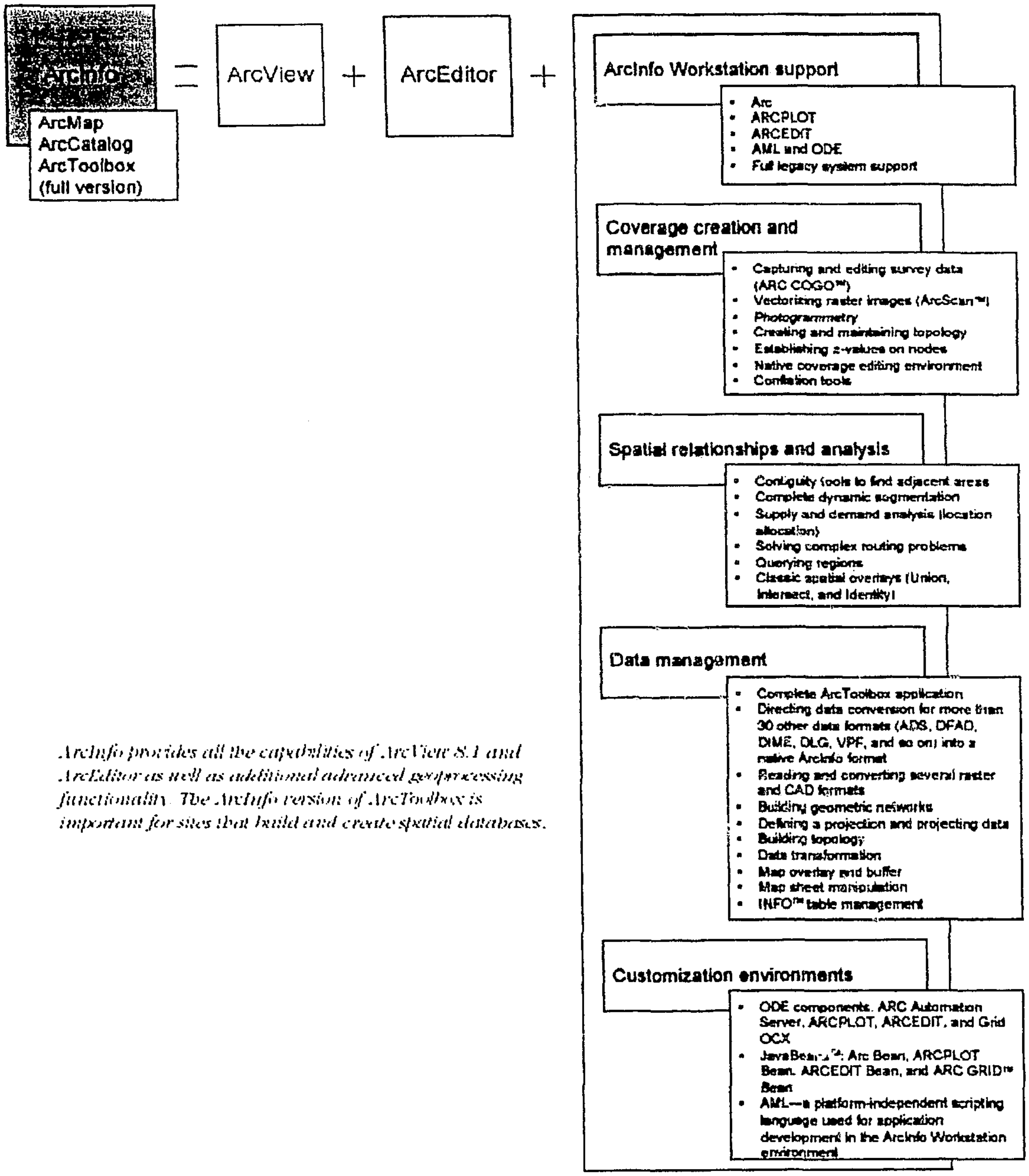
ArcView 8.1 offers many exciting capabilities including expanded symbology and editing tools, metadata management, and on-the-fly projection.

Appendix C-2. Functionality of the ArcEditor block (ESRI, 2001).



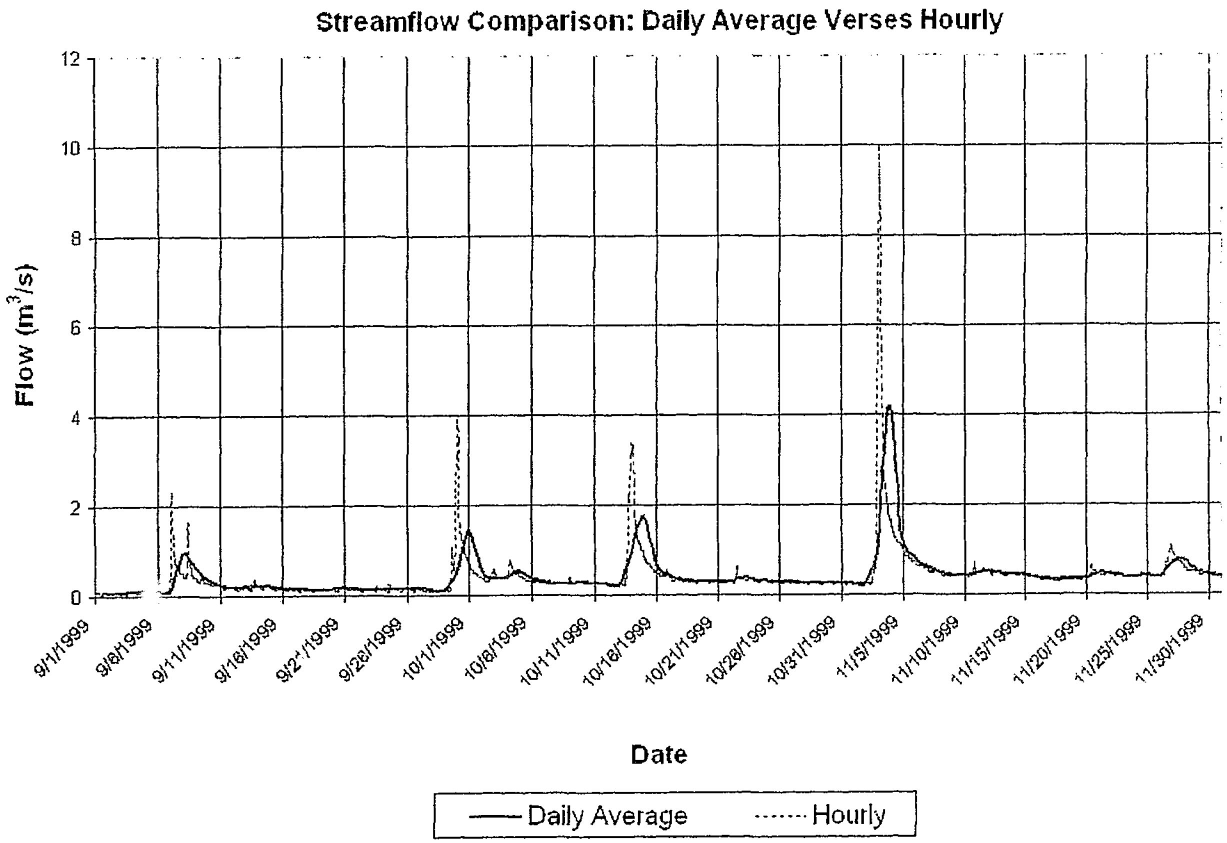
ArcEditor offers the same three applications as ArcView 8.1—ArcMap, ArcCatalog, and ArcToolbox—but with advanced editing capabilities.

Appendix C-3. The functionality of the ArcInfo block (ESRI, 2001).



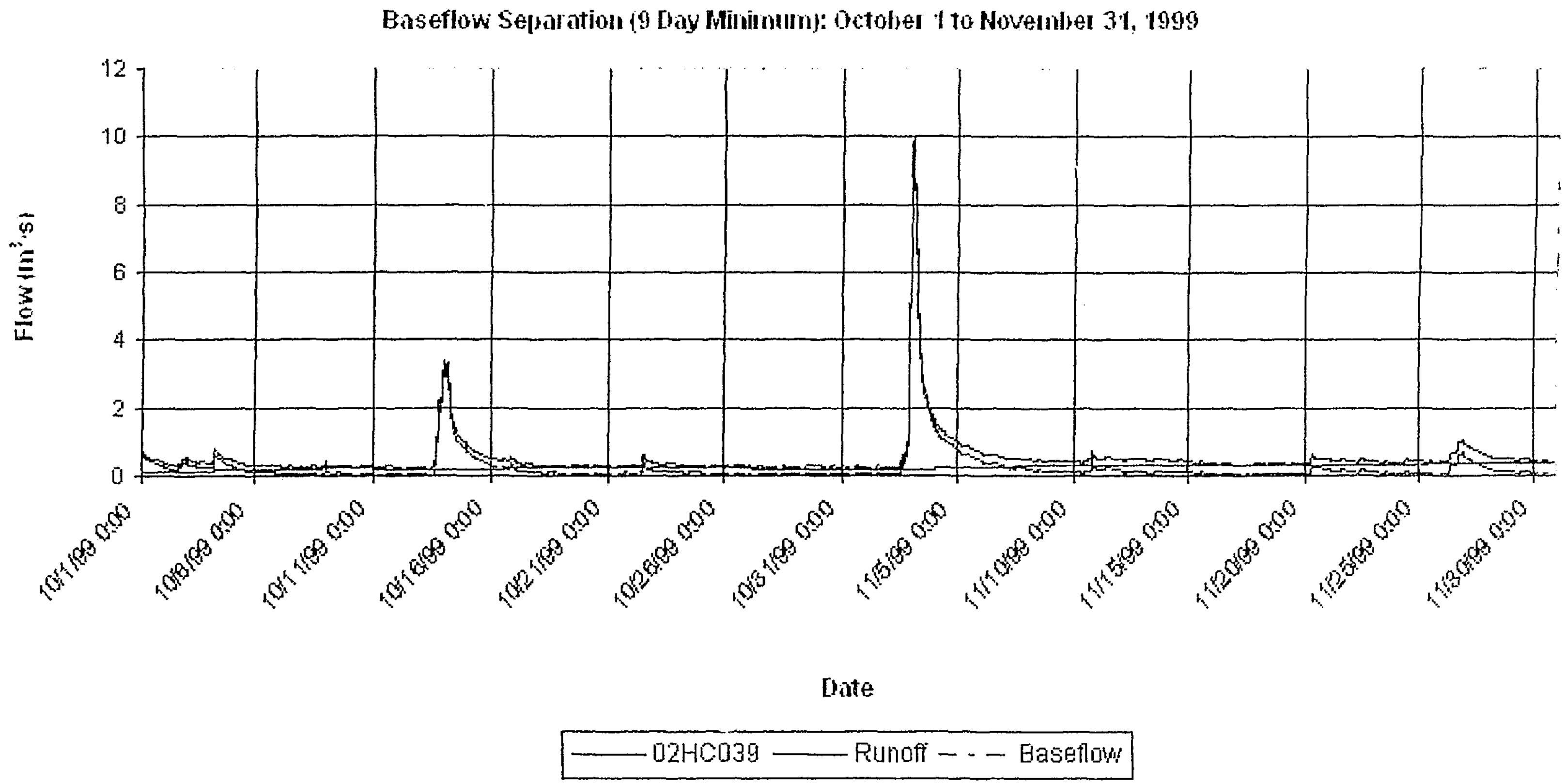
Appendix D

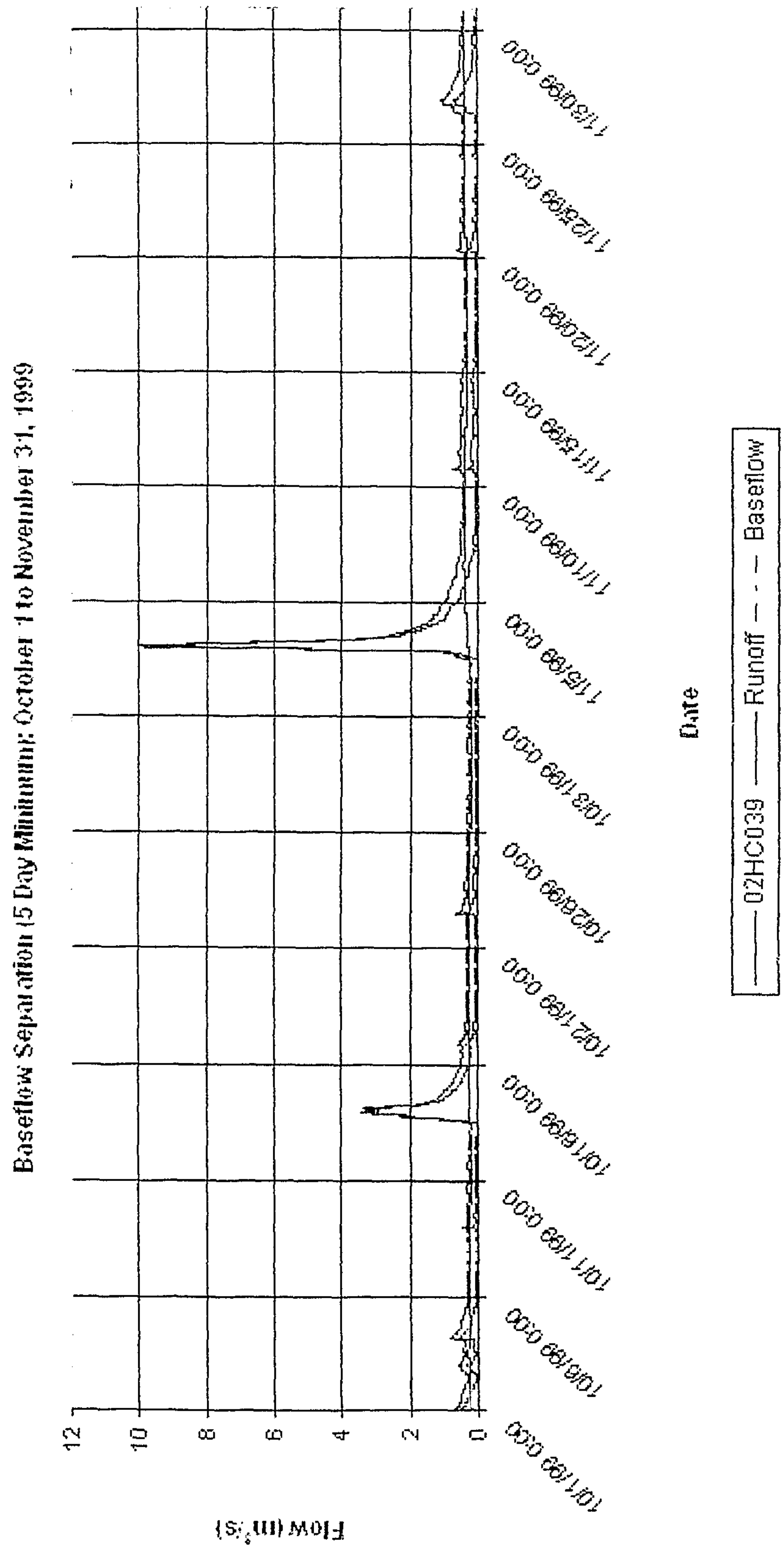
Appendix D. Comparison of daily average stream flow verses hourly stream flow. There is a -0.16 percent error with the daily averages measuring less flow.



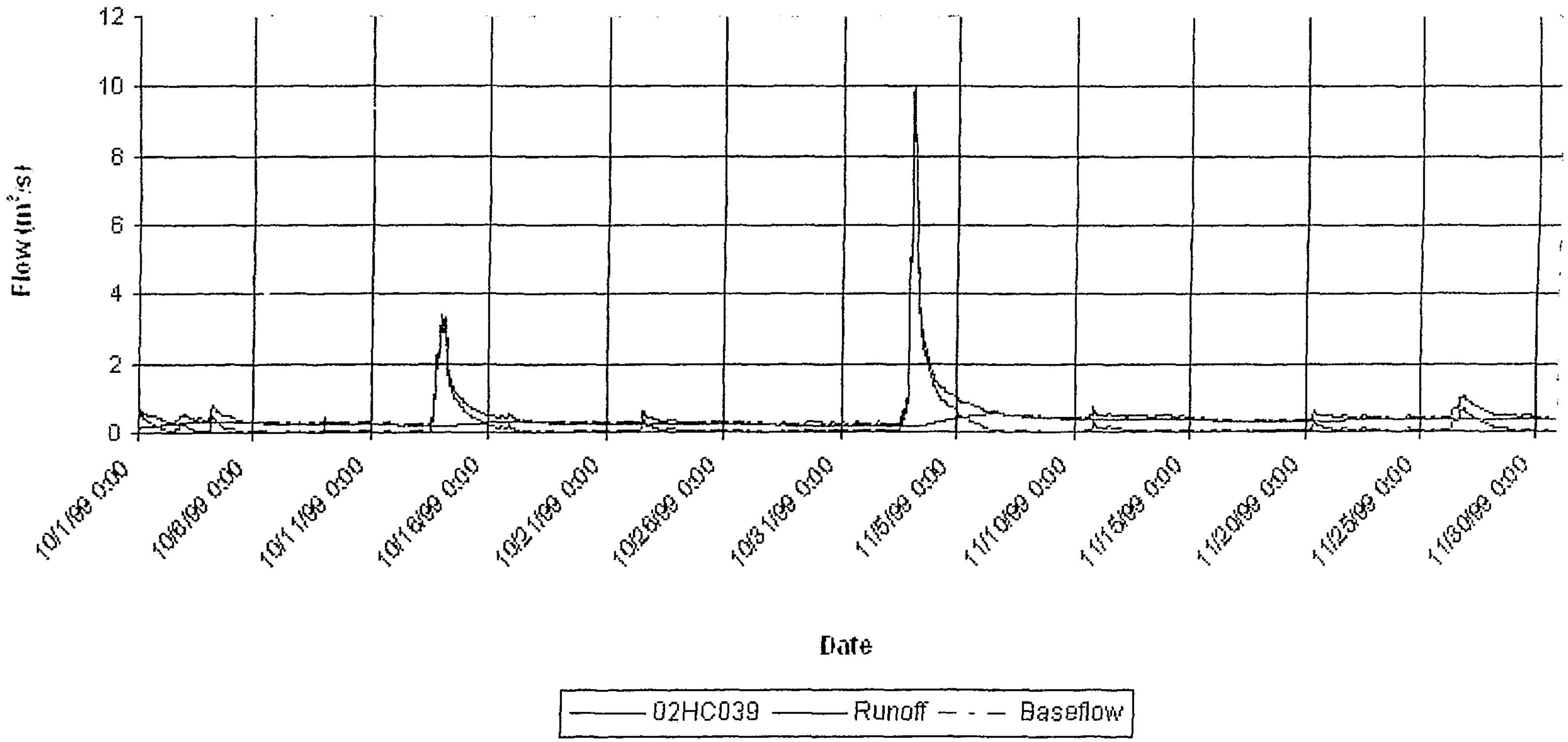
Appendix E

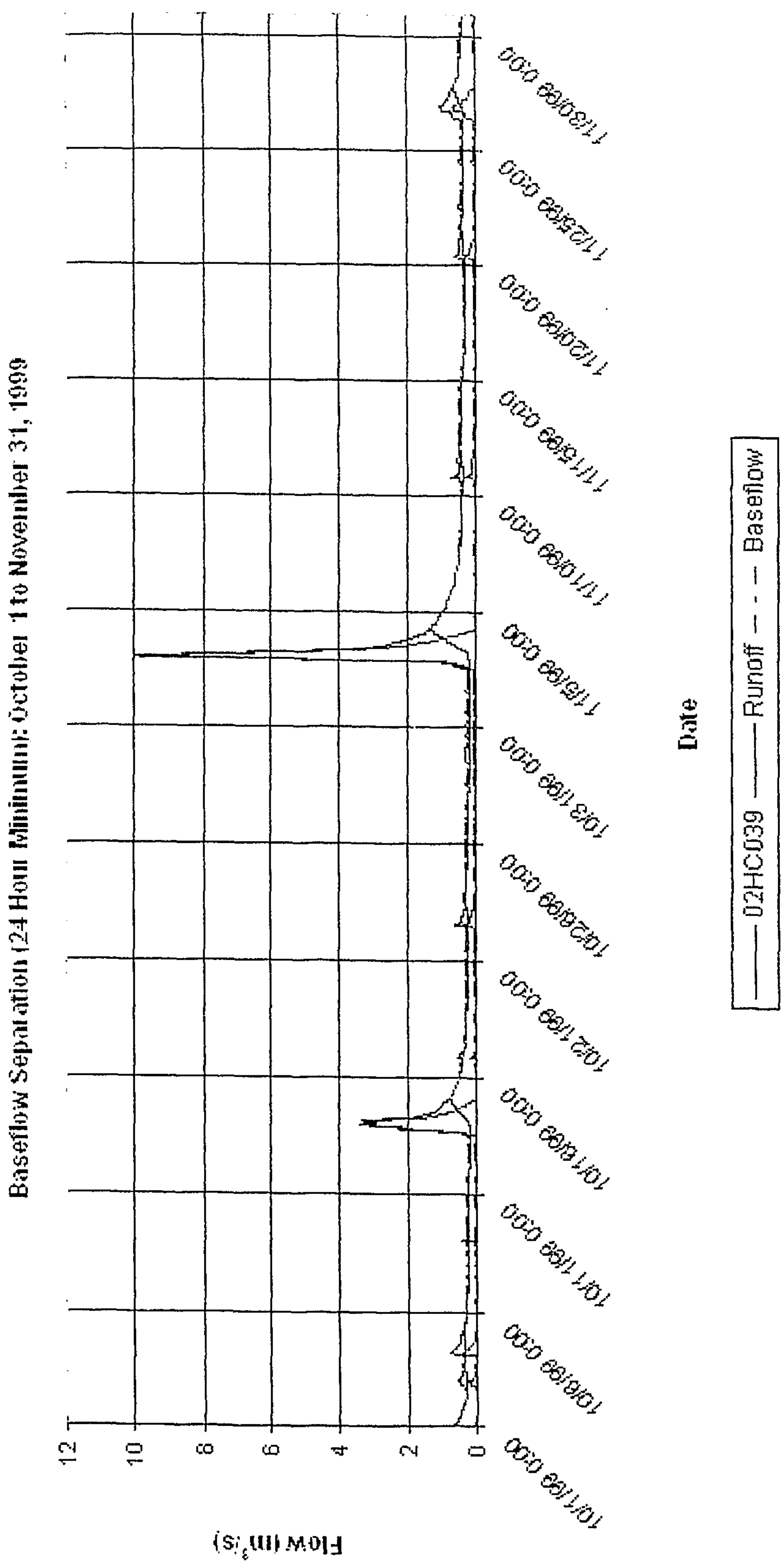
Appendix E. Baseflow separation results. Several variations of this formula was considered where the minimum was exaggerated over 9, 5, and 3 days, as well as 24 and 12 hours.



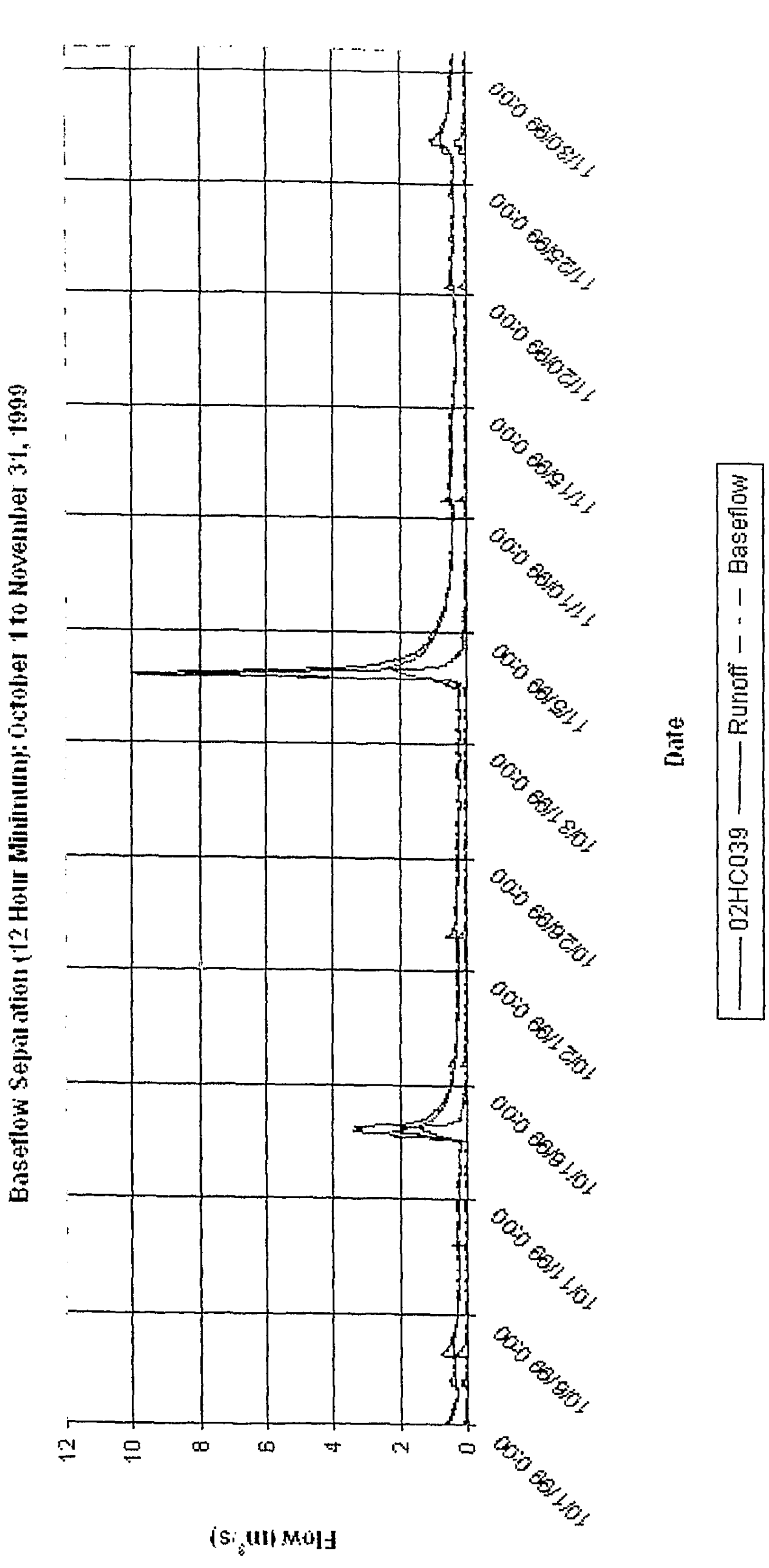

Baseflow Separation (5 Day Minimum): October 1 to November 31, 1999
Flow (m³/s)
12
10
8
6
4
2
0
10/1/99 0:00
10/6/99 0:00
10/11/99 0:00
10/16/99 0:00
10/21/99 0:00
10/26/99 0:00
10/31/99 0:00
11/5/99 0:00
11/10/99 0:00
11/15/99 0:00
11/20/99 0:00
11/25/99 0:00
11/30/99 0:00
Date
02HC039 —— Runoff - - - Baseflow

Baseflow Separation (3 Day Minimum): October 1 to November 31, 1999





Baseflow Separation (24 Hour Minimum: October 1 to November 31, 1999
Flow (m^3/s)
12
10
8
6
4
2
0
10/1/99 0:00
10/6/99 0:00
10/11/99 0:00
10/16/99 0:00
10/21/99 0:00
10/26/99 0:00
10/31/99 0:00
11/5/99 0:00
11/10/99 0:00
11/15/99 0:00
11/20/99 0:00
11/25/99 0:00
11/30/99 0:00
Date
02HC039 —— Runoff - - - Baseflow


Baseflow Separation (12 Hour Minimum): October 1 to November 31, 1999
Flow (m³/s)
12
10
8
6
4
2
0
10/1/99 0:00
10/6/99 0:00
10/11/99 0:00
10/16/99 0:00
10/21/99 0:00
10/26/99 0:00
10/31/99 0:00
11/5/99 0:00
11/10/99 0:00
11/15/99 0:00
11/20/99 0:00
11/25/99 0:00
11/30/99 0:00
Date
02HC039 —— Runoff — - — Baseflow

Appendix F

Appendix F. Visual basic script used to calculate the centroids from the grid layer and select rainfall values from the kirged rainfall layer (ESRI, 2003; Ryerson University, 2003).

```
Option Explicit

'*****************************************************************
'This script output the centroids of the first feature class feature (in position 0 in
TOC)
'into the second feature class (in position 1 in TOC).
'The output feature class must be a ShapeFile. The first layer must be of type
'polygon and the second of type point
'Note : The Centroid is not always inside of the polygon.
'Uses the label point if you need a point always inside the polygon.
'*****************************************************************


Sub ExtractValueTOPointFeatureClass(pInRaster As IRaster, pInFeatureClass As
IFeatureClass, sFieldName As String)
   ' pInRaster: input raster
   ' pInFeatureClass: input point feature class
   ' sFieldName: name of the field that stores the values

   On Error GoTo ERH

   ' Define field name
   Dim pFld As IFieldEdit
   Set pFld = New Field
   pFld.Name = sFieldName

   ' Define field type
   Dim pProp As IRasterProps
   Set pProp = pInRaster
   If pProp.PixelType = PT_CHAR Or pProp.PixelType = PT_UCHAR Then
      pFld.Type = esriFieldTypeString
      pFld.Length = 20
      pFld.Required = 0
   ElseIf pProp.PixelType = PT_FLOAT Or pProp.PixelType = PT_DOUBLE Or
 pProp.PixelType Then
      pFld.Type = esriFieldTypeDouble
      pFld.Length = 24
      pFld.Required = 8
   Else  ' for integer case
      pFld.Type = esriFieldTypeInteger
      pFld.Length = 24
      pFld.Required = 0
   End If
```

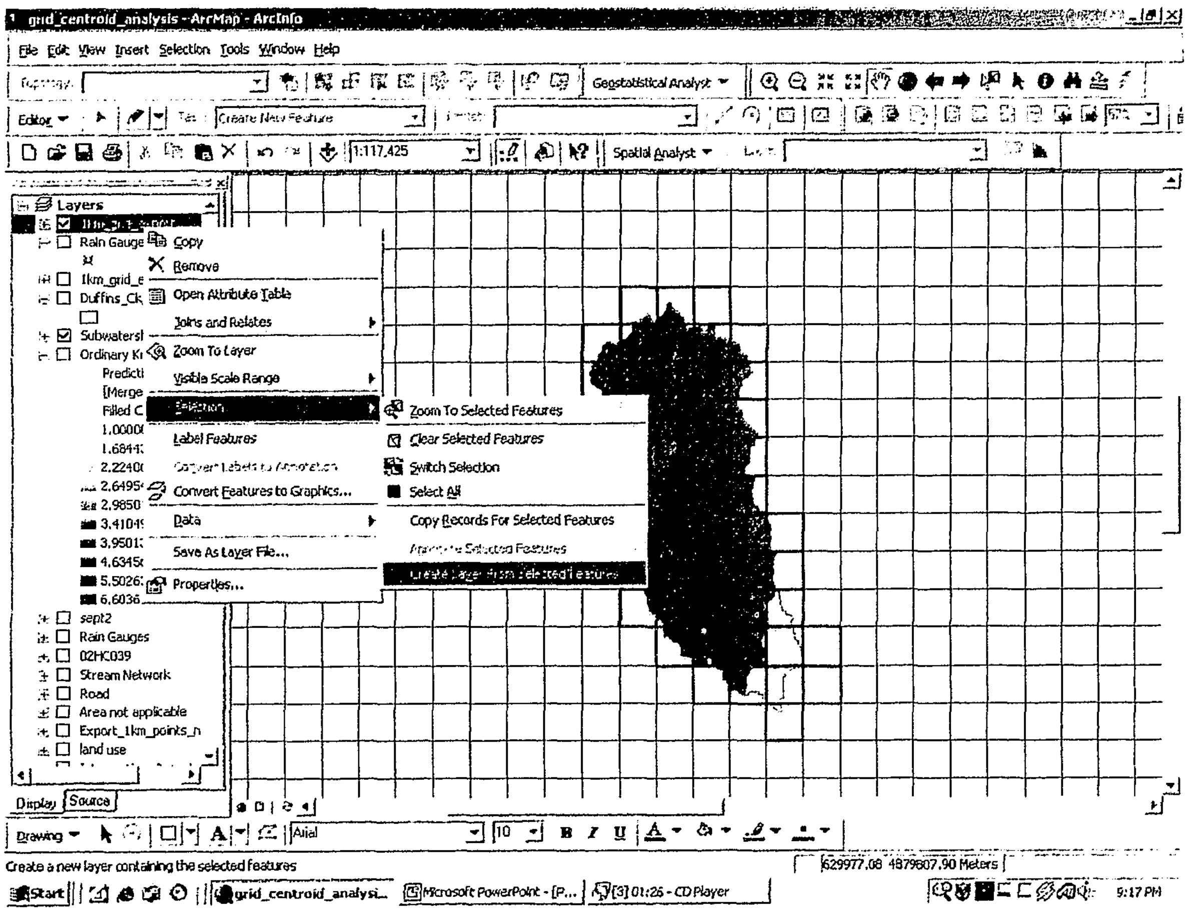
```
' Add field
pInFeatureClass.AddField pFld

' Get field index
Dim FieldIndex As Integer
FieldIndex = pInFeatureClass.FindField(sFieldName)
If FieldIndex < 0 Then Exit Sub

' Create a raster layer and QI for IIdentify interface
Dim pRLayer As IRasterLayer
Set pRLayer = New RasterLayer
pRLayer.CreateFromRaster pInRaster
Dim pIdentify As IIdentify
Set pIdentify = pRLayer

Dim pIDArray As IArray
Dim pRIDObj As IRasterIdentifyObj
Dim I As Long
Dim pPoint As IPoint
Dim pFeature As IFeature
Dim pNewPoint As IPoint
Set pNewPoint = New Point

'Loop through each point in the feature class and obtain value of the
'raster on that point
Dim NumOfRow As Integer
NumOfRow = pInFeatureClass.FeatureCount(Nothing)
For I = 0 To NumOfRow - 1
    'Get point
    Set pFeature = pInFeatureClass.GetFeature(I)
    Set pPoint = pFeature.Shape
    pNewPoint.X = pPoint.X
    pNewPoint.Y = pPoint.Y
    'Get RasterIdentifyObject on that point
    Set pIDArray = pIdentify.Identify(pNewPoint)
    If Not pIDArray Is Nothing Then
        Set pRIDObj = pIDArray.Element(0)
        'Get the value of the RasterIdentifyObject and add it to the field
        If pProp.PixelType = PT_CHAR Or pProp.PixelType = PT_UCHAR Then
        pFeature.Value(FieldIndex) = pRIDObj.Name
        ElseIf pProp.PixelType = PT_FLOAT Or pProp.PixelType = PT_DOUBLE Or
pProp.PixelType Then
            If pRIDObj.Name <> "NoData" Then
            pFeature.Value(FieldIndex) = CDbl(pRIDObj.Name)
            End If
        Else    ' for integer case
            If pRIDObj.Name <> "NoData" Then
            pFeature.Value(FieldIndex) = CLng(pRIDObj.Name)
```

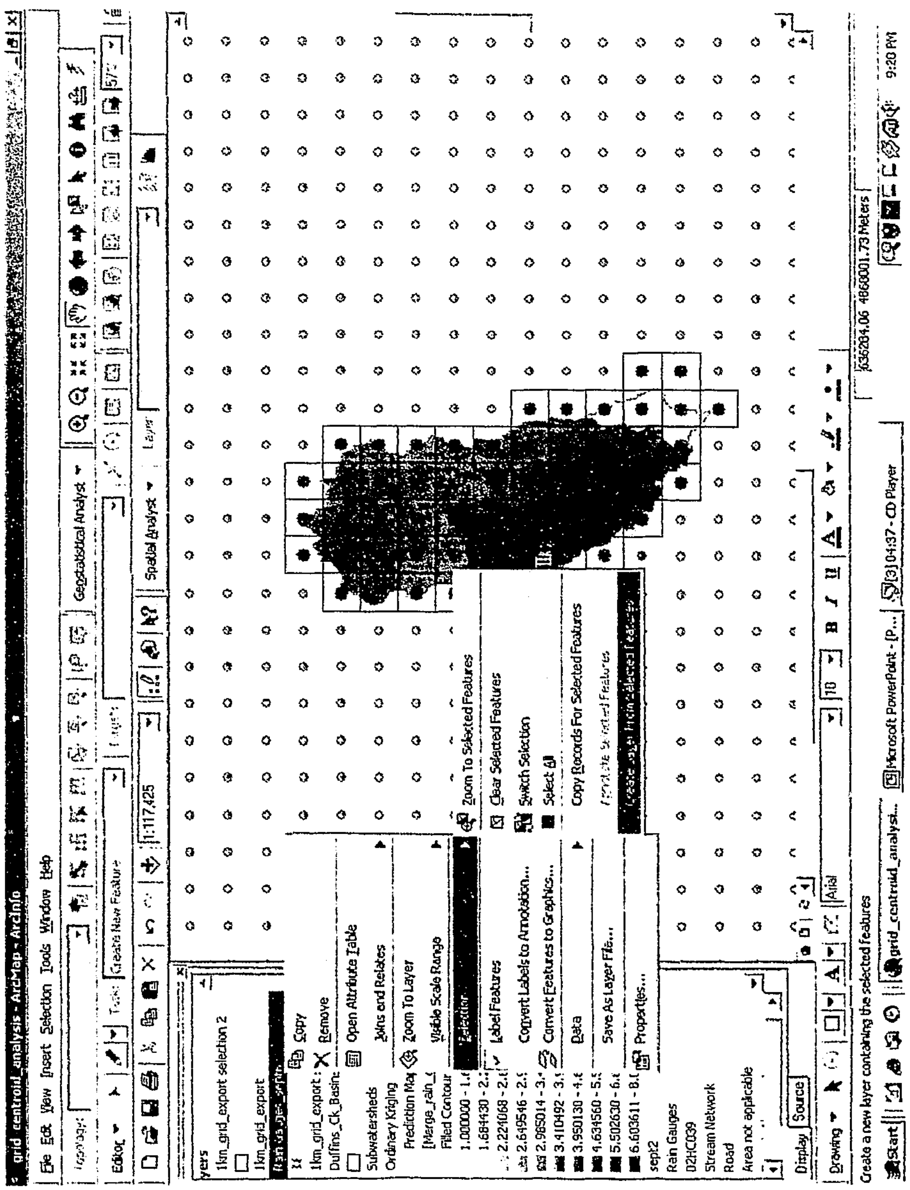
```
        End If
      End If
      pFeature.Store
    End If
  Next I
  Exit Sub
ERH:
  MsgBox Err.Description
End Sub



Public Sub RasterJoin()
Dim pMxDoc As IMxDocument
Set pMxDoc = ThisDocument

Dim pMap As IMap
Set pMap = pMxDoc.FocusMap

Dim pFeatureLayer As IFeatureLayer
Set pFeatureLayer = pMap.Layer(0)

Dim pFeatureClass As IFeatureClass
Set pFeatureClass = pFeatureLayer.FeatureClass

'Dim pFeatureEnum As IEnumFeature
'Set pFeatureEnum = pFeatureClass.Search(Nothing, False)

Dim pRasterLayer As IRasterLayer
Set pRasterLayer = pMap.Layer(1)

Dim pRaster As IRaster
Set pRaster = pRasterLayer.Raster

Call ExtractValueTOPointFeatureClass(pRaster, pFeatureClass, "RainFall")



End Sub



Public Sub GetPolygonCentroid()
  Dim pMxDoc As IMxDocument
  Set pMxDoc = ThisDocument
  'Get the polygon feature
  Dim pFLayerPoly As IFeatureLayer
  Set pFLayerPoly = pMxDoc.FocusMap.Layer(0)
```

```
Dim pFClassPoly As IFeatureClass
Set pFClassPoly = pFLayerPoly.FeatureClass
Dim pDatasetPoly As IDataset
Set pDatasetPoly = pFClassPoly
Dim pWorkSpacePoly As IWorkspace
Set pWorkSpacePoly = pDatasetPoly.Workspace
Dim pFCursorPoly As IFeatureCursor
Set pFCursorPoly = pFClassPoly.Search(Nothing, True)
Dim pFeaturePoly As IFeature
Set pFeaturePoly = pFCursorPoly.NextFeature
'Verify if the first layer is of type polygon
If Not pFClassPoly.ShapeType = esriGeometryPolygon Then
MsgBox "Your first (in Position 0 in TOC)layer must be of type Polygon !"
Exit Sub
End If
Dim pCentroidTemp As IPoint
Dim pArea As IArea
Dim pFLayerOut As IFeatureLayer
Set pFLayerOut = pMxDoc.FocusMap.Layer(1)
Dim pFClassOut As IFeatureClass
Set pFClassOut = pFLayerOut.FeatureClass
Dim pFeatureOut As IFeature
'Verify if the second layer is of type point
If Not pFClassOut.ShapeType = esriGeometryPoint Then
MsgBox "Your second (in Position 1 in TOC)layer must be of type Point !"
Exit Sub
End If
'Create an instance of point that will be reused for each polygon
Set pCentroidTemp = New Point
'Loop over the polygon
While Not pFeaturePoly Is Nothing
  Set pArea = pFeaturePoly.Shape
  'Get a copy of the centroid point
  'pArea.QueryCentroid pCentroidTemp
  pCentroidTemp.PutCoords pArea.LabelPoint.X, pArea.LabelPoint.Y

  Set pFeatureOut = pFClassOut.CreateFeature
  'Store the centroid
  Set pFeatureOut.Shape = pCentroidTemp
  pFeatureOut.Store
  Set pFeaturePoly = pFCursorPoly.NextFeature
 Wend
End Sub
```

Appendix G

Appendix G. The development of the virtual rain gauge layer. The centroids should be selected only when the grid is completed.




grid_centroid_analysis - ArcMap - ArcInfo
File Edit View Insert Selection Tools Window Help
Geostatistical Analyst
Spatial Analyst
Editor
Create New Feature
1:117,425
Copy
Remove
Open Attribute Table
Joins and Relates
Zoom To Layer
Visible Scale Range
Selection
Label Features
Convert Labels to Annotation...
Convert Features to Graphics...
Data
Save As Layer File...
Properties...
Zoom To Selected Features
Clear Selected Features
Switch Selection
Select All
Copy Records For Selected Features
Create Layer From Selected Features
1km_grid_export selection 2
1km_grid_export
Duffins_Ck_Basin
Subwatersheds
Ordinary Kriging
Prediction Map
Filled Contour
Rain Gauges
02HC039
Stream Network
Road
Area not applicable
Display
Source
Drawing
Arial
Create a new layer containing the selected features
636204.06 4868001.73 Meters
Start
grid_centroid_analysi...
Microsoft PowerPoint - [P...
[3] 04:37 - CD Player
9:20 PM

Appendix H

Appendix H. Attribute table for raingauge layer of virtual rainfall generated from kriged layer and *raster_join* macro.

Attributes of Export_sept2

FID	Shape*	Id	RainFall
0	Point	0	0.0776
1	Point	1	0.0777
2	Point	2	0.077
3	Point	3	0.0802
4	Point	4	0.0811
5	Point	5	0.0812
6	Point	6	0.0805
7	Point	7	0.0789
8	Point	8	0.0834
9	Point	9	0.0846
10	Point	10	0.0847
11	Point	11	0.0838
12	Point	12	0.0819
13	Point	13	0.0864
14	Point	14	0.0879
15	Point	15	0.0881
16	Point	16	0.0869
17	Point	17	0.0845
18	Point	18	0.0892
19	Point	19	0.0912
20	Point	20	0.0913
21	Point	21	0.0897

Record: 1 Show: All Selected Records (0 c

Appendix I

Appendix I-1. PCSWMM input file for the lumped model from May 1 to November 31, 1999 for the Reesor Creek watershed.

$RUNOFF														
*	Title	Lines												
A1	'Reesor	Creek	1999	LUMPED'										
A2	'no	quality	simulated'											
*	Run	Control												
*	METRIC	ISNOW	NRGAG	INFILM	KWALTY	IVAP	NHR	NMN	NDAY	MONTH	IYRSTR	IVCHAN		
B1	1	0	13	0	0	0	23	45	1	5	1999	0		
*	IPRN1	IPRN2	IPRN3	IRPNGW										
B2	0	1	0	0	0	1								
*	WET	WETDRY	DRY	LUNIT	LONG									
B3	3600	7200	86400	3	214									
*	PCTZER	REGEN												
B4	25	0.1												
*	Precipitation	Data												
*	ROPT													
D1	0													
*	KTYPE	KINC	KPRINT	KTHIS	KTIME	KPREP	NHISTO	THISTO	TZRAIN					
E1	2	1	0	0	1	1	214	24	0					
*														
*	TIME	Oshawa	Mark	Bowman	Button	Stouff	Cherry	Bed	Kim	Udora	Burke	Janet	Ponty	Tyrone
E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E3	24	0	0	0	0	0	0	0	0	0	0	0	0	0
E3	48	0	0	0	0	0	0	0	0	0	0	0	0	0

E3	72	0	0	0	0	0	0	0	0	0	0	0	0	0		
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.		
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.	.	.	.	.	.	.	.	.	.	.	.	.	.	.		
E3	5088	0	0	0	0	0	0	0	0	0	0	0	0	0		
E3	5112	0	0	0	0	0	0	0	0	0	0	0	0	0		
*	Subcatchments															
*	JK	NAMEW	NGTO	WW(1)	WAREA	WW(3)	WSLOPE	WW(5)	WW(6)	WSTORE1	WSTORE2	WLMAX	WLMIN	DECAY	RMAXINF	
H1	1	1	100	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0	
H1	2	2	200	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0	
H1	3	3	300	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0	
H1	4	4	400	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0	
H1	5	5	500	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0	
H1	6	6	600	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0	
H1	7	7	700	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0	
H1	8	8	800	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0	
H1	9	9	900	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0	
H1	10	10	1000	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0	
H1	11	11	1100	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0	
H1	12	12	1200	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0	
H1	13	13	1300	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0	
*	Print	Control														
*	NPRNT	INTERV														
M1	1	0														
*	NDET	STARTP1	STOPPR1													

```
M2      1       0       0
*       IPRNT
M3      100     200     300     400     500     600     700     800     900     1000    1100    1200    1300
*
$ENDPROGRAM
```

Appendix I-2. PCSWMM input file for the lumped model from May 1 to August 31, 1999 (summer) of the Reesor Creek watershed.

$RUNOFF														
*	Title	Lines												
A1	'Reesor	Creek	1999	LUMPED summer'										
A2	'no	quality	simulated'											
*	Run	Control												
*	METRIC	ISNOW	NRGAG	INFILM	KWALTY	IVAP	NHR	NMN	NDAY	MONTH	IYRSTR	IVCHAN		
B1	1	0	13	0	0	0	23	45	1	5	1999	0		
*	IPRN1	IPRN2	IPRN3	IRPNGW										
B2	0	1	0	0	0	1								
*	WET	WETDRY	DRY	LUNIT	LONG									
B3	3600	7200	86400	3	123									
*	PCTZER	REGEN												
B4	25	0.01												
*	Precipitation	Data												
*	ROPT													
D1	0													
*	KTYPE	KINC	KPRINT	KTHIS	KTIME	KPREP	NHISTO	THISTO	TZRAIN					
E1	2	1	0	0	1	1	123	24	0					
*														
*	TIME	Oshawa	Mark	Bowman	Button	Stouff	Cherry	Bed	Kim	Udora	Burke	Janet	Ponty	Tyrone
E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E3	24	0	0	0	0	0	0	0	0	0	0	0	0	0

E3	48	0	0	0	0	0	0	0	0	0	0	0	0	0		
E3	72	0	0	0	0	0	0	0	0	0	0	0	0	0		
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.		
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.		
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.		
E3	2904	0	0	0	0	0	0	0	0	0	0	0	0	0		
E3	2928	0	0	0	0	0	0	0	0	0	0	0	0	0		
*	Subcatchments															
*	JK	NAMEW	NGTO	WW(1)	WAREA	WW(3)	WSLOPE	WW(5)	WW(6)	WSTORE1	WSTORE2	WLMAX	WLMIN	DECAY		RMAXINF
H1	1	1	100	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115		0
H1	2	2	200	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115		0
H1	3	3	300	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115		0
H1	4	4	400	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115		0
H1	5	5	500	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115		0
H1	6	6	600	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115		0
H1	7	7	700	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115		0
H1	8	8	800	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115		0
H1	9	9	900	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115		0
H1	10	10	1000	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115		0
H1	11	11	1100	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115		0
H1	12	12	1200	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115		0
H1	13	13	1300	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115		0
*	Print	Control														
*	NPRNT	INTERV														
M1	1	0														

```
*       NDET     STARTP1  STOPPR1
M2      1        0        0
*       IPRNT
M3      100      200      300      400      500      600      700      800      900      1000      1100      1200      1300
*
$ENDPROGRAM
```

Appendix I-3. PCSWMM input file for the lumped model from September 1 to November 31, 1999 (fall) of the Reesor Creek watershed.

$RUNOFF														
*	Title	Lines												
A1	'Reesor	Creek	1999	LUMPED	fall'									
A2	'no	quality	simulated'											
*	Run	Control												
*	METRIC	ISNOW	NRGAG	INFILM	KWALTY	IVAP	NHR	NMN	NDAY	MONTH	IYRSTR	IVCHAN		
B1	1	0	13	0	0	0	23	45	1	9	1999	0		
*	IPRN1	IPRN2	IPRN3	IRPNGW										
B2	0	1	0	0	0	1								
*	WET	WETDRY	DRY	LUNIT	LONG									
B3	3600	7200	86400	3	91									
*	PCTZER	REGEN												
B4	25	0.01												
*	Precipitation	Data												
*	ROPT													
D1	0													
*	KTYPE	KINC	KPRINT	KTHIS	KTIME	KPREP	NHISTO	THISTO	TZRAIN					
E1	2	1	0	0	1	1	91	24	0					
*														
*	TIME	Oshawa	Mark	Bowman	Button	Stouff	Cherry	Bed	Kim	Udora	Burke	Janet	Ponty	Tyrone
E3	0	0	0	0	0	0	0.6	0	0	0	0	0	0	0
E3	24	0	0	0	0	0.1	0	0	0	0	0	0	0	0
E3	48	0	0	0	0	0	0	0	0	0	0	0	0	0
E3	72	0	0	0	0	0	0	0	0	0	0	0	0	0
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.

.	.	.	.	.	.	.	.	.	.	.	.	.	.	.		
E3	2136	0	0	0	0	0	0	0	0	0	0	0	0	0		
E3	2160	0	0	0	0	0	0	0	0	0	0	0	0	0		
*	Subcatchments															
*	JK	NAMEW	NGTO	WW(1)	WAREA	WW(3)	WSLOPE	WW(5)	WW(6)	WSTORE1	WSTORE2	WLMAX	WLMIN	DECAY	RMAXINF	
H1	1	1	100	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0	
H1	2	2	200	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0	
H1	3	3	300	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0	
H1	4	4	400	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0	
H1	5	5	500	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0	
H1	6	6	600	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0	
H1	7	7	700	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0	
H1	8	8	800	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0	
H1	9	9	900	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0	
H1	10	10	10[illegible]	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0	
H1	11	11	11[illegible]	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0	
H1	12	12	1[illegible]00	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0	
H1	13	13	1300	3200	3505.04	8.41	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0	
*	Print	Control														
*	NPRNT	INTERV														
M1	1	0														
*	NDET	STARTP1	STOPPR1													
M2	1	0	0													
*	IPRNT															
M3	100	200	300	400	500	600	700	800	900	1000	1100	1200	1300			
*																

$ENDPROGRAM

Appendix I-4. PCSWMM input file for the subcatchment model of the Reesor Creek watershed.

$RUNOFF														
*	Title	Lines												
A1	'Reesor	Creek	1999	subwatershed'										
A2	'no	quality	simulated'											
*	Run	Control												
*	METRIC	ISNOW	NRGAG	INFILM	KWALTY	IVAP	NHR	NMN	NDAY	MONTH	IYRSTR	IVCHAN		
B1	1	0	13	0	0	0	23	45	1	5	1999	0		
*	IPRN1	IPRN2	IPRN3	IRPNGW										
B2	0	1	0	0	0	1								
*	WET	WETDRY	DRY	LUNIT	LONG									
B3	3600	7200	86400	3	214									
*	PCTZER	REGEN												
B4	25	0.01												
*	Precipitation	Data												
*	ROPT													
D1	0													
*	KTYPE	KINC	KPRINT	KTHIS	KTIME	KPREP	NHISTO	THISTO	TZRAIN					
E1	2	1	0	0	1	1	214	24	0					
*														
*	TIME	Oshawa	Mark	Bowman	Button	Stouff	Cherry	Bed	Kim	Udora	Burke	Janet	Ponty	Tyrone
E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E3	24	0	0	0	0	0	0	0	0	0	0	0	0	0
E3	48	0	0	0	0	0	0	0	0	0	0	0	0	0

E3	72	0	0	0	0	0	0	0	0	0	0	0	0	0	
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
E3	5088	0	0	0	0	0	0	0	0	0	0	0	0	0	
E3	5112	0	0	0	0	0	0	0	0	0	0	0	0	0	
*	Subcatchments														
*	JK	NAMEW	NGTO	WW(1)	WAREA	WW(3)	WSLOPE	WW(5)	WW(6)	WSTORE1	WSTORE2	WLMAX	WLMIN	DECAY	RMAXINF
H1	1	1	100	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	1	1	100	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	1	1	100	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	1	1	100	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	2	2	200	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	2	2	200	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	2	2	200	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	2	2	200	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	3	3	300	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	3	3	300	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	3	3	300	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	3	3	300	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	4	4	400	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	4	4	400	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	4	4	400	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	4	4	400	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	5	5	500	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	5	5	500	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	5	5	500	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0

H1	5	5	500	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	6	6	600	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	6	6	600	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	6	6	600	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	6	6	600	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	7	7	700	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	7	7	700	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	7	7	700	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	7	7	700	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	8	8	800	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	8	8	800	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	8	8	800	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	8	8	800	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	9	9	900	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	9	9	900	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	9	9	900	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	9	9	900	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	10	10	1000	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	10	10	1000	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	10	10	1000	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	10	10	1000	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	11	11	1100	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	11	11	1100	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	11	11	1100	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	11	11	1100	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	12	12	1200	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	12	12	1200	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	12	12	1200	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	12	12	1200	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0

H1	13	13	1300	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	13	13	1300	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	13	13	1300	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	13	13	1300	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
*	Print	Control													
*	NPRNT	INTERV													
M1	1	0													
*	NDET	STARTP1	STOPPR1												
M2	1	0	0												
*	IPRNT														
M3	100	200	300	400	500	600	700	800	900	1000	1100	1200	1300		
*															
$ENDPROGRAM															

Appendix I-5. PCSWMM input file for the subcatchment model from May 1 to August 31, 1999 (summer) of the Reesor Creek watershed.

$RUNOFF														
*	Title	Lines												
A1	'Reesor	Creek	1999	subwatershed summer'										
A2	'no	quality	simulated'											
*	Run	Control												
*	METRIC	ISNOW	NRGAG	INFILM	KWALTY	IVAP	NHR	NMN	NDAY	MONTH	IYRSTR	IVCHAN		
B1	1	0	13	0	0	0	23	45	1	5	1999	0		
*	IPRN1	IPRN2	IPRN3	IRPNGW										
B2	0	1	0	0	0	1								
*	WET	WETDRY	DRY	LUNIT	LONG									
B3	3600	7200	86400	3	123									
*	Precipitation	Data												
*	ROPT													
D1	0													
*	KTYPE	KINC	KPRINT	KTHIS	KTIME	KPREP	NHISTO	THISTO	TZRAIN					
E1	2	1	0	0	1	1	123	24	0					
*														
*	TIME	Oshawa	Mark	Bowman	Button	Stouff	Cherry	Bed	Kim	Udora	Burke	Janet	Ponty	Tyrone
E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E3	24	0	0	0	0	0	0	0	0	0	0	0	0	0
E3	48	0	0	0	0	0	0	0	0	0	0	0	0	0
E3	72	0	0	0	0	0	0	0	0	0	0	0	0	0

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E3	2904	0	0	0	0	0	0	0	0	0	0	0	0	0	
E3	2928	0	0	0	0	0	0	0	0	0	0	0	0	0	
*	Subcatchments														
*	JK	NAMEW	NGTO	WW(1)	WAREA	WW(3)	WSLOPE	WW(5)	WW(6)	WSTORE1	WSTORE2	WLMAX	WLMIN	DECAY	RMAXINF
H1	1	1	100	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	1	1	100	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	1	1	100	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	1	1	100	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	2	2	200	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	2	2	200	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.001.5	0
H1	2	2	200	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	2	2	200	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	3	3	300	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	3	3	300	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	3	3	300	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	3	3	300	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	4	4	400	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	4	4	400	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	4	4	400	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	4	4	400	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	5	5	500	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	5	5	500	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	5	5	500	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	5	5	500	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0

H1	6	6	600	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	6	6	600	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	6	6	600	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	6	6	600	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	7	7	700	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	7	7	700	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	7	7	700	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	7	7	700	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	8	8	800	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	8	8	800	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	8	8	800	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	8	8	800	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	9	9	900	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	9	9	900	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	9	9	900	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	9	9	900	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	10	10	1000	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	10	10	1000	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	10	10	1000	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	10	10	1000	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	11	11	1100	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	11	11	1100	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	11	11	1100	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	11	11	1100	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	12	12	1200	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	12	12	1200	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	12	12	1200	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	12	12	1200	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	13	13	1300	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0

H1	13	13	1300	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	13	13	1300	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	13	13	1300	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
*	Print	Control													
*	NPRNT	INTERV													
M1	1	0													
*	NDET	STARTP1	STOPPR1												
M2	1	0	0												
*	IPRNT														
M3	100	200	300	400	500	600	700	800	900	1000	1100	1200	1300		
*															
$ENDPROGRAM															

Appendix I-6. PCSWMM input file for the subcatchment model from September 1 to November 31, 1999 (fall) of the Reesor Creek watershed.

$RUNOFF														
*	Title	Lines												
A1	'Reesor	Creek	1999	subwatershed fall'										
A2	'no	quality	simulated'											
*	Run	Control												
*	METRIC	ISNOW	NRGAG	INFILM	KWALTY	IVAP	NHR	NMN	NDAY	MONTH	IYRSTR	IVCHAN		
B1	1	0	13	0	0	0	23	45	1	5	1999	0		
*	IPRN1	IPRN2	IPRN3	IRPNGW										
B2	0	1	0	0	0	1								
*	WET	WETDRY	DRY	LUNIT	LONG									
B3	3600	7200	86400	3	91									
*	Precipitation	Data												
*	ROPT													
D1	0													
*	KTYPE	KINC	KPRINT	KTHIS	KTIME	KPREP	NHISTO	THISTO	TZRAIN					
E1	2	1	0	0	1	1	91	24	0					
*														
*	TIME	Oshawa	Mark	Bowman	Button	Stouff	Cherry	Bed	Kim	Udora	Burke	Janet	Ponty	Tyrone
E3	0	0	0	0	0	0	0.6	0	0	0	0	0	0	0
E3	24	0	0	0	0	0.1	0	0	0	0	0	0	0	0
E3	48	0	0	0	0	0	0	0	0	0	0	0	0	0
E3	72	0	0	0	0	0	0	0	0	0	0	0	0	0

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E3	2136	0	0	0	0	0	0	0	0	0	0	0	0	0	
E3	2160	0	0	0	0	0	0	0	0	0	0	0	0	0	
*	Subcatchments														
*	JK	NAMEW	NGTO	WW(1)	WAREA	WW(3)	WSLOPE	WW(5)	WW(6)	WSTORE1	WSTORE2	WLMAX	WLMIN	DECAY	RMAXINF
H1	1	1	100	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	1	1	100	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	1	1	100	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	1	1	100	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	2	2	200	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	2	2	200	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	2	2	200	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	[illegible]
H1	2	2	200	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	3	3	300	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	3	3	300	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	3	3	300	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	3	3	300	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	4	4	400	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	4	4	400	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	4	4	400	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	4	4	400	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	5	5	500	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	5	5	500	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	5	5	500	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	5	5	500	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0

H1	6	6	600	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	6	6	600	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	6	6	600	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	6	6	600	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	7	7	700	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	7	7	700	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	7	7	700	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	7	7	700	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	8	8	800	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	8	8	800	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	8	8	800	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	8	8	800	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	9	9	900	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	9	9	900	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	9	9	900	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	9	9	900	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	10	10	1000	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	10	10	1000	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	10	10	1000	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	10	10	1000	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	11	11	1100	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	11	11	1100	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	11	11	1100	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	11	11	1100	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	12	12	1200	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	12	12	1200	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	12	12	1200	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	12	12	1200	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	13	13	1300	1677.9	281.6	10	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0

H1	13	13	1300	3294.2	1085.2	15	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	13	13	1300	4356.6	1898	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
H1	13	13	1300	1545	238.7	2	0.012	0.011	0.035	3.413	6.81	7.62	1.572	0.00115	0
*	Print	Control													
*	NPRNT	INTERV													
M1	1	0													
*	NDET	STARTP1	STOPPR1												
M2	1	0	0												
*	IPRNT														
M3	100	200	300	400	500	600	700	800	900	1000	1100	1200	1300		
*															
$ENDPROGRAM															

Appendix J

Appendix J. Calculated area or each polygon for landuse and soil type in grid cells 0 through 53--average width of each polygon was calculated by taking the square root of the area. The majority soil type is listed as MAX. All area values were calculated using ArcMap.

	Cell Landuse Area (hectares)								Average Width of Landuse (metres)						
Grid #	Urban Open Space	Agri / Rural	Federal Airport Lands	Meadow	Forest	Urban	Wetland	Total Area	Urban Open Space	Agri / Rural	Federal Airport Lands	Meadow	Forest	Urban	Wetland
0	0.0	5.1	0.0	4.9	0.0	0.0	0.0	10.0	0.0	224.8	0.0	221.9	0.0	0.0	0.0
1	0.0	22.9	0.0	0.9	2.5	0.0	0.0	26.3	0.0	478.0	0.0	96.9	159.1	0.0	0.0
2	0.0	0.3	0.0	0.0	0.3	0.0	0.0	0.6	0.0	51.2	0.0	0.0	55.1	0.0	0.0
3	0.0	26.7	0.0	0.0	0.0	0.0	0.0	26.7	0.0	516.8	0.0	0.0	0.0	0.0	0.0
4	0.0	64.3	0.0	23.4	0.6	0.0	0.3	88.7	0.0	802.1	0.0	484.1	80.4	0.0	50.3
5	0.0	55.5	0.0	33.2	2.8	6.0	0.1	97.5	0.0	744.7	0.0	575.8	166.3	245.1	37.4
6	0.0	64.6	0.0	7.5	4.0	0.0	2.2	78.3	0.0	803.8	0.0	273.0	200.4	11.6	148.6
7	0.0	15.0	0.0	0.0	1.5	0.0	2.0	18.6	0.0	387.8	0.0	0.0	123.5	0.0	141.2
8	0.0	40.2	0.0	9.2	17.4	0.0	0.4	67.3	0.0	634.1	0.0	304.1	416.9	0.0	65.6
9	0.0	71.1	0.0	16.7	12.1	0.0	0.0	100.0	0.0	843.5	0.0	409.1	348.1	0.0	0.0
10	0.0	62.1	0.0	31.0	5.7	1.2	0.0	100.0	0.0	787.9	0.0	556.4	239.4	110.7	6.2
11	0.0	43.0	0.0	5.5	47.0	0.0	4.5	100.0	0.0	656.1	0.0	233.5	685.4	0.0	212.7
12	0.0	9.2	0.0	1.0	21.9	0.0	6.9	39.0	0.0	304.0	0.0	97.5	468.0	0.0	261.9
13	0.0	28.5	0.0	6.5	2.5	0.0	7.4	45.0	0.0	534.1	0.0	255.5	159.1	0.0	271.8

	Cell Landuse Area (hectares)								Average Width of Landuse (metres)						
Grid #	Urban Open Space	Agri / Rural	Federal Airport Lands	Meadow	Forest	Urban	Wetland	Total Area	Urban Open Space	Agri / Rural	Federal Airport Lands	Meadow	Forest	Urban	Wetland
14	0.0	51.9	0.0	6.4	14.5	24.6	2.6	100.0	0.0	720.2	0.0	252.1	380.9	496.4	162.1
15	0.0	51.3	0.0	10.5	14.6	5.0	18.9	100.4	0.0	716.4	0.0	324.5	382.1	223.2	435.0
16	0.0	29.9	0.0	2.9	22.4	0.0	44.8	100.0	0.0	546.5	0.0	170.1	473.6	0.0	669.4
17	0.0	28.7	0.0	0.0	4.3	0.0	9.0	42.0	0.0	536.0	0.0	0.0	206.7	0.0	299.6
18	0.0	15.0	0.0	0.0	8.3	0.0	0.2	23.5	0.0	387.9	0.0	0.0	288.4	0.0	41.4
19	0.0	54.2	0.0	2.6	22.7	15.0	5.4	100.0	0.0	736.5	0.0	161.9	475.9	387.9	233.3
20	0.0	90.7	0.0	0.3	4.7	2.2	2.4	100.2	0.0	952.2	0.0	53.9	216.3	147.3	153.6
21	0.0	82.0	0.0	0.1	16.5	0.0	1.3	100.0	0.0	905.8	0.0	38.3	406.5	0.0	113.9
22	0.0	53.4	0.2	0.0	0.2	0.0	0.0	53.8	0.0	730.8	43.0	0.0	46.0	0.0	0.0
23	0.0	3.5	0.0	0.0	1.4	0.0	0.0	5.0	0.0	187.5	0.0	0.0	120.2	0.0	0.0
24	0.0	68.1	0.0	1.4	29.1	0.0	0.0	98.6	0.0	825.5	0.0	117.5	539.3	0.0	0.0
25	0.0	84.4	0.0	6.1	5.6	2.9	1.0	100.0	0.0	918.7	0.0	248.0	236.0	170.7	98.6
26	0.0	79.0	0.0	10.6	10.1	0.3	0.0	100.0	0.0	889.1	0.0	325.1	317.9	53.0	0.0
27	0.0	19.9	39.5	0.9	5.8	0.0	0.8	67.0	0.0	446.3	628.6	95.9	241.3	0.0	88.2
28	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.2	0.0	39.8	0.0	0.0	0.0	0.0	0.0
29	8.8	17.4	0.0	9.3	23.3	30.5	6.3	95.7	297.3	417.6	0.0	305.7	482.7	552.7	250.1
30	0.3	15.3	0.0	3.6	0.6	80.2	0.0	100.0	55.9	391.2	0.0	190.7	76.5	895.3	0.0
31	0.0	37.8	0.0	14.5	4.2	43.5	0.2	100.1	0.0	614.6	0.0	380.3	204.7	659.2	49.8
32	0.0	64.0	5.9	7.4	21.2	0.0	0.0	98.5	0.0	800.2	243.0	271.2	459.9	0.0	16.9

	Cell Landuse Area (hectares)								Average Width of Landuse (metres)						
Grid #	Urban Open Space	Agri / Rural	Federal Airport Lands	Meadow	Forest	Urban	Wetland	Total Area	Urban Open Space	Agri / Rural	Federal Airport Lands	Meadow	Forest	Urban	Wetland
33	0.0	6.5	3.0	0.0	0.1	0.0	0.0	9.5	0.0	254.9	172.3	0.0	25.5	0.0	0.0
34	8.5	10.5	0.0	1.8	3.5	42.5	0.4	67.2	291.2	323.7	0.0	135.5	187.5	652.0	65.8
35	4.0	16.0	0.0	0.0	6.6	73.4	0.0	100.0	199.0	399.9	0.0	0.0	257.3	856.9	0.0
36	0.0	80.8	0.0	0.2	3.7	14.9	0.3	100.0	0.0	898.9	0.0	48.4	192.2	386.3	59.0
37	0.0	65.0	7.1	9.4	18.5	0.0	0.0	100.0	0.0	806.4	266.2	306.9	429.8	0.0	0.0
38	0.0	4.6	14.9	0.0	0.7	0.0	0.0	20.2	0.0	215.5	385.9	0.0	80.7	0.0	0.0
39	0.0	12.5	0.0	1.7	1.1	0.0	0.0	15.4	0.0	353.9	0.0	131.8	105.7	0.0	0.0
40	0.0	82.5	0.0	0.0	12.9	0.0	0.0	95.4	0.0	908.1	0.0	0.0	359.3	0.0	0.0
41	0.0	79.7	13.5	0.1	6.7	0.0	0.0	100.0	0.0	892.7	366.8	36.6	259.4	0.0	0.0
42	0.0	12.1	63.0	5.1	19.3	0.0	1.4	100.9	0.0	347.4	794.0	225.1	439.1	0.0	120.3
43	0.0	0.0	47.1	0.4	1.1	0.0	0.0	48.6	0.0	0.0	686.2	61.7	106.7	0.0	0.0
44	0.0	11.0	21.6	2.3	3.9	0.0	1.0	39.8	0.0	331.2	464.8	152.2	198.7	0.0	99.7
45	0.0	0.1	78.9	7.0	7.0	0.0	3.0	95.9	0.0	27.0	888.2	264.3	264.5	0.0	172.8
46	0.0	0.0	65.9	9.9	20.9	0.0	3.3	100.0	0.0	0.0	811.9	314.4	457.7	0.0	180.4
47	0.0	0.0	46.6	12.3	27.0	0.0	1.9	87.8	0.0	0.0	682.4	350.6	519.4	0.0	138.8
48	0.0	0.0	0.9	0.0	0.1	0.0	0.0	1.0	0.0	0.0	95.5	0.0	35.0	0.0	0.0
49	0.0	0.0	11.0	0.0	0.1	0.0	0.0	11.1	0.0	0.0	331.1	0.0	31.2	0.0	0.0
50	0.0	0.0	58.9	0.5	13.2	0.0	1.4	74.0	0.0	0.0	767.3	67.2	363.6	0.0	119.1
51	0.0	0.0	31.2	4.5	14.6	0.0	0.0	50.3	0.0	0.0	558.6	212.2	381.5	0.0	0.0

	Cell Landuse Area (hectares)								Average Width of Landuse (metres)						
Grid #	Urban Open Space	Agri / Rural	Federal Airport Lands	Meadow	Forest	Urban	Wetland	Total Area	Urban Open Space	Agri / Rural	Federal Airport Lands	Meadow	Forest	Urban	Wetland
52	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0	32.3	0.0	1.0	0.0	0.0
53	0.0	0.0	0.6	0.7	3.9	0.0	0.0	5.2	0.0	0.0	75.7	84.6	196.6	0.0	0.0

GRID 8 — Agricultural/Rural (m^2)

	loam	organic	clay	sand	clay loam	sandy loam	variable	MAX
0	0	0	0	50521	0	0	0	50521
1	169625	0	0	58905	0	0	0	169625
2	2626	0	0	0	0	0	0	2626
3	124141	0	0	142929	0	0	0	142929
4	161495	0	0	481665	0	0	0	481665
5	501965	0	0	52607	0	0	0	501965
6	646046	0	0	0	0	0	0	646046
7	88326	627	0	0	0	61434	0	88326
8	393558	8476	0	0	0	0	0	393558
9	711421	0	0	0	0	0	0	711421
10	615607	0	0	0	0	0	0	615607
11	384685	45768	0	0	0	0	0	384685
12	77442	2761	0	0	0	12217	0	77442
13	285262	0	0	0	0	0	0	285262
14	518670	0	0	0	0	0	0	518670
15	451291	61820	0	0	0	0	0	451291
16	214457	57431	0	0	0	0	26756	214457
17	286525	741	0	0	0	0	0	286525
18	125695	0	0	0	0	0	24783	125695
19	511849	0	0	0	0	0	30548	511849
20	888938	0	0	0	0	0	17716	888938
21	757635	0	0	0	0	0	62864	757635
22	534098	0	0	0	0	0	0	534098
23	33193	0	0	0	0	0	1962	33193
24	628799	0	0	0	0	0	52635	628799
25	679190	0	0	0	157681	0	7083	679190
26	733102	0	0	0	2655	0	54714	733102
27	129913	0	12079	0	0	0	57194	129913
28	1588	0	0	0	0	0	0	1588
29	155253	0	0	0	0	0	19156	155253
30	149565	0	0	0	3487	0	0	149565
31	345622	0	0	0	0	0	32153	345622
32	363155	0	209748	0	0	0	67493	363155
33	9800	0	55167	0	0	0	0	55167
34	104752	0	0	0	0	0	0	104752
35	153491	0	0	0	0	0	6398	153491
36	734235	63177	0	0	0	0	8544	734235
37	550419	0	54269	0	0	0	45541	550419
38	67	0	46353	0	0	0	0	46353
39	125236	0	0	0	0	0	0	125236
40	711758	0	0	0	0	0	112923	711758
41	732601	0	0	0	0	0	64233	732601
42	99485	0	170	0	0	0	21026	99485
43	0	0	0	0	0	0	0	0
44	102987	0	0	0	0	0	6699	102987
45	730	0	0	0	0	0	0	730
46	0	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0
51	0	0	0	0	0	0	0	0
52	0	0	0	0	0	0	0	0
53	0	0	0	0	0	0	0	0

GRID #	Agricultural/Rural (m^2)							
	loam	organic	clay	sand	clay loam	sandy loam	variable	MAX
0	0	0	0	50521	0	0	0	50521
1	169625	0	0	58905	0	0	0	169625
2	2626	0	0	0	0	0	0	2626
3	124141	0	0	142929	0	0	0	142929
4	161495	0	0	481665	0	0	0	481665
5	501965	0	0	52607	0	0	0	501965
6	646046	0	0	0	0	0	0	646046
7	88326	627	0	0	0	61434	0	88326
8	393558	8476	0	0	0	0	0	393558
9	711421	0	0	0	0	0	0	711421
10	615607	0	0	0	0	0	0	615607
11	384685	45768	0	0	0	0	0	384685
12	77442	2761	0	0	0	12217	0	77442
13	285262	0	0	0	0	0	0	285262
14	518670	0	0	0	0	0	0	518670
15	451291	61820	0	0	0	0	0	451291
16	214457	57431	0	0	0	0	26756	214457
17	286525	741	0	0	0	0	0	286525
18	125695	0	0	0	0	0	24783	125695
19	511849	0	0	0	0	0	30548	511849
20	888938	0	0	0	0	0	17716	888938
21	757635	0	0	0	0	0	62864	757635
22	534098	0	0	0	0	0	0	534098
23	33193	0	0	0	0	0	1962	33193
24	628799	0	0	0	0	0	52635	628799
25	679190	0	0	0	157681	0	7083	679190
26	733102	0	0	0	2655	0	54714	733102
27	129913	0	12079	0	0	0	57194	129913
28	1588	0	0	0	0	0	0	1588
29	155253	0	0	0	0	0	19156	155253
30	149565	0	0	0	3487	0	0	149565
31	345622	0	0	0	0	0	32153	345622
32	363155	0	209748	0	0	0	67493	363155
33	9800	0	55167	0	0	0	0	55167
34	104752	0	0	0	0	0	0	104752
35	153491	0	0	0	0	0	6398	153491
36	734235	63177	0	0	0	0	8544	734235
37	550419	0	54269	0	0	0	45541	550419
38	67	0	46353	0	0	0	0	46353
39	125236	0	0	0	0	0	0	125236
40	711758	0	0	0	0	0	112923	711758
41	732601	0	0	0	0	0	64233	732601
42	99485	0	170	0	0	0	21026	99485
43	0	0	0	0	0	0	0	0
44	102987	0	0	0	0	0	6699	102987
45	730	0	0	0	0	0	0	730
46	0	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0
51	0	0	0	0	0	0	0	0
52	0	0	0	0	0	0	0	0
53	0	0	0	0	0	0	0	0

GRID #	Federal Airport Lands (m^2)							
	loam	organic	clay	sand	clay loam	sandy loam	variable	MAX
0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0
22	1845	0	0	0	0	0	0	1845
23	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0
27	183379	0	211741	0	0	0	0	211741
28	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0
31	0	0	0	0	0	0	0	0
32	8923	0	50123	0	0	0	0	50123
33	15822	0	13868	0	0	0	0	15822
34	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0
36	0	0	0	0	0	0	0	0
37	70031	0	695	0	0	0	116	70031
38	59697	0	89233	0	0	0	0	89233
39	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0
41	134555	0	0	0	0	0	0	134555
42	434617	0	85273	0	0	0	50529	434617
43	24458	0	446476	0	0	0	0	446476
44	213566	0	0	0	0	0	2457	213566
45	434210	0	273033	0	0	0	81740	434210
46	508071	0	39543	0	0	0	111357	508071
47	152167	0	313524	0	0	0	0	313524
48	7116	0	2009	0	0	0	0	7116
49	0	0	109633	0	0	0	0	109633
50	276853	0	272418	0	0	0	39304	276853
51	268064	0	0	0	0	0	43995	268064
52	1043	0	0	0	0	0	0	1043
53	2879	0	0	0	0	0	2850	2879

GRID 8 Meadow (m^2)

	loam	organic	clay	sand	clay loam	sandy loam	variable	MAX
0	0	0	0	49248	0	0	0	49248
1	0	0	0	9387	0	0	0	9387
2	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0
4	21868	0	0	212532	0	0	0	212532
5	254127	0	0	77438	0	0	0	254127
6	74546	0	0	0	0	0	0	74546
7	0	0	0	0	0	0	0	0
8	86464	5988	0	0	0	0	0	86464
9	167400	0	0	0	0	0	0	167400
10	308429	0	0	0	0	0	0	308429
11	46606	7897	0	0	0	0	0	46606
12	9509	0	0	0	0	0	0	9509
13	65264	0	0	0	0	0	0	65264
14	63570	0	0	0	0	0	0	63570
15	96650	8644	0	0	0	0	0	96650
16	8064	20875	0	0	0	0	0	20875
17	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0
19	21642	0	0	0	0	0	4584	21642
20	2890	0	0	0	0	0	15	2890
21	1470	0	0	0	0	0	0	1470
22	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0
24	10030	0	0	0	0	0	3766	10030
25	18971	0	0	0	42508	0	4	42508
26	25339	0	0	0	49858	0	30474	49858
27	1213	0	0	0	0	0	7991	7991
28	0	0	0	0	0	0	0	0
29	61846	0	0	0	0	0	31605	61846
30	23327	0	0	0	13044	0	0	23327
31	78671	0	0	0	38253	0	27268	78671
32	47611	0	11467	0	0	0	14447	47611
33	0	0	0	0	0	0	0	0
34	17762	0	0	0	0	0	606	17762
35	0	0	0	0	0	0	0	0
36	2344	0	0	0	0	0	0	2344
37	85348	0	374	0	0	0	8492	85348
38	0	0	0	0	0	0	0	0
39	17373	0	0	0	0	0	0	17373
40	0	0	0	0	0	0	0	0
41	1343	0	0	0	0	0	0	1343
42	26997	0	16708	0	0	0	6976	26997
43	0	0	3811	0	0	0	0	3811
44	22995	0	0	0	0	0	158	22995
45	7413	0	53242	0	0	0	9209	53242
46	57003	0	5639	0	0	0	36177	57003
47	114798	0	8139	0	0	0	0	114798
48	0	0	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0
50	4220	0	297	0	0	0	0	4220
51	33049	0	0	0	0	0	11990	33049
52	0	0	0	0	0	0	0	0
53	1050	0	0	0	0	0	6109	6109

GRID #	Forest (m^2)							
	loam	organic	clay	sand	clay loam	sandy loam	variable	MAX
0	0	0	0	0	0	0	0	0
1	25322	0	0	0	0	0	0	25322
2	3035	0	0	0	0	0	0	3035
3	0	0	0	0	0	0	0	0
4	6457	0	0	0	0	0	0	6457
5	27672	0	0	0	0	0	0	27672
6	40149	0	0	0	0	0	0	40149
7	1096	802	0	0	0	13347	0	13347
8	143138	30686	0	0	0	0	0	143138
9	121179	0	0	0	0	0	0	121179
10	56484	0	0	0	0	0	0	56484
11	409377	60427	0	0	0	0	0	409377
12	136916	3941	0	0	0	78132	0	136916
13	25326	0	0	0	0	0	0	25326
14	145107	0	0	0	0	0	0	145107
15	142147	3675	0	0	0	0	0	142147
16	94342	129940	0	0	0	0	0	129940
17	42726	0	0	0	0	0	0	42726
18	54127	0	0	0	0	0	29018	54127
19	181506	0	0	0	0	0	45011	181506
20	33689	0	0	0	0	0	13080	33689
21	152588	0	0	0	0	0	12638	152588
22	2116	0	0	0	0	0	0	2116
23	3340	0	0	0	0	0	11116	11116
24	263360	0	0	0	0	0	27474	263360
25	29829	0	0	0	14125	0	11754	29829
26	55737	0	0	0	12125	0	33190	55737
27	45774	0	4692	0	0	0	7744	45774
28	0	0	0	0	0	0	0	0
29	212807	0	0	0	0	0	20221	212807
30	5845	0	0	0	0	0	0	5845
31	23276	0	0	0	663	0	17965	23276
32	64021	0	76924	0	0	0	70602	76924
33	652	0	0	0	0	0	0	652
34	23355	0	0	0	0	0	11805	23355
35	31173	0	0	0	0	0	35026	35026
36	34420	121	0	0	0	0	2414	34420
37	98291	0	5250	0	0	0	81172	98291
38	2347	0	4172	0	0	0	0	4172
39	11163	0	0	0	0	0	0	11163
40	115193	0	0	0	0	0	13895	115193
41	41828	0	0	0	0	0	25441	41828
42	77585	0	12036	0	0	0	103175	103175
43	0	0	11377	0	0	0	0	11377
44	31784	0	0	0	0	0	7679	31784
45	41692	0	11094	0	0	0	17199	41692
46	106316	0	5823	0	0	0	97333	106316
47	232828	0	36914	0	0	0	0	232828
48	27	0	1198	0	0	0	0	1198
49	0	0	975	0	0	0	0	975
50	82060	0	6976	0	0	0	43173	82060
51	94835	0	0	0	0	0	50744	94835
52	1	0	0	0	0	0	0	1
53	11393	0	0	0	0	0	27253	27253

GRID #	Wetland (m^2)							
	loam	organic	clay	sand	clay loam	sandy loam	variable	MAX
0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0
4	0	0	0	2526	0	0	0	2526
5	1396	0	0	0	0	0	0	1396
6	22069	0	0	0	0	0	0	22069
7	5039	1726	0	0	0	13172	0	13172
8	4303	0	0	0	0	0	0	4303
9	0	0	0	0	0	0	0	0
10	38	0	0	0	0	0	0	38
11	20743	24497	0	0	0	0	0	24497
12	23231	35544	0	0	0	3814	0	35544
13	73860	0	0	0	0	0	0	73860
14	26262	0	0	0	0	0	0	26262
15	42687	146502	0	0	0	0	0	146502
16	148119	279959	0	0	0	0	20056	279959
17	72303	17465	0	0	0	0	0	72303
18	1303	0	0	0	0	0	411	1303
19	33047	0	0	0	0	0	21381	33047
20	23602	0	0	0	0	0	0	23602
21	12708	0	0	0	0	0	255	12708
22	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0
25	9719	0	0	0	0	0	0	9719
26	0	0	0	0	0	0	0	0
27	7780	0	0	0	0	0	0	7780
28	0	0	0	0	0	0	0	0
29	38205	0	0	0	0	0	24363	38205
30	0	0	0	0	0	0	0	0
31	2479	0	0	0	0	0	0	2479
32	285	0	0	0	0	0	0	285
33	0	0	0	0	0	0	0	0
34	4334	0	0	0	0	0	0	4334
35	0	0	0	0	0	0	0	0
36	2582	895	0	0	0	0	0	2582
37	0	0	0	0	0	0	0	0
38	0	0	0	0	0	0	0	0
39	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0
41	0	0	0	0	0	0	0	0
42	14238	0	0	0	0	0	241	14238
43	0	0	0	0	0	0	0	0
44	1732	0	0	0	0	0	8207	8207
45	850	0	13527	0	0	0	15490	15490
46	13733	0	0	0	0	0	18805	18805
47	16463	0	2789	0	0	0	0	16463
48	0	0	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0
50	7830	0	0	0	0	0	6359	7830
51	0	0	0	0	0	0	0	0
52	0	0	0	0	0	0	0	0
53	0	0	0	0	0	0	0	0

GRID #	Urban (m^2)							
	loam	organic	clay	sand	clay loam	sandy loam	variable	MAX
0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0
5	60066	0	0	0	0	0	0	60066
6	135	0	0	0	0	0	0	135
7	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0
10	12255	0	0	0	0	0	0	12255
11	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0
14	246392	0	0	0	0	0	0	246392
15	49809	0	0	0	0	0	0	49809
16	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0
19	141308	0	0	0	0	0	9123	141308
20	21689	0	0	0	0	0	0	21689
21	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0
25	0	0	0	0	29137	0	0	29137
26	2071	0	0	0	659	0	78	2071
27	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0
29	264026	0	0	0	0	0	41428	264026
30	757472	0	0	0	44137	0	0	757472
31	286615	0	0	0	118944	0	28604	286615
32	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0	0	0
34	357759	0	0	0	0	0	67322	357759
35	730023	0	0	0	0	0	4299	730023
36	148942	0	0	0	0	0	0	148942
37	0	0	0	0	0	0	0	0
38	0	0	0	0	0	0	0	0
39	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0
41	0	0	0	0	0	0	0	0
42	0	0	0	0	0	0	0	0
43	0	0	0	0	0	0	0	0
44	0	0	0	0	0	0	0	0
45	0	0	0	0	0	0	0	0
46	0	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0
51	0	0	0	0	0	0	0	0
52	0	0	0	0	0	0	0	0
53	0	0	0	0	0	0	0	0

Appendix K

Appendix K. Daily precipitation values for virtual rain gauges (mm/day).

Date	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
9/1/1999	0.01	0.02	0.02	0.01	0.01	0.01	0.02	0.03	0.00	0.01	0.01	0.02	0.03	0.00	0.00	0.01	0.02	0.03	0.01	0.00	0.01
9/2/1999	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.09	0.09	0.09	0.09	0.08	0.09	0.09	0.09
9/3/1999	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	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/4/1999	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	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/5/1999	0.51	0.55	0.61	0.39	0.42	0.47	0.53	0.60	0.31	0.34	0.39	0.45	0.53	0.23	0.26	0.31	0.38	0.46	0.15	0.18	0.23
9/6/1999	27.47	28.47	28.41	27.90	28.07	28.10	28.77	27.08	28.30	28.56	27.51	27.35	27.54	28.61	28.17	28.26	28.05	27.57	28.33	28.81	28.90
9/7/1999	5.34	5.53	5.85	4.59	4.68	4.90	5.26	5.75	3.91	4.01	4.27	4.67	5.20	2.92	2.97	3.20	4.07	4.66	2.38	2.43	2.68
9/8/1999	9.98	9.99	9.97	9.86	9.91	9.92	9.90	9.84	9.79	9.85	9.86	9.83	9.75	9.72	9.79	9.80	9.75	9.66	9.64	9.73	9.74
9/9/1999	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	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/10/1999	0.07	0.09	0.12	0.03	0.05	0.08	0.11	0.16	0.01	0.03	0.07	0.11	0.16	0.01	0.02	0.06	0.11	0.17	0.03	0.00	0.05
9/11/1999	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	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/12/1999	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	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/13/1999	8.82	8.83	8.87	8.53	8.51	8.52	8.56	8.62	8.23	8.20	8.21	8.25	8.31	7.95	7.90	7.90	7.94	8.02	7.68	7.61	7.60
9/14/1999	0.29	0.29	0.29	0.30	0.29	0.29	0.29	0.29	0.30	0.30	0.29	0.29	0.29	0.30	0.30	0.30	0.30	0.29	0.30	0.30	0.30
9/15/1999	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	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/16/1999	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	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/17/1999	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	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/18/1999	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	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/19/1999	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	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/20/1999	2.86	2.86	2.86	2.82	2.82	2.82	2.81	2.81	2.78	2.77	2.77	2.76	2.76	2.74	2.73	2.72	2.71	2.70	2.69	2.68	2.67
9/21/1999	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	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Date	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
9/22/1999	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	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/23/1999	0.53	0.54	0.55	0.46	0.46	0.47	0.49	0.50	0.39	0.40	0.41	0.42	0.43	0.33	0.33	0.34	0.35	0.37	0.27	0.27	0.27
9/24/1999	1.98	2.01	2.00	2.02	2.03	2.05	2.04	2.03	2.07	2.08	2.11	2.09	2.07	2.13	2.16	2.16	2.15	2.12	2.19	2.22	2.22
9/25/1999	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	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/26/1999	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	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/27/1999	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	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/28/1999	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	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/29/1999	36.67	36.70	36.74	36.57	36.61	36.64	36.67	36.70	36.50	36.54	36.57	36.60	36.63	36.43	36.47	36.50	36.52	36.55	36.36	36.39	36.42
9/30/1999	3.60	3.61	3.61	3.74	3.78	3.79	3.78	3.74	3.91	3.95	3.97	3.96	3.91	4.07	4.12	4.15	4.13	4.08	4.23	4.30	4.33

Date	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41
9/1/1999	0.02	0.04	0.01	0.00	0.01	0.02	0.04	0.01	0.00	0.01	0.03	0.05	0.07	0.00	0.01	0.03	0.06	0.08	0.01	0.02	0.04
9/2/1999	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.10	0.10	0.09	0.09	0.08	0.10	0.10	0.09	0.09	0.08	0.09	0.09	0.09
9/3/1999	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	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/4/1999	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	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/5/1999	0.31	0.39	0.08	0.10	0.16	0.24	0.36	0.05	0.03	0.09	0.20	0.32	0.44	0.00	0.05	0.17	0.29	0.42	0.00	0.06	0.17
9/6/1999	28.60	28.00	28.73	29.34	29.42	28.97	28.21	28.91	29.72	29.80	29.06	28.11	27.07	29.47	29.53	28.64	27.62	26.54	28.14	28.20	27.62
9/7/1999	3.14	3.75	1.86	1.87	2.15	2.69	3.40	1.42	1.33	1.63	2.28	3.09	3.99	1.07	1.38	2.16	3.01	3.90	1.29	1.63	2.27
9/8/1999	9.67	9.55	9.54	9.67	9.68	9.57	9.38	9.44	9.60	9.61	9.41	9.20	8.99	9.41	9.38	9.17	8.95	8.73	8.96	8.93	8.80
9/9/1999	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	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/10/1999	0.12	0.19	0.04	0.01	0.05	0.13	0.22	0.04	0.02	0.04	0.14	0.25	0.36	0.01	0.07	0.18	0.30	0.42	0.04	0.13	0.24
9/11/1999	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	0.00	0.00	0.00	0.00	0.00	0.00	0.00

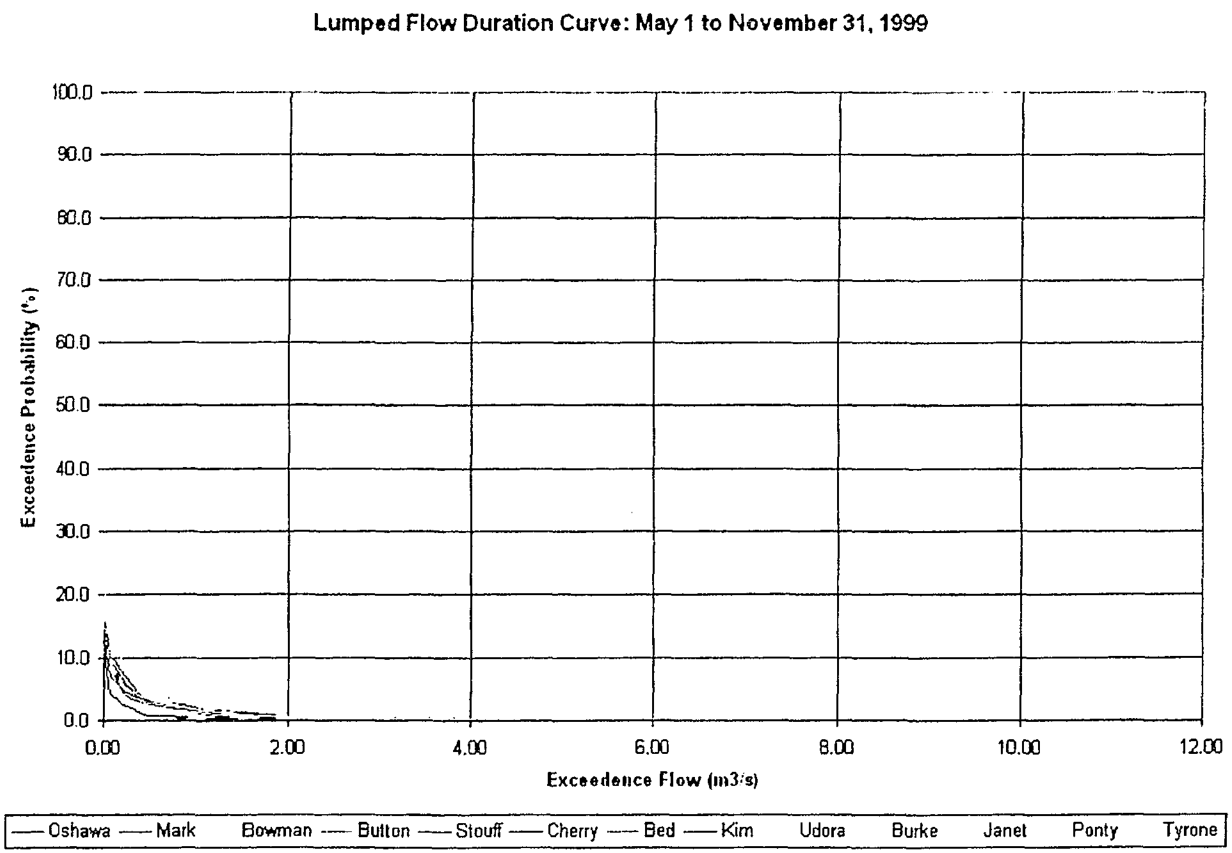
Date	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41
9/12/1999	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/13/1999	7.66	7.75	7.43	7.33	7.32	7.39	7.66	7.34	7.06	7.05	7.29	7.45	7.61	7.02	7.00	7.16	7.33	7.48	7.12	7.08	7.17
9/14/1999	0.30	0.30	0.30	0.30	0.30	0.30	0.27	0.29	0.30	0.30	0.28	0.28	0.27	0.30	0.28	0.28	0.28	0.28	0.28	0.28	0.28
9/15/1999	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	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/16/1999	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	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/17/1999	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	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/18/1999	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	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/19/1999	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	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/20/1999	2.66	2.65	2.65	2.63	2.62	2.60	2.57	2.59	2.58	2.56	2.53	2.51	2.49	2.53	2.50	2.48	2.45	2.43	2.48	2.45	2.42
9/21/1999	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	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/22/1999	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	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/23/1999	0.29	0.31	0.21	0.20	0.21	0.23	0.25	0.16	0.14	0.15	0.17	0.20	0.23	0.10	0.10	0.13	0.16	0.18	0.08	0.08	0.10
9/24/1999	2.20	2.17	2.24	2.28	2.28	2.25	2.19	2.44	2.34	2.34	2.28	2.29	2.25	2.41	2.38	2.34	2.30	2.26	2.36	2.34	2.32
9/25/1999	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	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/26/1999	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	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/27/1999	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	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/28/1999	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	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/29/1999	36.44	36.46	36.28	36.31	36.34	36.36	37.28	36.94	36.23	36.26	37.18	37.19	37.20	36.89	37.08	37.08	37.08	37.09	36.93	36.95	36.95
9/30/1999	4.30	4.25	4.38	4.47	4.50	4.47	4.39	4.51	4.64	4.68	4.60	4.52	4.42	4.74	4.78	4.70	4.61	4.51	4.72	4.77	4.74

Date	42	43	44	45	46	47	48	49	50	51	52	53
9/1/1999	0.07	0.09	0.04	0.06	0.08	0.11	0.13	0.07	0.09	0.12	0.14	0.13
9/2/1999	0.08	0.08	0.08	0.08	0.08	0.07	0.07	0.07	0.07	0.07	0.06	0.06
9/3/1999	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/4/1999	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/5/1999	0.29	0.42	0.08	0.18	0.30	0.43	0.57	0.20	0.32	0.45	0.59	0.48
9/6/1999	26.73	25.70	26.70	26.29	25.55	24.60	23.52	25.15	24.49	23.60	22.56	22.27
9/7/1999	3.06	3.92	1.94	2.50	3.21	4.01	4.88	2.72	3.37	4.11	4.94	4.27
9/8/1999	8.61	8.41	8.45	8.37	8.22	8.05	7.85	8.01	7.89	7.73	7.56	7.33
9/9/1999	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/10/1999	0.36	0.49	0.19	0.30	0.43	0.57	0.70	0.36	0.49	0.63	0.77	0.71
9/11/1999	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/12/1999	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/13/1999	7.29	7.42	7.21	7.25	7.32	7.41	7.50	7.33	7.37	7.43	7.50	7.49
9/14/1999	0.28	0.28	0.29	0.28	0.28	0.28	0.28	0.29	0.29	0.28	0.28	0.29
9/15/1999	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/16/1999	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/17/1999	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/18/1999	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/19/1999	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/20/1999	2.40	2.37	2.41	2.37	2.34	2.31	2.28	2.33	2.30	2.26	2.22	2.20
9/21/1999	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/22/1999	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

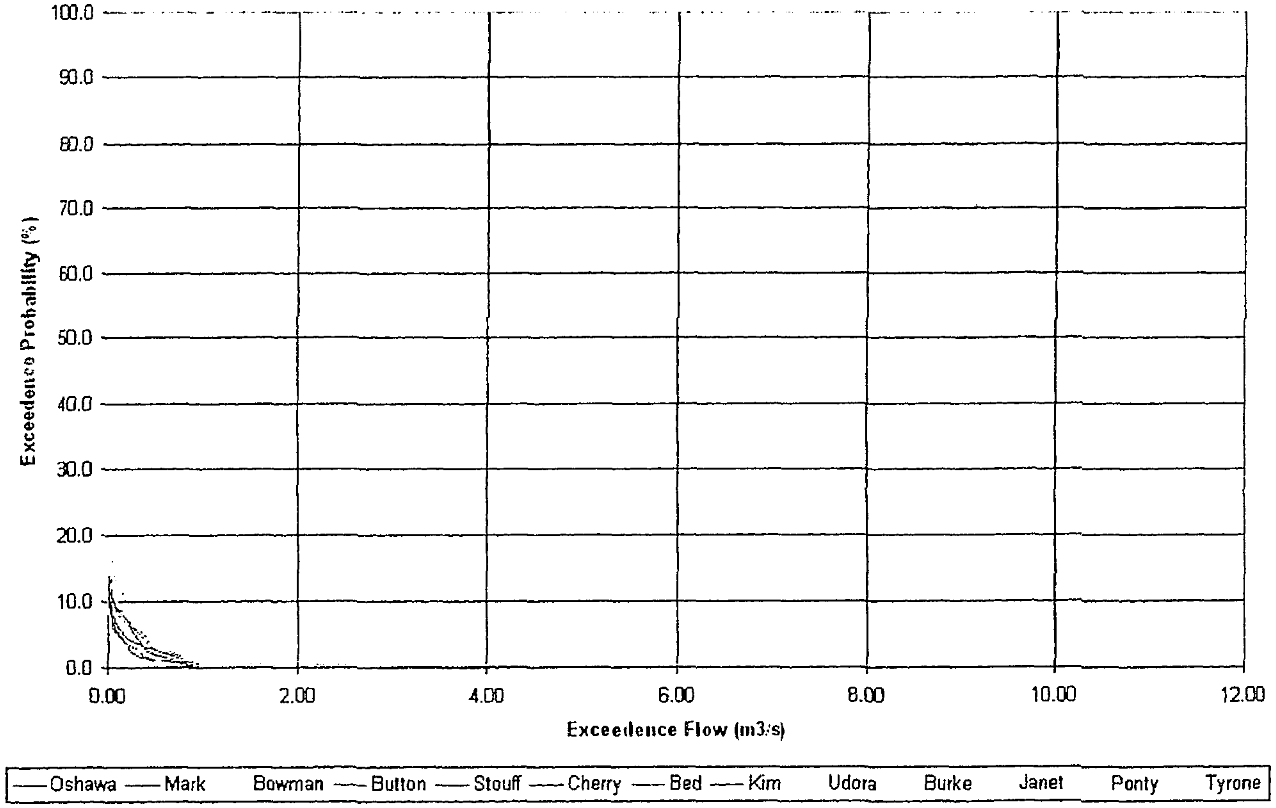
Date	42	43	44	45	46	47	48	49	50	51	52	53
9/23/1999	0.12	0.14	0.07	0.08	0.09	0.11	0.13	0.06	0.08	0.09	0.11	0.07
9/24/1999	2.28	2.25	2.30	2.29	2.26	2.23	2.20	2.27	2.25	2.22	2.18	2.22
9/25/1999	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/26/1999	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/27/1999	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/28/1999	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9/29/1999	36.96	36.97	36.81	36.82	36.83	36.84	36.86	36.70	36.72	36.73	36.76	36.59
9/30/1999	4.67	4.59	4.74	4.74	4.70	4.64	4.55	4.74	4.72	4.67	4.60	4.70

Appendix L

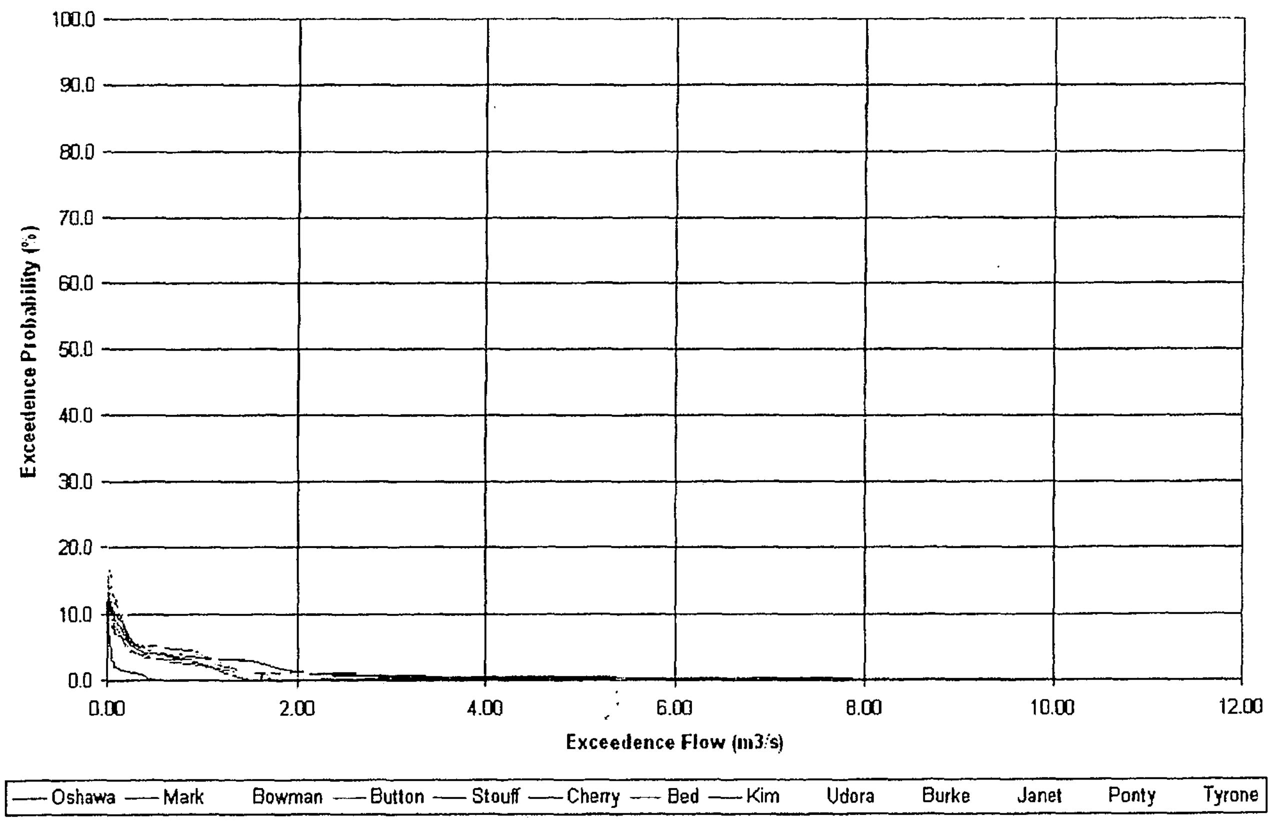
Appendix I. Lumped and subwatershed flow duration curves for the full study time period (May to November), summer, fall, and September, 1999.



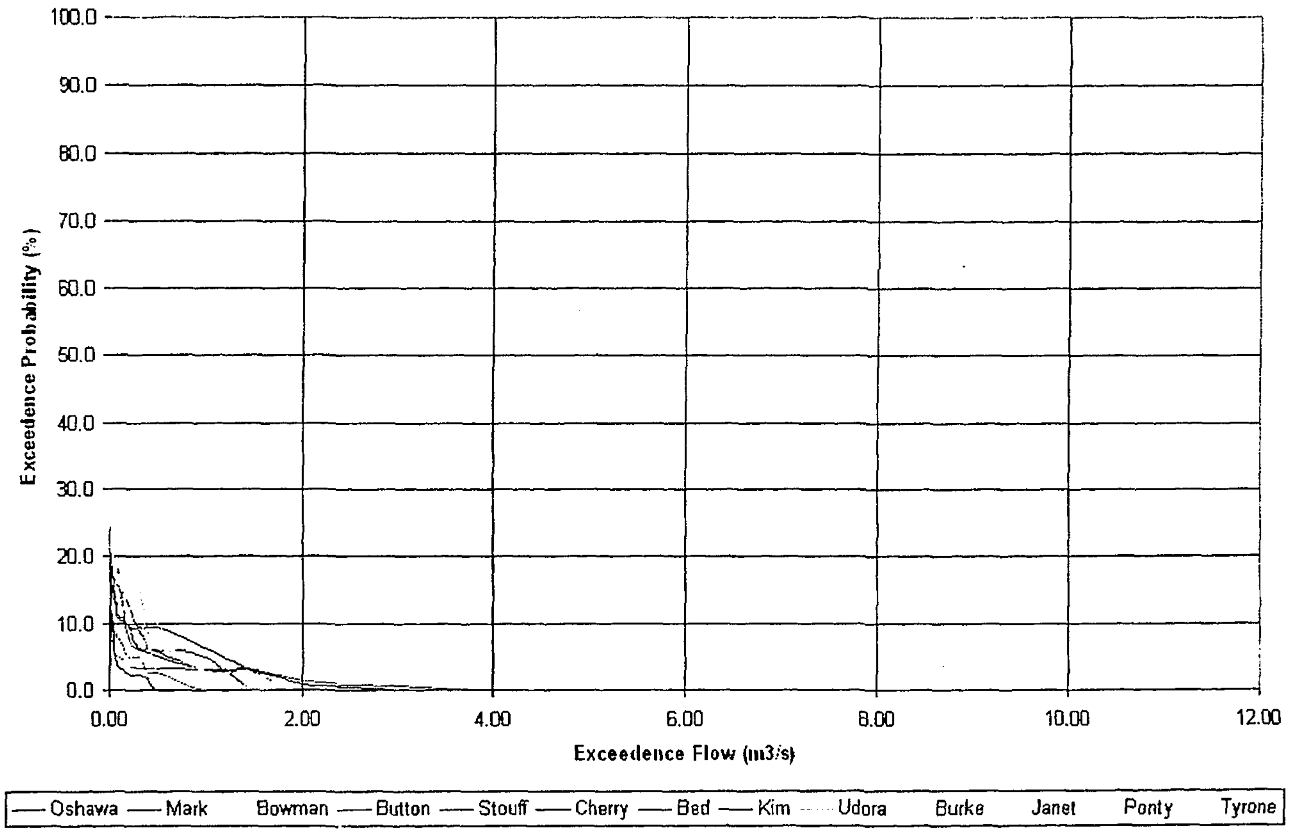
Lumped Summer Flow Duration Curve: May 1 to August 31, 1999



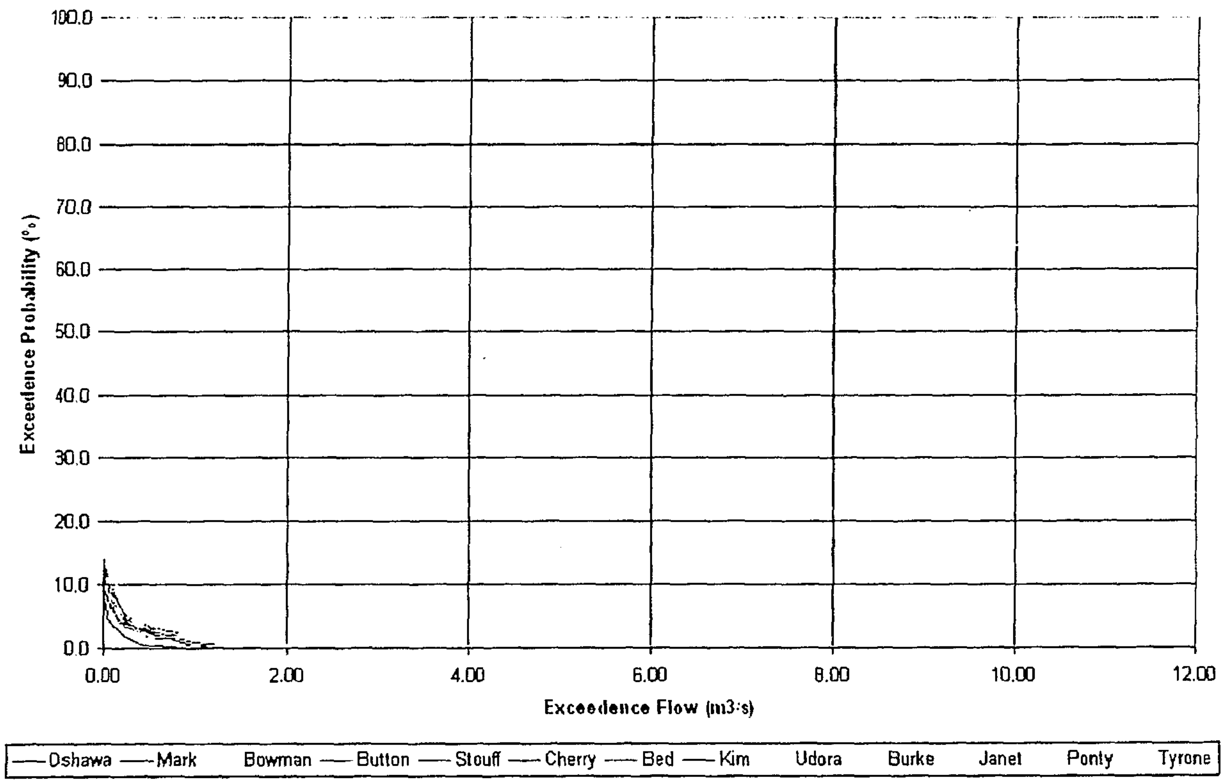
Lumped Fall Flow Duration Curve: September 1 to November 31, 1999



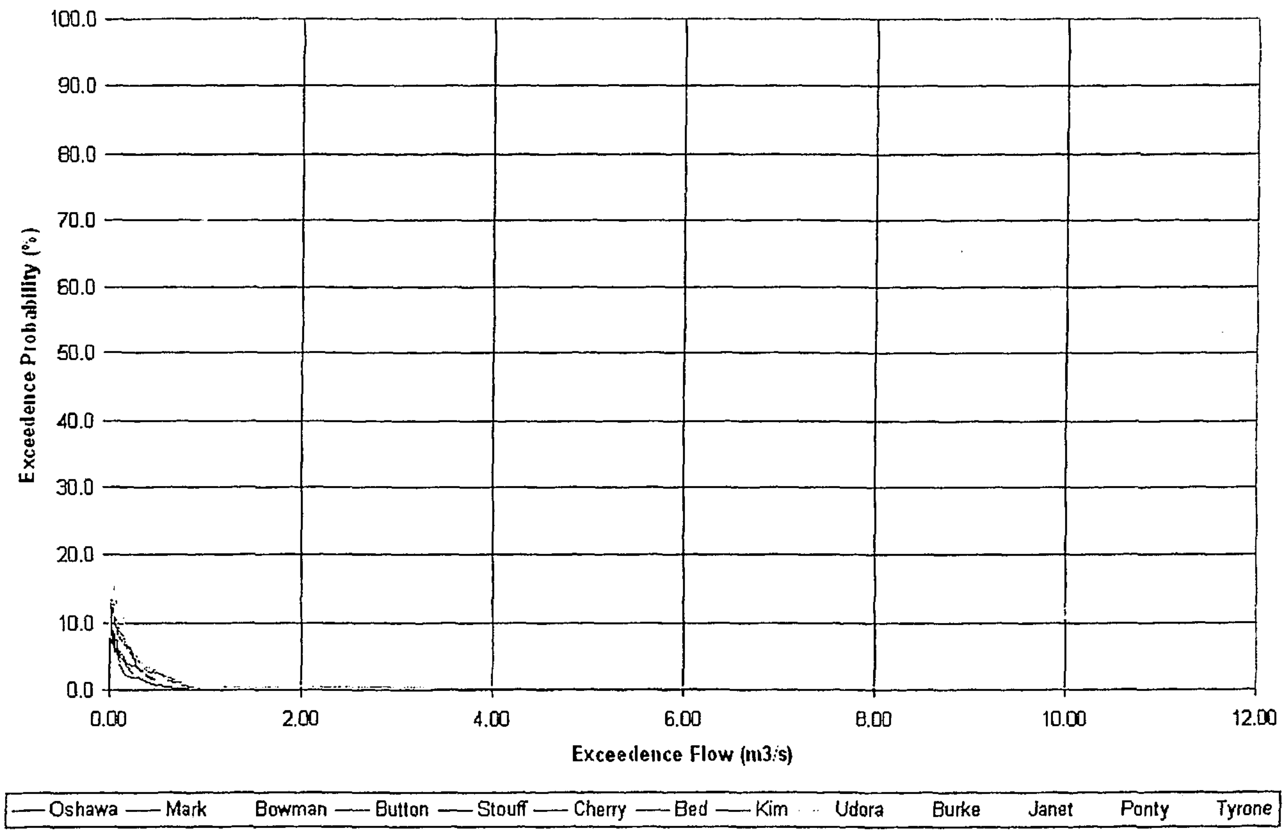
Lumped Flow Duration Curve: September, 1999



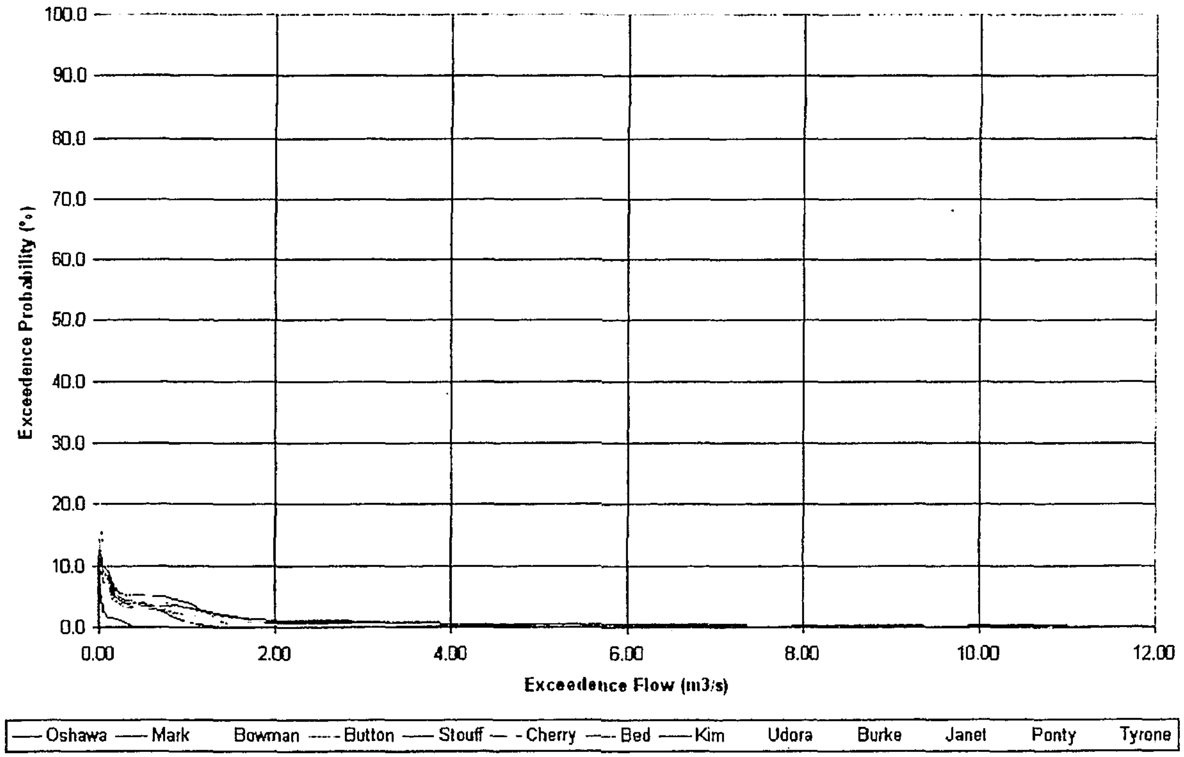
Subwatershed Flow Duration Curve: May 1 to November 31, 1999



Subwatershed Summer Flow Duration Curve: May 1 to August 31, 1999



Subwatershed Fall Flow Duration Curve: September 1 to November 31, 1999



Subwatershed Flow Duration Curve: September, 1999