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**HYDROLOGICAL
PARAMETERIZATION AND
MODELING USING GEOGRAPHIC
INFORMATION SYSTEMS**

by
MICHAEL RODNEY BALLARD, B.A.

**A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfillment of
the requirements for the degree of**

MASTER OF ARTS

Department of Geography

Carleton University

Ottawa, Ontario

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**"HYDROLOGICAL
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MODELING USING GEOGRAPHIC
INFORMATION SYSTEMS"**

**submitted by Michael Rodney Ballard, B.A.
in partial fulfillment of the requirements for
the degree of Master of Arts**

Thesis Supervisor

Chair, Department of Geography

**Carleton University
May 17, 1993**

ABSTRACT

This study assesses the role of geographic information technology in hydrological studies. A review of rainfall modeling, drainage network and watershed data structures for representation in a GIS, the preparation of hydrologically sound digital elevation models and the delineation of watersheds is provided. A shell program was written which uses the IDRISI GIS software to map soil and land use features and delineate watershed boundaries from a digital elevation model, calculates infiltration factors and prepares an input file for the OTTHYMO hydrological model for storm water management and flood control. The effectiveness of using a simple raster GIS for the parameterization of a lumped hydrological storm water model is assessed.

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CHAPTER I: INTRODUCTION

This thesis begins by examining some of the technical issues that arise when the technology of geographic information systems (GIS) is applied to typical hydrological problem solving. An examination of the basic needs for analytical GIS methods in rainfall modeling, drainage network characterization, watershed characterization, infiltration pattern mapping and principles of runoff modeling is undertaken. A considerable proportion of the examination focuses on the preparation of hydrologically sound digital elevation models, as these form a foundation for subsequent hydrological analyses. The various methods covered by this examination are not the only methods of interest to hydrologists, but are considered to be the technological provinces in which geographic information technology might be of practical or theoretical value.

A specific application of GIS technology to hydrological modeling and the results achieved is documented. A computer program, HYDROGIS, was developed which functions as a shell for the IDRISI geographic information system. This shell is used to compile hydrological parametric data from a set of maps produced with the GIS and prepare an input file for the OTTHYMO lumped hydrological storm water runoff model. The functions of this shell program are detailed, and a case study is documented.

A summary, based on the case study, of the applicability of GIS technology to hydrological modeling, including comments on the feasibility of certain functions in a professional working environment, is provided. The case study application of the simplified shell program functions provides some evidence that GIS technology can be applied to hydrological problem solving within a predefined and limited set of problem definitions. A cursory examination of available technology provides some evidence that more complex methods may also be applied to hydrological problem solving. An important caveat is included in the conclusions: that the successful and reliable application of GIS technology to hydrological problem solving is dependent on adequate training of GIS/hydrology scientists.

In conducting typical hydrological studies, a civil engineer or hydrologist will use a wide variety of techniques involving some measures of geography. The initial steps in preparing a model of a watershed's storm water runoff patterns primarily consist of the

collection of map based information pertaining to that particular watershed. Once the appropriate geographic parameters are compiled, computerized hydrological modeling can be conducted.

Observing the detailed activities of hydrological scientists preparing a hydrological model of a particular watershed reveals that questions of "where ?", "how much ?", and "in what relationship with other locations ?" are frequently asked. Hydrological scientists typically answer these questions with precision, by measuring the parameters that they need from maps of appropriate scale, making field surveys or consulting reliable databases. Potential applications of GIS technology are found in those activities involving the compilation, storage and querying of information that can answer spatially dependent questions. There are many such potential applications to be found within the activities of a typical hydrological study.

For the purposes of this thesis, a distinction is being made between two types of geographic inquiry observed in hydrological studies. First, the parameterization of a watershed is the compilation and measurement of unique landscape components such as the distribution of varying soil infiltration rates or percentages of impervious surfaces. Maps of various themes are compiled and the amounts or areas of various landscape features are measured. These map measurements are conducted manually or with the aid of mechanical tools. Values such as percentages of impervious surface are tabulated from map observations, and lengths and areas of particular features are measured with rulers or planimeters. A watershed is said to be parametrized for a hydrological study when all the required measurements needed to describe the basic physical conditions of the watershed have been compiled and tabulated.

The second group of activities in a hydrological study that include geographic analysis is the examination of the response of a parameterized watershed model to some change in physical conditions. Today this is usually carried out with the help of a computer program that uses the parametric information compiled for the particular watershed and mathematical relationships describing the complex interactions of a drainage system, to produce a hydrograph. This is usually what is meant by the term hydrological modeling.

Potential GIS applications can be found in both types of activities: parameterization and modeling. Using GIS for parameterization would involve the replacement of

manual compilation and measurement of geographic parameters from maps of physical landscape features. A GIS software program would be used to store, manipulate and query maps and prepare tables of parametric values that could then be transferred to a hydrological modeling program. Using GIS for modeling would involve parameterization plus the calculation of complex hydrological system interactions through mathematical relationships included in the geographic information system configuration. This second, more complex type of application is not discussed at any length in this thesis. The focus is on the parameterization of watershed features.

OVERVIEW OF RESEARCH OBJECTIVES

To shift hydrological problem solving from the current praxis to GIS based methodologies will require considerable expertise in both GIS and hydrology methods. Many different GIS related techniques will be needed if the current manual geographic analyses performed by hydrologists are to be replaced by computer based methods. As GIS technology is adopted by the hydrological community, a wide variety of geographic analyses and data base structures will develop, and no one particular type of analysis will suffice for complex watershed studies. Within the wide variety of possible hydrological / geographical techniques that GIS technology may be applied to, only a very limited set of methods are studied in this thesis. One particular hydrological modeling technique has been selected (Lumped Storm water Modeling¹) and the feasibility of applying GIS technology to this technique is examined.

Objectives for applying GIS technology successfully in any working environment should include the maintenance or improvement of the current levels of accuracy and precision being achieved by manual methods, while providing benefits either in terms of methodological ease, cost effectiveness, or by the creation of by-products of additional value. The GIS methods used in this study to conduct hydrological modeling are assessed in these terms in the conclusion of this thesis.

¹ Hydrological scientists distinguish between lumped and distributed modelling approaches. This is further addressed in Chapter Two.

STATEMENT OF THE PROBLEM

To identify within the scope of lumped hydrological modeling the specific problem solving activities to which the GIS technology may be applied; to design and develop a computer program that integrates GIS and hydrological modeling; to examine and describe the methods as they are applied to the parameterization of a watershed for a lumped hydrological model; and to discuss the implications and suitability of this undertaking.

CHAPTER TWO: REVIEW OF CONCEPTS

There are several different types of computer based hydrological models. In this thesis the potential benefits of GIS technology are investigated for a particular type of hydrological model: the lumped empirical model type. This chapter begins with a discussion of hydrological modeling, taking a brief look at the hydrological cycle and its representation as a model of a cascading system. This is followed by a topic by topic review of issues pertaining to rainfall modeling, watersheds and drainage networks. The preparation of hydrologically sound digital elevation models is discussed in preparation for a review of automated watershed boundary delineation, and this is followed by a review of the calculation of the time lag between the start of a storm and the resulting peak in runoff.

HYDROLOGICAL MODELING

Hydrological modeling takes many forms. Of primary interest here are models that are used to simulate and predict the volume of storm water runoff that will be generated by a watershed in response to a rain storm. This is different from models which take specified runoff volumes and determine the elevation of peak floods within a defined stream channel. The latter models are usually referred to as hydraulic models. Distinct types of hydrological models are used to determine the storm water runoff response of a watershed to a rain event. Mathematical models are used widely in storm water runoff studies, although material models are sometimes constructed to simulate specific scenarios. Mathematical models can be characterized as either empirical models or as physical models.

A model that is empirical in character may use a limited number of mathematical relationships representing the processes of infiltration, runoff and stream flow. The ability of a simple empirical model to predict real world flows is dependent on prior knowledge of stream flows under very similar conditions to those being modeled, and on incorporated indices or dimensionless variables that can be used to calibrate the model.

A physical model is also a mathematical construct based on the relationships between infiltration, runoff and stream flow processes. However, a physical model will

incorporate very many mathematical relationships each representing our understanding of the underlying physics involved in these processes. A true physical model is considered a more accurate representation of the real world conditions than is a non-calibrated empirical model. Yet despite a better representation of the real world, physical models are difficult to implement in specific locations because of the vast amount of detailed field information required.

When either a material or mathematical model is used, and regardless of the number of physical relationships accounted for, a hydrological model must have some method of incorporating the spatial characteristics of the real world watersheds being modeled. Material models, by their very nature as three dimensional objects, incorporate real world watershed characteristics, albeit usually at a reduced scale and with different surface textures than the real world. Mathematical hydrological models, however, must in some fashion represent discrete elements of the real world watershed. Portions of the real world watershed are represented by numeric values. How a watershed is portioned for mathematical modeling falls into two classes, based on how they represent spatially significant parameters. They can be either lumped or distributed.

Without the aid of computers, performing a mathematical simulation of a watershed required the subdivision of the watershed into a relatively small number of manageable areas. Each of these unique pieces represented an area assumed to have a unique value for every parameter required by the model. Sub-watersheds are often used as convenient subdivisions, and modeling is conducted assuming that variables such as infiltration rate, slope or surface roughness are consistent throughout the sub-watershed. This type of model has come to be referred to as a lumped model, as the values for a parameter taken from a continuously varying landscape are lumped together in large reporting units.

In theory, the greater the number of geographic reporting units used to model the real world landscape, the more accurate the model will be. The limiting factors in the age before computers were probably time and cost. However, with some empirical models, there is also a logical limitation to the increase in accuracy provided by more geographical sub-units (Stephenson, 1989). With the aid of computers the need to aggregate parametric information into manageable units is not driven by the labour of calculating very many mathematical relationships. In theory, a study area may be

divided into a number of individual reporting cells limited only by computing power and disk storage capacity. A grid cell structure can be used as the parametric reporting frame. So called grid based runoff models do not lump or aggregate parametric data, but perform the full range of runoff calculations for each grid sample point. There are many differences between a lumped model and a fully distributed model, some of which will be discussed later in this chapter. At this point it is sufficient to recognize that the following discussion is intended to address the spatial information needs of empirical models, and not physical models, and that either a lumped or distributed model would benefit from the GIS technology discussed.

THE HYDROLOGICAL CYCLE AS A CASCADING SYSTEM MODEL

How an empirical model determines the storm water response of a watershed is dependent on the model's representation of the "hydrological cycle". The hydrological cycle is an explanation of the interrelationships between the various forms in which we find water in the atmosphere, on the landscape and beneath the ground. The "hydrological cycle" is described in many ways, and is quite often described as a closed system in which an unchanging number of water molecules continuously pass from one state to another. In order to study particular components of the hydrological cycle, hydrologists use theoretical paradigms in which the hydrological cycle is explained as a system of interacting components. A system is described by Chorley & Kennedy (1971) as:

a structured set of objects and/or attributes. These objects and attributes consist of components or variables (i.e., phenomena which are free (sic) to assume variable magnitudes) that exhibit discernible relationships with one another and operate together as a complex whole, according to some observed pattern.

Systems can be either isolated, exchanging no mass or energy outside the bounds of the system; closed, exchanging energy but not mass; or open, exchanging both mass and energy outside the bounds of the system. These definitions are based on functional properties of systems. Chorley & Kennedy also define systems as morphological or cascading systems, based on structural aspects of a system. A morphological system is a simple network of relationships between components. A

cascading system has a distinct path through which energy or mass flows. The cascading system paradigm is naturally well suited to hydrological studies, as even the name implies. This is the paradigm that is most commonly applied by hydrologists in computer modeling studies. In theory, all parts of hydrological cycle may be considered as flows of both energy and mass. Rainfall, surface runoff, groundwater flow and stream flows all conveniently fit into a cascading system paradigm. These flows are theoretically distinct pathways, which are more or less discrete components. However, there are components of the hydrological cycle that are not so easily distinguished as flows, and hydrologists tend to refer to these as storage components. Soil moisture, lakes and reservoirs are frequently characterized as storage components rather than as flows. Yet the functional structure of hydrological computer models still follows the cascading system paradigm. Components of the hydrological cycle that have such distinctly slow rates of flow that in practice can be considered stable reservoirs of water are still considered to have a distinct path through which mass and energy flow. The underlying rule is that water flows downhill.

Figure 1 Schematic of Hydrological Cycle as Cascading System

Figure 1 shows a schematic of the hydrological cycle as a cascading system, with rainfall as the primary input. A distinct set of pathways are shown, with system outputs in the form of evaporation, groundwater flow and river flow. This relatively simple system schematic represents a more complex system than the one usually studied by hydrologists in common storm water modeling studies. The geographic information technology that is discussed in this thesis is intended to address the information management needs of a hydrological computer model that has the following components found in the above schematic:

- precipitation
- the catchment distribution subsystem
- the surface subsystem

- overland flow and interflow combined
- base flow
- the drainage network subsystem
- stream flow

SOME BASIC TERMS:

Stream flow is the total water flowing through a defined stream channel over a specific time period, or the rate of net discharge from a channel. Significant contributions to stream flow are direct precipitation, surface runoff, subsurface flow, and ground water contributions or base flow. The changes in stream flow are most significantly affected by changes in surface runoff and subsurface interflow. The common method of displaying stream flow is a stream hydrograph showing volume over time.

Surface Runoff is that portion of the total precipitation that is not consumed by evapotranspiration, or infiltration to ground water. Surface runoff is also referred to as overland flow, which is excess water pulled across the surface by gravitational forces. Water is excess when it falls on an impervious area, saturated areas, or when the rate of rainfall exceeds the infiltration rate of soil. A significant consideration in determining the quantity of runoff from a given rain event is the allocation of fractions of precipitation to soil infiltration and to runoff. Runoff is sometimes used to refer to channel or stream flow as well as overland flow. In this thesis the term runoff will refer only to overland flow, and is distinct from stream flow.

Subsurface or Interflow is that portion of precipitation which drains through the soil and subsequently contributes through seeps and springs to stream flow and does not contribute to ground water. Interflow is distinct from ground water recharges. Streams that are fed by interflow contributions are called effluent streams. In this thesis, as in many lumped hydrological models, the general term runoff includes both surface runoff (overland flow) and subsurface runoff (interflow).

Base flow is a portion of stream flow that is present at times other than when runoff is being contributed by a storm event, and is usually added to modeling parameters as a result of field measurements during dry weather.

RAINFALL MODELING

Whether characterized as a process-response system, a cascading system or a controlled system (Chorley & Kennedy, 1971), when the hydrological cycle is described, rainfall is usually the first element to be considered.

Most common conceptual models of the hydrological cycle start with rainfall as an initial system input; one that determines the behavior of subsequent system processes. Precipitation is inherently studied in terms of events. The type of precipitation delivered to the earth surface by these events varies: drizzle, rain, sleet, snow, hail, vapour moisture. The intensity of precipitation (volume / unit time) also varies. Measurement of changes in precipitation intensity are usually a function of time within an event. The rate of rainfall is measured at time intervals and characteristic curves are draw from these time sequence data. Just as changes in rainfall intensity can vary from minute to minute within a storm event, the intensity of precipitation may also vary from place to place within the area of a storm.

The combination of moving storms that have temporal and spatial patterns makes the prediction of detailed precipitation at large scales a very complex task. Meteorologist and hydrologists find it practical to work with average statistics, rather than very detailed precipitation data. For hydrological studies, rainfall data is usually aggregated so as to represent the average precipitation intensity at time intervals within a typical storm. Time / intensity data is collected for typical storms of various magnitudes. For each of several storm magnitudes, the frequency of events within a season or year is derived from historical records.

For accurate hydrological studies at large scales (i.e., small areas), information on typical rainfall patterns in the study area is needed. This information should ideally describe not only the average rainfall over a time period, but the typical patterns of rainfall in both space and time. Data used for storm water modeling may include total rainfall volume within an event, the average rate of rainfall at time intervals during an event, or the return periods of events of specific magnitude. Some of the commonly used reference methods for characterizing rainfall data include:

- **Intensity Duration Frequency (IDF) Curves:** an IDF curve is an aggregation of historically recorded intense periods of rainfall. Several large storms that have occurred in a study area are isolated and examined. Peak recorded rainfall and associated times from the start of a storm are extracted from several storms and ranked. The result is a series of maximum rainfall rates that correspond to given times from the beginning of a synthetic storm event. Many government agencies have prepared IDF curves for local and regional areas for use in hydrological studies, and they are available as curves on a graph or as a table of step values.
- **Standard Design Storms and Hyetographs:** a "design storm" is a time series of sequential rainfall rates intended to represent either typical or large storm events. Block design storms are simplified representations of typical storms; they consist of only a few rainfall rate values, typically for the start, peak and tail end of a storm. Block diagrams assume consistent rainfall intensity over each time period represented by a rainfall value. Simple block design storms can be derived from IDF curves for storms of various duration.
- **Modified Block design storms:** a modified block storm typically uses trapezoid functions to describe the intensity curve at the head and tail of a standard block storm, thus representing the natural variation in rainfall intensity within a storm more realistically. Two widely used variations of a modified block storm are the "Chicago Storm" and the Illinois State Water Survey (ISWS) Storm .
- **Actual recorded storm rainfall values** can be used for local critical historic storms. Examples include Hurricane Hazel, which inundated parts of Southern Ontario or the July 14, 1987 storm that flooded parts of urban Montreal.

Common sources of rainfall data are either rain gauge recordings or radar images. There are inherent short comings with either data collection method: rain gauges are accurate, but only sample a narrow band of a storm as it passes the gauge, whereas radar can sample entire storm events, but is less accurate. The existing network of rain

gauge stations is widely and unevenly dispersed. The resolution of the radar systems used to monitor and forecast weather patterns can be as fine as 1 km^2 (Robinson, 1986), which is a vast improvement over the spatial resolution of a network of rain gauges.

INTERSTORM VARIATION and TIME SERIES

Storms vary in size and larger storms occur less frequently than moderately sized storms. The frequency of storm events of large and potentially destructive size is an important factor in modeling storm runoff, and synthetic or aggregated "design storm" data or actual storm records that are used for modeling are usually selected to represent a given probability of returning once within 5, 10 or 25 years. Thus a 5 year storm is a storm of such intensity that it is likely to occur only once in five years, on average. Determining what size of storm is likely to be a 5 year storm requires an appreciation of historical rainfall patterns for a study area.

While modeling the runoff response of a watershed from a single real or design storm can produce reasonable results, some critical analyses require more sophisticated handling of the sequence of multiple storm events occurring in one watershed. The effects of more than one storm occurring in a relatively short time frame may be more significant in terms of runoff response than the effects of single storms occurring in isolation. Runoff from sequential storm events may have compound effects. The antecedent moisture of soil is taken into account in some sophisticated models, and this will vary with the time between storms and the intensity of preceding storm rainfall. Hydrologists have developed computer runoff models which can accommodate multiple storm event inputs (Wisner, 1989) or simulate multiple design storm inputs using stochastic modeling techniques.

INTRASTORM SPATIAL PRECIPITATION VARIATION

The variations in rainfall intensity at different times within a storm, and changes in peak intensities from one storm to another and the likely return periods of certain storms are relatively well understood. The variation in rainfall intensity from one location to another within a storm appears to be less well known. Intrastorm variation

refers to the amount of spatial variation in rainfall rates at various locations within a storm.

A brief examination of the literature in geographic, hydrological and civil engineering journals reveals surprisingly little discussion on the spatial variation of rainfall volumes and rates within storms. This is likely due to the sampling limitations of rain gauges. A dense network of rain gauges would be required to generate accurate information on the variation of rainfall within storms. The predominant characteristic measured within a storm is the variation in rainfall rate over time as described by the measurements of single stationary rain gauges, which only monitor that part of a storm that passes over a gauging station. In many instances storms cover areas smaller than the space between gauging stations, and are not monitored. With increased use of radar to collect rainfall data, examination of the spatial variation of rainfall within a storm may soon be better understood.

GIS REPRESENTATION OF PRECIPITATION

This is one area of meteorology that GIS technology may be successfully applied, but is not the primary focus of this thesis. The following discussion of GIS representation of rainfall data is at best preliminary, and is provided as background to the more specific examination of GIS representation of other significant hydrological cycle components.

The use of the rainfall data types mentioned above has evolved out of the technological capabilities and needs of hydrologists who did not have GIS technology at hand. GIS technology offers the ability to store, manage and analyze rainfall data. Point data from rain gauges provide information only on the amount and rate of rainfall at the location of the gauge. GIS technology provides the opportunity to automate the interpolation of rainfall data between gauging stations.

The Thiessen polygon method defines areas from point locations such that the area around a point includes only those locations that are closest to that point rather than other points. This is the same as defining the geometric area of influence of each point. The method of creating Thiessen polygons is to join nearby points with non-intersecting arcs, then construct a series of perpendicular bisectors on each arc, which form the polygon boundaries (Petri, 1990). The division of a space in this fashion is

also referred to as Voronoi Tessellation (Clark, 1992). By creating Thiessen polygons around rain gauge locations, the geometric area of influence of each rain gauge can be defined. This provides a method of estimating rainfall values from known rain gauge locations for areas between rain gauges. For areas within the Thiessen polygon for a rain gauge, the rainfall rate of the station can be assumed. This also offers a means to correct for missing data at a gauge in a rain gauge network.

Figure II Delauney Triangulation and Thiessen Polygon Construction

An alternative to Thiessen polygonization is to interpolate specific rainfall values on a grid structure, or to generate contour lines from the point rainfall data. Some of the alternative grid interpolation algorithms are discussed in later sections of this thesis. However, the density of rainfall gauge locations is usually insufficient to generate reliable contours for large scale hydrological studies. Only on regional scale studies where the number of rain gauge locations is high will contouring provide suitable results. GIS technology allows the rapid and accurate calculation of rainfall values either through the creation of Thiessen polygons, interpolated grid values or contours from known rainfall values.

Some GIS packages also provide convenient data handling via attribute tables. An attribute table is a simple database in which each record is linked to a graphic entity on a map, and each field in the database represents a different attribute variable. This provides a possible method of storing and manipulating time series rainfall data. A

Theissen polygon map representing the zone of influence of each rain gauge may be linked to a table with different attribute fields for the different time units being studied. In this fashion, the polygon map may be reclassified to represent data values in any of the time steps in the attribute table, or any combination of values. Similarly, the attribute fields may represent the different time steps used in defining a design storm.

It is also possible with some GIS packages to have multiple attribute tables related to a single map, and perform operations on the data. This may be of advantage in arranging multiple storm simulations from point rain gauge data where the interpolation of rainfall rates or volumes to full surfaces is desirable. In effect, a series of rainfall density maps can be created by assigning values from different attribute fields within the database.

An additional functional capability of a GIS would be the simulation of storm travel across a watershed. With control over the geographic referencing of rainfall data, a map of rainfall rate can be shifted in x,y coordinates to simulate the travel of a storm through a study area. This would provide a means of comparing the effects of rainfall distribution from storms passing in different directions and at different speeds through a watershed.

RAINFALL LOSS: EVAPOTRANSPIRATION AND INFILTRATION

EVAPOTRANSPIRATION

Evapotranspiration and infiltration account for a very large proportion of the total rainfall inputs to a hydrological system. Evapotranspiration alone can account for greater than 90% of total precipitation. Water vapour evaporates or is transpired from plants and soil, and urban surfaces, into the atmosphere. In sophisticated hydrological modeling, evaporation and transpiration rates are accounted for. The rates of evaporation and transpiration are a function of local air pressure potential (primarily the influence of wind, which is usually neglected), thermal potential and matric (capillary attraction) potential. Potential evapotranspiration estimates for a watershed

rely on water budget analyses, paired watershed comparisons or temperature and radiation data.

A water budget method can be conducted rationally, accounting for 100% of the rainfall measured by subtracting the runoff and infiltration rates observed to derive the evapotranspiration proportion. Rational water budget studies indicate that there is often a wide variation in evapotranspiration values due to differences in vegetation type and changes in climatic conditions. Alternatively, a more physical approach can be used in which detailed measurements of vegetation type, antecedent moisture and thermal conditions are calibrated for a given area and used to predict evapotranspiration conditions under changing environmental conditions.

GIS REPRESENTATION OF EVAPOTRANSPIRATION

In detailed hydrological models, particularly physical type mathematical models, satellite and remotely sensed images are used to provide raster based data on vegetation class, moisture conditions and solar radiation values for evapotranspiration subsystem modeling. In less complicated modeling, infiltration parameters are adjusted to account for evapotranspiration.

INFILTRATION

Infiltration is the flow of water from the ground surface into the soil column. These flows can eventually become either groundwater or subsurface interflow. Precipitation that exceeds the maximum infiltration rate of the soil, or falls after the soil has reached saturation, puddles and forms surface flows.

Soil type and vegetation have the greatest influence on the rate of infiltration, but other factors include surface slope and antecedent moisture conditions. The initial infiltration response of soil depends on the initial water storage capacity of the soil when it is dry, and the infiltration rate varies as the soil reaches saturation. Infiltration rates also vary depending on the percentage of the soil that is covered with impervious surfaces. In urban areas this leads to a significant reduction in infiltration relative to the same soils in a rural landscape.

Infiltration curves are methods of recording the rate at which water penetrates a soil column, and standard infiltration curves have been developed for many soil types under many conditions. "SCS Curve Numbers" are standardized infiltration rate curves developed by the U.S. Soil Conservation Service, which has a widely used method for determining and recording soil infiltration under various conditions. Soils are classified into seven types ranging from poor drainage characteristics to very rapid drainage characteristics. For each soil drainage type, there may be many representative infiltration curves depending on surface conditions. Many hydrologists use the SCS Curve Number method of calculating the rainfall losses due to infiltration. In practice, matrix tables listing combinations of soil type and land use cover indicate which SCS curve best represents the average infiltration characteristics. Curve Numbers have been identified for a great many soil type and land use combinations, and lookup tables are common in hydrology text books.

Slope also has some effect on infiltration, with the amount of infiltration declining as slope increases.

GIS REPRESENTATION OF INFILTRATION

In modeling runoff using less sophisticated models, the net loss from evapotranspiration and infiltration are calculated using the SCS curve number as an input parameter. SCS curve numbers are usually assigned to a specific combination of land use and soil type. In subsequent sections of this thesis, a matrix listing the soil type/land use combinations and curve numbers is provided. In parameterizing a watershed for modeling, the SCS curve number of each sub-drainage area is usually required. To achieve this with the aid of GIS technology, maps of land use and soil drainage type can be combined to form a map of SCS curve number values through a process known as an indexed overlay. The representation of soil and landscape polygons is relatively straight forward and poses no special GIS technology related problems.

Slope and the function of slope relative to infiltration rates is a more complex GIS problem. Infiltration rates cannot be adequately calculated without accounting for variations in slope within a watershed. To calculate slope values using a GIS, a digital elevation model is required. This is a more complex GIS undertaking, and is dealt with in more detail later in this thesis.

DRAINAGE NETWORKS, DATA STRUCTURES AND MEASUREMENTS

Hydrologists study the flow of water through a stream and river system, and evaluate flow characteristics under different drainage system configurations and rainfall inputs. A primary tool for evaluating a stream and river system is a classification of the pattern of the streams and rivers comprising the drainage system.

A drainage network is a series of connected streams, channels or rivers which conduct concentrated runoff and interflow to a particular point. Conceptually, a drainage network must have a lowest point, sometimes referred to as the gauging station, the mouth of the network or the pour point. While many rivers and streams are ultimately connected in some fashion to seas and oceans, for study purposes hydrologists describe limited drainage networks in terms of a selected lowest point, and the upstream area flowing to that point. In most cases the lowest point of a defined drainage network is a point where water flows into another river system or drainage pattern. Where the lowest point of a drainage network leads into another drainage network, the point can be referred to as a pour point.

In some instances, a drainage network does not have a pour point to a lower elevation. A drainage pattern of this type might be referred to as a storage system, distinct from a drainage network. A small stream network draining into a lake that has no apparent outlet may be considered a storage system rather than a drainage system.

STREAM HIERARCHIES AND ORDERING

Drainage networks and the stream segments comprising the drainage network vary in size and number. In order to relate characteristic processes within drainage networks to the size and number of reaches, hierarchical segment numbering systems are used. Widely used systems have been developed by Horton in 1945, Strahler in 1952, Shreve in 1957 and Scheidegger in 1965 (Gregory and Walling, 1973). In either of the ordering schema, the small headwater streams are considered first order streams and attributed with a low identification number. Where small upstream reaches combine to

To encode Shreve ordering values in a GIS, arcs must be individually digitized or derived automatically for each stream segment, and attributed with the appropriate integer value for position in the hierarchical ordering system. With arc data the two dimensional pattern of a drainage network in space can be represented and displayed. Simple analysis can also be conducted with ordered arc segments.

An alternative data structure may be based on the nodes joining the drainage network arcs. A node based data structure for Shreve ordering would require attributing each node with the sum of the values attributed to the two closest upstream nodes. With a node based structure the relative magnitude of flow expected at each node is represented by the node ordering.

A third data structure combining both arcs and nodes might be considered, as this may offer a method of encoding not only the relative magnitude of expected flow from one stream segment to another or one node to another, but also the variation of expected flows within one stream segment between two nodes.

STREAM LENGTH

Stream length is a fundamental measurement used for a variety of drainage analyses, as is overall watershed length. However, stream length is rarely the same as the watershed length, and may not be the same as the length of the valley through which a stream meanders (Gregory and Walling, 1973). With an arc-node data structure for representing the drainage network in a watershed, each stream segment may be represented by a single arc with a Shreve ordering value. If that stream segment meanders at all from the straight line of the arc, the length of that stream segment is under estimated in the data structure.

Alternatively, a sinuous stream segment may be represented by a series of arc-nodes which together form a line data structure. Thus a sinuous stream segment may have one Shreve ordering value and many straight arcs which follow the drainage network more closely. In practice the digitizing of all the watershed stream segments using digitizer "stream mode" will result in multiple-arc lines. By following this approach the under-estimation of stream length will be consistent throughout the watershed and will not be a function of the irregular shapes of individual stream segments.

WATERSHEDS, DATA STRUCTURES AND MEASUREMENTS

A simple definition of a watershed is the unique area delineated by a line of maximum elevation between one drainage network and adjacent drainage networks. A landscape with several distinct drainage networks may be divided into unique watersheds by tracing along the highest elevations found between adjacent drainage networks. This is the definition most commonly used in hydrological studies, as it is relatively simple to work with.

The common method of delineating a watershed boundary is to interpret contours on a topographic map manually, tracing the watershed "divide" or "water parting". With the introduction of automated watershed delineation algorithms in GIS software, the traditional definition of a watershed needs to be changed to reflect the approach taken by GIS algorithms. A new definition of a watershed should be all locations which would contribute overland runoff flows to a defined drainage network, not just the area contained by the watershed "divide". In other words, areas which have runoff of excessive surface water and contribute via overland flow and channel flow to the net flow reaching a particular point are part of a watershed. Conceptually a watershed must have a lowest point, which by definition must be the same point as the lowest point in the drainage network.

If a basin does not have a pour point to a lower elevation, the basin can be referred to as a storage basin, distinct from a watershed. These sorts of closed storage basins are also referred to as depressions or pits (Jenson, 1987), and as can significantly effect the characteristics of storm runoff in a study area.

If the area of a watershed includes all locations where typical surface water runoff would result in surface flow which would eventually pass the pour point of the basin, there can conceivably be locations which because of local topography, will not contribute flow to the drainage network. These non-contributing areas may be depressions, pits, or dam formations that stop overland flow. There may also be artificially created non-contributing areas, if, for example, storm sewers route flow from part of one watershed into another watershed. In either case, the area defined by the old definition based on delineating the divide may encompass non-contributing

areas within it. By the new definition, these non-contributing areas are not part of the defined watershed. At the risk of confounding the above definition, every location on the earth surface has a corresponding watershed or storage basin. What distinguishes one basin from another is the delineation of the drainage network, and there can be countless delineations of a drainage network for a given landscape. Thus there can be countless watershed delineations for a given landscape.

Watersheds are typically areas that are believed to be drained by large streams or rivers, and are typically composed of several smaller watersheds. The task for a hydrologist studying a watershed is to delineate the watersheds within the watershed for detailed analysis. As the possible delineations of a drainage network / basin allows for a great number of possible watershed arrangements within a watershed, a hydrologist must make meaningful judgments as to which points within the watershed will be used as pour points to define drainage networks / watersheds.

Figure IV Watershed Delineation

WATERSHEDS DEFINED BY STREAM ORDER

By adopting the method of identifying watersheds by the drainage network, watersheds can be ranked in the same fashion used for the stream network ordering (Marsh, 1991), where first order watersheds are drained by first order streams, second order watersheds by second order streams, and so on. It is important to note that just as higher order streams are a combination of upstream lower order streams, so too are higher order watersheds a combination of lower order watersheds. Marsh (1991) refers to this as the *nested hierarchy* of watersheds.

Jenson (1987) makes a distinction between a watershed and a drainage polygon. A watershed, may include several lower order sub-watersheds, and mapping both the higher order and lower order watersheds results in the overlapping areas that Marsh referred to. A drainage polygon is defined by Jenson as including the area drained by one watershed but excluding the areas of other upstream sub-watersheds. Thus drainage polygons do not overlap but watersheds do.

However, the different types of flows within a watershed may include surface runoff, interflow, base flow and a variety of routing possibilities. Discrepancies between the location of the topographic divide which is based on a surface digital elevation model, and the phreatic divide based on groundwater flow patterns and subsurface structures should be expected. Unless extraordinary measures are taken, such as the preparation and analysis of a digital elevation model of the watershed, the area of a watershed usually includes only those areas defined by potentially contributing *surface flows*.

MEASUREMENTS

Watershed length is a measurement that is used in a number of runoff calculations, including time lags to peak floods. While drainage network length is best measured by multiple arcs approaching the truly curving stream path, basin length is usually measured in a single straight line, from the pour point of the basin to a point somewhere at the divide of the basin. Various methods have been employed to determine where to appropriately measure watershed length, including a line parallel to the main channel of the drainage network, a line describing the greatest basin

diameter from mouth to the divide, and other methods using the basin's center of gravity (Gregory and Walling, 1973).

The area of a watershed influences the rate and volume of runoff from a watershed, and must be delimited with precision. Manual methods of determining the area of irregularly shaped watersheds include overlaying grid paper and counting squares, using mechanical planimeters or cutting out the basin area on high quality paper and weighing the paper (Gregory and Walling, 1973). Reporting the area using GIS is a simple procedure once the watershed has been delineated. Most GIS packages offer a simple area analysis function that can calculate the area of each sub-watershed defined in the database.

DIGITAL ELEVATION MODEL STRUCTURES AND PREPARATION

Digital elevation models (DEM's) are also known as digital terrain models (DTM's). While the terms are interchangeable, digital elevation model is preferred by some because terrain model implies more than the representation of elevation data (Burrough, 1986). Others seem to make a distinction between DEM's and DTM's based on the data structure of the model (Ministry of Natural Resources GIS Conference, 1992, conversation with delegates). This distinction is misleading. A digital elevation model should be defined as any digital representation of a topographic surface. Carter (1988) states that a DEM is an inferred mathematically continuous surface that can be represented by grid matrices of elevations, series of parallel profiles, digitized contours or triangulated irregular networks.

The computer representation is usually derived from discrete data such as contours or spot heights, but the surface that is represented is considered to be a continuous phenomenon. Thus a DEM is usually a continuous model of discrete data, and this distinguishes DEM's from other thematic spatial information (Jenson and Trautwein, 1987) and from classified remote sensing imagery.

Some of the possible applications of digital elevation models as listed by Burroughs (1986) are:

- storage of elevation data for national topographic mapping
- three dimensional visual displays for landscape planning and military purposes
- as a backdrop for displays of soil or vegetation maps, or remotely sensed images
- visibility studies for environmental impact assessment
- slope, aspect and statistical analysis for geological (and hydrogeological) studies
- transportation route planning, cut and fill and other engineering studies

In studies of physical geography, terrain features are of primary importance. Terrain information is common in most geological, hydrogeological and civil engineering studies. As familiarity with digital elevation modeling increases, the DEM may become a "base currency" or common element found in most physical geography data sets.

While DEM processing was once the province of mainframe programs and specialized engineering applications, many workstation and personal computer based commercial GIS packages are now capable of preparing DEM's and by-products such as slope and aspect maps. Among the better known commercial GIS packages incorporating some form of DEM specific functions are ArcInfo, Spans, Intergraph, and Pamap (Ministry of Natural Resources GIS Conference, 1992, observation), and probably many more.

Many specialized civil engineering programs for DEM production have been available for some time. Among those listed by Kennie (1990) are: GHOST, SURFACE II, GINOSURF, GPCP (General Purpose Contouring Package), SACM (Surface Approximation and Contouring Mapping), HIFI (Height Interpolation by Finite Elements), CIP (Contour Interpolation Program), Wild System 9-DEM, Intergraph DEM, MOSS surveying system, AXIS surface modeling system, and PANTERRA (now integrated into PANACEA). A program called SURFER is also widely available for the personal computer.

These engineering and geographic information systems offer a variety of data structures for the storage, analysis and retrieval of spatially referenced information. Digital elevation models have specific requirements that limit the types of data structures that are used to represent elevation at referenced locations. The principal

determinant of the potential data structures is the assumption that the surface to be represented is a continuous phenomenon, with high spatial variability, rather than discrete phenomena.

Despite the variety of data structures that might be used to handle digital elevation data and modeling, there are two dominant data models being used: a regular grid raster and a triangulated irregular network (Petrie, 1990). It should be noted that some geographic information systems use one type of data structure for data storage and analysis, and another for graphic display. This reflects the limitations of common display devices to display subtle color or tonal differences. Other less common data handling structures include rectangular grids and hexagonal grids and the once dominant polynomial data surface representation. These other representations appear to have many short comings either in representing the topographic surface accurately, or integrating the data with other digital data sets in an information system.

Many geographic information systems have initially been designed to facilitate thematic mapping. With thematic mapping of discrete phenomena, polygon data structures consist of individual polygons that represent areas within which the feature of interest is considered continuous and uniform. Areas outside the feature polygon are considered as not having that feature present, and can be represented in a Boolean or binary fashion. This condition does not occur with elevation, which is assumed to be a continuously varying surface. Thus a polygon data structure has theoretical limitations to representing elevation. Despite this limitation, the polygon structure is often used to display topographical data on a monitor that has a limited color palette.

REGULAR GRID RASTER

The regular grid raster data structure is perhaps the simplest and most common GIS data structure. Regular grid rasters are sequential stored attribute data that are assumed to represent regularly spaced points on a planar surface. Each datum is assumed to represent the average value of an attribute spanning a square or rectangular area called a cell. All cells in a raster have the same dimensions, and cells are arranged in a consistent number of rows and columns. The cells may be displayed as individual screen pixels (picture elements) or as large rectangular graphic elements. The raster data structure is commonly used to store remotely sensed images and scanned images. The advantages of a raster are derived from its relatively simple

structure. Geographic coordinates are required only for the origin of the array of cells, along with the cell dimensions and number of rows and columns in the raster. Because of the simple structure, performing functions such as filtering attribute values or overlaying one raster with another are relatively easy.

The primary shortcoming of the regular grid is that the pattern of the data points in the grid is not related to patterns in the terrain. Consequently, to portray terrain features, which are usually irregularly shaped phenomena, the density of the grid sample data must be high enough to capture the most subtle characteristics of the phenomena being represented. This will often result in redundant and unnecessary data points where there is little variation in the phenomena being studied. Thus the regular grid raster suffers either from an excessive data overhead problem or a degree of abstraction from the field sample data. Figure V shows a regular grid raster.

Figure V Regular Grid Raster

IRREGULAR RASTER

A hybrid form of grid data structure is the quadratic or quadtree structure. This structure represents unique areas by repeatedly subdividing the study area into quadrants, further subdividing where the boundary of an area bisects a quadrant. The resulting representation of an area may include several square cells of differing dimension. The quadtree structure offers some advantages over the regular grid raster. Most significantly, the resolution of the grid cells can vary (by multiple powers

of 2) to provide more resolution where required, and less resolution when not required. As many as 15 quadtree levels may be used within one raster image in the Spans GIS package, thus providing a range of relative cell sizes from 1 to 2^{-14} . The direct advantage of this variable resolution is in data storage and handling. To represent data with a specified resolution, the regular grid structure must have all cells at that desired resolution, whereas the irregular quadtree may be able to represent some areas with larger cells, using the finest cells only where required. Advantages are reduced storage requirements and increased processing speeds. The magnitudes of these gains are a function of the variability within the data being represented. A continuously varying surface may require representation using the finest quadtree level throughout, thus missing out on any advantages. With a surface that is not continuously varying, the quadtree structure can be advantageous. Figure VI shows an irregular grid raster.

Figure VI Irregular Grid Raster Quadtree

PROFILE AND CONTOUR VECTORS

The continually varying surface can also be represented by various isoline methods. Contour lines are familiar representations of surface elevation. Contours can be obtained from existing contour maps, or they can be constructed from point data. Methods used to construct contours from data points can affect the accuracy and visual appeal of resultant contours (Lowden, 1984). A method of generating a set of contours via computer program developed by Lowden first constructs a DEM via

triangulation and interpolation, then draws smoothed lines at specified elevations. Figure VII shows a contour representation of point data.

Figure VII Contour Representation

TRIANGULATED IRREGULAR NETWORKS

The triangulated irregular network (TIN) is a slightly different method of constructing a digital elevation model. A TIN is not a common final product of GIS software functions, as most systems display and analyze data in either a raster or irregular polygon structure. It is not common as a primary data structure. However, this data structure is often generated as an intermediate function when interpolating areas from point data. The TIN has some unique properties that are useful in digital elevation modeling, and these properties may attract more attention to the TIN as a primary data structure.

A triangulated irregular network consists of number of triangles whose vertices are original data points. There are a number of methods of determining the triangular tessellation. Older triangulation methods would produce different results depending upon at which data point the triangulation started, while newer algorithms produce the same unique results regardless of the starting point of triangulation (Rencz et al., 1991). The Delauney triangulation method is currently the preferred method of triangulation. The TIN has two distinct advantages over rectangular grid and irregular polygon structure:

- preservation of original values at data points

- variation of triangle size, shape and density in relation to the data density and distribution pattern.

The most important property of the TIN is the preservation of both the value and location of original data points at the triangle vertices. With other structures this is not necessarily the case. The second property, of varying the size of the basic data structure element, in this case the triangle, in relation to the number of original data points, is advantageous from two points of view. Firstly, data storage can be better than regular grid methods, as can speed of calculation. In a TIN the number of triangles is approximately twice the number of original data points, while the storage requirements of a TIN are approximately three times that of the original data (Smith and Smart, 1990). Secondly, a regular grid raster requires interpolation to assign values to cells located between data points, and depending on the interpolation routine, the accuracy of the assigned value may decline rapidly with distance from the original data points. Despite the potential error in grid interpolation, a raster image shows individual data values between original data points, implying accuracy where it may not be. With a triangulated irregular network, the spaces between data points is represented by a triangular facet, which does not imply more information than is provided by the original data. TIN's can be generated from point data rather easily. It is also possible to produce TIN's from contours, although doing so would require additional processing of contours, converting them to points and reducing the number of points to only those points of importance. Figure VIII shows a triangulated irregular network.

Figure VIII Triangulated Irregular Network

INTERPOLATION METHODS

Interpolation is an essential function in generating a DEM whenever the field sampling data is in a form other than the desired GIS data structure. It is most often the case that irregularly distributed sample data points are available, such as a set of spot heights or a series of contours, which have been selectively chosen to reflect terrain features of interest. This type of field sampling is referred to as progressive sampling (Petrie, 1990). The density of sampling is varied to match the amount of variation in the terrain. For example, contour density increases where slope is greater, or the number and positioning of spot heights selected by a survey team is based on the particular features that they are interested in. In such cases where the irregularly distributed data must be converted to a regular grid structure, an irregular grid structure, or contour lines to meet the needs of the GIS being used, the conversion must be accomplished through a process of interpolation.

The methods of data interpolation used to form a regular grid from point data fall into three basic types (Petrie, 1990):

- point methods which determine the value of each resultant grid point independently. For each grid cell being produced, the values of the irregularly distributed data points within a search radius are examined, and some form of inverse relationship between height and distance is used to assign a weighted average to the grid cell. This is conducted for every cell required and the resultant grid surface is a continuous surface.
- global methods of interpolation are complex, and involve the generation of an intermediate three dimensional surface passing through every point in the irregularly distributed sample data, and then obtaining each regular grid value from the three-dimensional surface. The intermediate surface is represented by high-order polynomials, which may lead to calculation problems with large sample data sets.

- Patch methods are a compromise between point and global methods. Small subsets of the sample data are interpolated using the global polynomial representation, and then recombined to form the resultant full grid coverage desired.

In addition to these interpolation methods, the use of a TIN as an intermediate step in interpolation can produce usable results. After building a triangulated irregular network from data points, the TIN is sampled at regular grid intervals and the "interpolated" value is derived from the geometric facet of the triangle found at each sample point. This method is widely used in GIS packages, but is not always made apparent to the GIS user. A point to grid interpolation using a TIN may not save or display the TIN used, and the user will not have access to the TIN for subsequent analyses such as slope and aspect mapping.

Interpolation might be undertaken at several stages of a project. In generating a DEM in the data storage structure that is required for subsequent analysis with other data sets, a number of interpolations may occur in the transition from raw field data to final DEM. Understanding and controlling these interpolations is essential to building an accurate and useful DEM. Significant error in DEM interpolation may occur by using a data source that is itself the product of interpolation without accounting for potential error accumulation. Equally significant errors may arise by using a data source that is inappropriate for the uses to which the resultant DEM will be put. Details on the appropriateness of DEM's made for various hydrological purposes follow. In general, the ability of a source data structure to represent accurately the feature of a landscape that will be analyzed subsequently should be evaluated prior to using any digital elevation data or interpolating data. The scale, resolution, distribution framework of sampling points and original data acquisition methods should be considered.

CHAPTER THREE: SPECIAL GIS ISSUES IN HYDROLOGICAL APPLICATION

SPECIAL DIGITAL ELEVATION MODEL REQUISITES FOR HYDROLOGICAL ANALYSES

As alluded to in the previous section, digital elevation models prepared for hydrological purposes must be generated from appropriate data and with appropriate methods. The application-specific requirements that hydrological analyses place on the construction of digital elevation models arise out of the need to construct models of the landscape that would result in runoff patterns similar to the runoff patterns in the real world landscape. A digital elevation model that successfully reproduces real world surface flow patterns is referred to as a hydrologically sound DEM. The following points expand on the concept of a hydrologically sound DEM:

- it must preserve the integrity of surface drainage characteristics found in the real world.
- the direction and magnitude of surface slope in each cell of a DEM must be representative of the actual direction and magnitude of surface slope at the equivalent real world location.

Natural landscapes are very complex structures with a variety of surface forms. Nine basic slope geometries for representing topography have been defined which consist of either straight, convex or concave elements for the vertical and horizontal directions (Ruhe, 1975). The variety of combinations of these geometries results in a number of different drainage patterns. To have these drainage patterns represented properly in a digital elevation model, the geometry of the real world situation must at least be represented in a way that does not change the general pattern in which water would flow across the surface of the landscape.

One definition of a hydrologically sound digital elevation model is used by Jenson (1987), who has developed a method of preparing a regular grid based digital elevation model for hydrological purposes. Jenson describes a hydrologically sound DEM as one in which every cell in the model shares a "monotonically decreasing pathway

leading to the edge of the study area". A monotonically decreasing pathway is a continuous series of adjacent cells that, when followed, decrease or do not change in value, and do not increase in value. A digital elevation model that meets this criteria will be a depressionless model, having no artificial pits or depressions that would prevent water from draining down the model.

Jenson uses a series of operations on a digital elevation model to remove any "hydrologically significant potholes", resulting in one version of a hydrologically sound model. The operations used by Jenson are describe later. Typically a landscape drainage pattern that exhibits the quality of drainage that Jenson is attempting to simulate is referred to as an "integrated" drainage pattern (Way, 1968). There are several possible integrated drainage pattern type identified by Mitchell (1991): Dendritic; Rectangular; Trellis; Parallel; Braided; Radial; Pintail and Annular. Each of these types is characteristic of certain underlying geologic conditions. They all share the characteristic of drainage down to higher order streams and eventually draining out of the basin in which they are defined.

Pits and depressions are natural and common elements of many landscape forms. Pits and depressions may often be found in a type of drainage pattern referred to by Way (1968) as "non-integrated". Figure IX shows four possible non-integrating drainage patterns which have naturally occurring hydrologically significant pits and depressions.

DERANGED: with many ponds, bogs of lakes. Indicates flat terrain.

CENTRIPETAL: a radial pattern towards a central point, usually a sink or syncline

INTERNAL: Indicates highly porous material or karst conditions

DISLOCATED: due to interruptions of drainage lines by faults or extrusions

Figure IX Various Non-Integrated Drainage Patterns, after Mitchell (1991)

The possibility of having landscape features that do not have monotonically decreasing pathways to the edge of the study area raises the question of whether the definition of hydrologically sound DEM's used by Jenson actually represents the real world. Pits and depressions do occur in natural landscapes, and are not necessarily erroneous in a DEM. Conversely, depressions can occur as an artifact in a DEM where the real world landscape is drained by an integrated network that has no depressions. Thus, a

hydrologically sound DEM should have a monotonically decreasing pathway for each cell except those in legitimate depressions.

Depressions in a DEM that should not be there are very problematic for hydrological analyses, particularly for algorithms that delineate drainage patterns or watershed boundaries. GIS software that delineate watershed boundaries commonly use an iterating growth algorithm that works it's way up a model landscape cell by cell, seeking the point where the landscape turns back downhill, presumably into another watershed. These algorithms can be thwarted by erroneous depressions. If a depression exists in a model somewhere along what should be a stream channel, where it really does not belong, the rim of the depression will function as a dam, incorrectly crossing the stream channel. Artificial dams may occur in a DEM for a number of reasons:

- as a result of too large a cell resolution. A raster representation of elevation data may have been made with a large cell size. The size of a cell may be greater than the width of a natural stream channel. If the cell representing the location where the stream channel should be is an average of several surrounding data points, it will not represent the elevation down in the stream channel. Thus the natural channel may, in cases where a stream channel narrows to less than the resolution of the grid cell, be blocked in the DEM by a dam.
- The interpolation routine used to prepare the DEM from original data creates artificially high or low values between data points. This is of particular concern where polynomial interpolations are used.
- The elevation of a stream channel in a drainage network was not explicitly included in the original elevation data set, and cannot therefore, be represented in the DEM.

It is not unusual to find errors due to interpolation in digital elevation models of areas of low relief. Where relief is low, the number of spot heights or contours in source data is correspondingly low. This can lead to a condition in which the variation in the representation of two adjacent areas (the signal) is less than the potential error introduced by interpolation and data handling (the noise). A low "signal to noise

ratio" in a digital elevation model can produce undesirable conditions. Interpolation routines are forced to span large areas between sparse data points, and some routines may result in the creation of artificial ridges. This is the case with the Intercon module of the IDRISI GIS:

"where very irregular shallow contours are encountered, it is possible for the interpolated value to oscillate sharply (although still within one contour interval)" (Eastman, 1992).

Units within a data structure used to represent the surface land forms vary in their ability to describe the actual direction and magnitude of surface slope at all points on the surface. Consider the difference between the geometric form that can be defined by four points (corners of a grid cell) as opposed to a triangle. The triangular facets of a TIN are better able to define simple slope magnitude and direction than the more complex three dimensional geometry of a four cornered facet. Add to this the property of a triangulated regular network of having preserved the original data values and it appears as though the TIN is a preferred structure for building hydrologically sound DEM's. The first two potential sources of artificial dams do not occur in a TIN structure, i.e., having too large a cell size and having interpolation error.

Only the third potential source of artificial dams is common to all DEM's, i.e., the lack of sufficient original data to describe drainage patterns with enough detail to be hydrologically sound. This is a crucial factor in building DEM's for storm water studies, and the following section describes a method of adding sufficient data to make adequate models.

BREAKLINES

It may be the case that data sampling is conducted following a regular grid pattern, in which case the sample data and the computer grid data represent the same points in space. It is not unusual, however, for benchmarks and easily surveyed locations to be used for elevation points. However, it is possible during a digital field survey to collect additional important points to better represent such features as peaks, pits, ridges, streams, or man made features such as road edges or drainage ditches. Particular emphasis in surveying may be placed on natural or artificial breaklines found in the terrain. Thus when the digital elevation model is constructed from field data, the

density of data points is higher where needed most. The addition of higher density data points where breaks in the natural terrain occur is referred to as adding breakline data.

Using a DEM constructed without breaklines resulted in very much lower contour quality in ravines than with breaklines (Smith and Smart, 1990). Without breaklines, DEM's represent sharp elevation breaking features such as streams poorly (Smith and Smart, 1990). Similarly, shorelines can be incorrectly represented on a DEM if breaklines are not used. If a DEM is interpolated from elevation data that does not explicitly position the shoreline of a lake, a contour traced at the lakes elevation may vary from the coordinate location of the true shoreline. Conversely, the elevation found on a DEM at the location of a shoreline may be, as a result of interpolation, higher or lower than the water level, resulting in obvious errors. A DEM that does not include breakline information will usually produce a smoothed surface at points where a true break should be found. While the role of breaklines in civil engineering projects is apparent, where man-made features such as road surfaces need to be modeled into the DEM, the role of breaklines in hydrologically sound digital elevation models receives less attention. This should not be the case.

The addition of subjectively placed additional elevation data is the key to producing better hydrologically sound DEM's. In order to address the third potential cause of artificial dams listed previously, either excessively dense regular grid data measurements need to be taken in the field, or additional points need to be added where appropriate. The most appropriate landscape feature to represent with additional data points is the bottom of any discernible stream channel. By placing additional elevation points along the bottom of stream channels, a DEM can be constructed that will be relatively free of inappropriate pits and dams, without compromising appropriate pits and depressions. Additionally Smith and Smart (1990), have shown that inserting additional shoreline data points into the raw elevation data file created a better DEM.

DEM WITHOUT PSEUDO-BREAKLINES

Idrisi

DEM WITH PSEUDO-BREAKLINES

1
2
3
4
5

Idrisi

PEAK AND DEPRESSION MANIPULATION

As indicated previously, Jenson (1987, 1988) has outlined a series of steps designed to remove pits and depressions from a grid based digital elevation model. Surface depression analysis can be useful in removing pits and depressions when it is known that they should not be present in a DEM. Where a DEM should have pits and depressions, analysis can derive factors such as their storage volume. Depressions also have a direct landscape form counterpart in peaks, and manipulation and analysis of peaks can be done with algorithms designed for studying pits and depressions. By inverting an elevation data set pits become peaks (Jenson, 1987).

Jenson's method begins with identifying the location of all depressions within a DEM. The procedure starts with the cells at the data set edges, then examines all neighboring cells and marks all cells that have higher value than the edge cells. This procedure is continued until no more cells of higher value are found. Some cells will remain unmarked, as they do not have a monotonically decreasing pathway to the study area boundary. Grouping all unmarked cells produces a map of depression locations. Next, a cell within each depression is selected and through recursive neighbor analysis, a set of cells that show the boundary and area of each depression is created. These cells can then be assigned the elevation value of the pit perimeter. i.e., raise the elevation value of the cells within the pit to the same as the lowest pour point or rim of the pit (Jenson, 1987). Once a DEM has had depressions filled, by subtracting the original DEM from the new monotonically decreasing DEM, a map showing each depression's depth, cell by cell is made (Jenson, 1987). Summing the groups of residual depression depths and multiplying by the horizontal map units provides a measure of each depression's storage volume.

TESTING THE ACCURACY OF DIGITAL ELEVATION MODELS

As the surface represented by a DEM is continuous, verification of all of a DEM would be very difficult. This would require a benchmark DEM of higher accuracy and at the same or better resolution (Ostrowski, Wasson, Horler (in-press)). It is possible to test a representative sample of locations, comparing known ground elevations with DEM values. Comparisons of several points distributed in a stratified random manner

can give an overall estimation of the DEM accuracy, but is not a test for obvious errors at specific locations. This is better accomplished by visual inspection (Ostrowski, Wasson, Horler (in-press)). The use of interpolations from contours as control points has been suggested to increase the number of control points available (Ostrowski, Wasson, Horler (in-press)), but this is not advisable. Interpolated control points are a secondary data source and not as reliable as primary point or contour data.

An example of digital elevation model accuracy testing is provided in the IDRISI GIS software manual (Eastman, 1992). In the example, elevation contours with ten foot intervals were digitized from 1:24 000 USGS topographic maps, and these were used to create a digital elevation model through the Intercon interpolation routine. Sixty random points were selected within the study area, and the values in the digital elevation model were compared to corresponding elevations visually interpolated from the original contours. The root mean square error of 0.0228 feet was not significantly different from 0 ($t=0.901$, $p<0.001$), and the standard deviation was 1.83 feet. This example demonstrates a common test of digital elevation model accuracy, but does not test the integrity of the surface with respect to drainage characteristics. After completing the preparation of hydrologically sound models following Jenison's method, the best available check of accuracy with respect to hydrological soundness would be visual inspection and comparison to source material or, ideally, the real world landscape.

Carter (1990) undertook a study of U.S.G.S. digital elevation models, and identifies "blunders" as major errors exceeding reasonable limits. For example, DEM elevation must be consistent with contours and with shoreline and water body elevations. Some error can occur where contour data is obtained by scanning topographic maps. In the scanned image, resolution may be insufficient for closely spaced contours in very steep areas to be differentiated. Other error may be introduced to a DEM generated from remotely sensed stereo image pairs (Carter, 1989).

WATERSHED DELINEATION

Watershed boundaries are usually derived by manually interpreting contour lines on a topographic map, and drawing a line where the divide between one watershed and another is thought to be. Delineating the extent of a watershed automatically from a digital elevation model is a different process and is likely to produce results differing from manual watershed delineation, for a number of reasons. The manual method uses visual interpolation from contours, imparting available expertise and knowledge of drainage network forming processes. With manual methods, exact replication of watershed boundaries delineated by different experts is not likely to be achieved. Each manual delineation of a watershed will be slightly different. With automated watershed delineation, the same results can be achieved each time a watershed is delineated, assuming that the underlying digital elevation model and the starting points for the watershed algorithm are the same.

The watershed delineation algorithm used in this study is based on the grid raster structure, and operates on a derivative of the DEM that represents aspect (direction of greatest downward slope), which is usually expressed in degrees from 0 to 360. It is recommended that the DEM being used first be prepared to represent hydrological characteristics. If the DEM is hydrologically sound, the watershed routine can determine areas that will contribute overland flow to a specified starting cell or cells.

The watershed algorithm requires as input an aspect map derived from a digital elevation model and a point, line or area defining the lowest part of the watershed to be defined. The point, line or area corresponds to the drainage outlet of the watershed, and is stored in a separate map file. The algorithm "grows" the watershed area out from the identified watershed outlet in successive passes over the study area. Thus the identified starting point, line or area is referred to as the "seeding feature" of the watershed. The aspect values of the adjacent cells surrounding the seeding feature are examined. All cells the aspect value of which points toward the seeding cell are considered to contribute flows to the seeding cell, and are included in a temporary data file of the watershed. These marked cells are then used in place of the seeding feature and recursion continues until no new cells are added to the watershed data file.

Figure XII Watershed Delineation Algorithm

EFFECTS OF VARIABLES ON WATERSHED DELINEATION

GRID RESOLUTION

Using a coarse grid in the development of a digital elevation model can lead to excessive error in the DEM, the derived Aspect map, and subsequent watershed delineation. A coarse grid allows only a few cells to represent the area between contours or data points. Depending on the interpolation routine used, this may result in a "staircase" effect which does not provide adequate definition of terrain features. This effect leads to errors in calculating slope and aspect, with resulting slopes being extremely exaggerated. Informal experimentation on interpolating contours from 1: 50 000 NTS topographic maps indicates that a grid dimension greater than 50 meters per side leads to excessive errors. Single cells of this size cover too great an area. Using a grid dimension of 25 meters or less improves the accuracy of the DEM

and the derived aspect map so that more reasonable watershed delineations can be made.

ANGLE OF ACCEPTANCE

Watershed routines examine the aspect value of cells adjacent to the seed cells, checking to see whether the aspect of cells adjacent to seed cells point directly into the seed cells or directly into other cells. The Idrisi watershed module used in this study allows the use of aspect maps with values between 0 and 360. For example, in a cell north-east of a seed cell, with an aspect of 225 degrees implies *direct* surface water flow into the seed cell, and aspects between 180 and 270 degrees imply that surface flow will *likely* be into the seed cells. In the Idrisi watershed routine, aspects falling within 45 degrees either side of the most direct aspect, giving a 90 degree "window", are accepted as contributing flow to the seed cell. This range can be increased so that cells with aspects that are within a 180 "window" are acceptable, or reduced to a 45 degree "window" that allows only cells that are contributing flows directly into the seed cell to be included in the watershed.

Figure XIII Two Different Angles of Acceptance for Building Watersheds

By increasing the angle of acceptance, the resulting watershed may increase in area. Informal experiments with this variable indicate that using a total angle of acceptance

between 135 and 180 degrees will produce slightly larger watersheds in steeply sloped areas and much larger watersheds in flatter areas.

Preliminary test watersheds were delineated using the IDRISI program modules, a DEM and an aspect map. Contours were used as the source elevation data and interpolated using the Intercon module. This module tends to produce an oscillation in interpolated values where the contour lines are sparse, i.e., in flat areas. It is suspected that by increasing the angle of acceptance used in the watershed routine, the pits and dams created by oscillating values were circumvented. Using a wider angle of acceptance may be necessary where flatter topography is encountered, although this is not expected to produce accurate results. It is better to find a method of improving the DEM, rather than increasing the angle of acceptance. Further experimentation is needed to determine the full influence of the angle of acceptance on watershed accuracy.

DEPRESSIONS IN THE DIGITAL ELEVATION MODEL

As indicated previously, any inappropriate pits or depressions remaining in a DEM will affect the results of the watershed delineation routine. The watershed routine checks the aspect of cells and accepts cells with aspect pointing into the seeding cells. If pits, dams, or interpolation oscillations occur in the DEM, a local change in aspect of *only one cell width* is sufficient to stop the watershed growing process. However, if only a few cells with non-contributing aspects block the growth algorithm, the watershed routine may not be blocked entirely at that point. Adjacent contributing cells may, due to the tolerance window provided by the angle of acceptance settings, work to lead the growth process around small blockages.

SEEDING METHOD

The watershed routine can build a watershed from either a point (i.e., theoretical hydrograph location), a line of cells (part of the drainage network), or an area (a known area of the watershed). When a point is used to seed the watershed routine, the probability that the routine will stop building the watershed because of a local dam or basin feature in the DEM is relatively high. This can lead to under-estimations of the area of watersheds. When a line is used to seed the watershed routine, there is a greater chance that the routine will build around local dams or basins and delineate

more of the true watershed. This is particularly true as most of the artificial pits and dams in a DEM occur where a drainage network is inadequately described by elevation data. By starting the watershed growth process from more than one cell it is likely that a seed cell will fall either side of an artificial dam or within a pit. Experiments with these two seeding methods indicate that in situations where relief is very high, the differences in watershed size are small, but in flat areas where the "signal to noise ratio" is small, the differences in the two methods are large. Again this may be due to a high number of artificial pits and dams within the DEM as a result of interpolation methods. The use of a line of cells defining the drainage network within these flat areas can increase the likelihood of circumventing such blockages.

TESTING ACCURACY OF WATERSHEDS

Defining the accuracy of watersheds that have been delineated with GIS using a digital elevation model as a base is a topic which requires some clarification. Comparing the shape and area of automatically delineated watersheds against manually delineated watersheds presents some methodological difficulties: is the manually delineated watershed boundary a suitable yardstick? The manual method that traces the drainage divide between two watersheds does not necessarily identify areas within the watershed that are non-contributing areas. Legitimate non-integrated drainage patterns produce areas within a watershed where runoff is not contributed to the larger drainage pattern being studied. Unless these non-contributing areas are removed from the watershed definition, the manual delineation method will over-estimate the area.

In a study by Faucher and Landreville (1991), manually delineated watershed boundaries were compared to the same boundaries after they had been digitized. Faucher advises that simply digitizing and converting the manually defined boundaries to quadtree rasters can result in $\pm 3\%$ error in the reported area of a watershed. This is not a comparison of automatic versus manual methods, but a warning that comparing the area of a digital watershed as reported by a GIS against the area of a hard copy watershed measured with a planimeter should take this unavoidable measurement error into account.

Testing of automatically delineated watersheds against watersheds delineated manually have been conducted by Stube & Douglas (1990). Of seven comparison watersheds, four had percent differences in area of less than 10 percent, while two had percent

differences in excess of 30 percent. These tests did not examine the effects of variables such as angle of acceptance or seeding methods within the algorithm.

In practical situations where a hydrologist is delineating watersheds for storm water runoff estimation, minor variations in the area of a watershed are not critical. The estimation of runoff is not such an exact science that a few percent difference in area between watersheds delineated by different methods is serious. However, a difference of 30 percent area is significant. Also of significance, but not addressed in the studies mentioned above, are differences in the shape of watersheds produced by manual and automatic methods. The watersheds prepared for the case study documented in chapter five have highly irregularly shaped boundaries (See Map 7 Watershed Configuration). These irregular shapes are not typical with manually delineated watersheds. Areas within a watershed that has been delineated by automatic methods, and which do not contribute runoff, are usually not distinguished in manually delineated watersheds. It is not clear which approach provides better simulation of actual storm runoff. A significant amount of experience would be required to determine which method is in most cases more likely to produce accurate runoff predictions.

MAPPING INFILTRATION PARAMETERS

SOIL MAPPING

Soil maps suitable for deriving input parameters for a hydrological model require some classification of the potential infiltration response of the particular soils in the map. One soil infiltration classification scheme, which is widely applied by hydrologists, is the Soil Conservation Service (SCS) drainage classification. This classification ranks soil infiltration capacity into seven classes, labeled A, AB, B, BC, C, CD, and D. The most rapidly infiltrating soils are assigned class A and the slowest soils to infiltrate are class D. For the practicing hydrologist, finding suitable soil mapping for a study area that has soils classified using the SCS soil type classification may be difficult. Most available soil maps will have some indication of the drainage characteristics of the local soil groups, and these characteristics must be interpreted to reclassify a soil map to include SCS infiltration attributes.

In the following chapter, a case study is presented in which available digital mapping of soils was used. The use of available digital mapping is highly preferable to manual or scanned digitizing of printed maps, for two primary reasons. Digitizing or scanning and reclassification of an image is costly in terms of operator time, and can be error prone. Currently, digital soil mapping is available inexpensively from government sources.

LAND USE COVER

There are many sources of land use mapping that the hydrologist may be required to use in parameterizing a watershed. The development plans of a municipality are most often used for this purpose. Many municipalities are implementing some level of GIS or computer aided drafting in land use planning or engineering departments. Access to digital mapping in a suitable form is important to the cost of a project, and where possible existing digital maps should be used. For detailed urban studies, current Zoning By-laws or Official Plans may be a source of land use mapping specified in project specifications or requests for proposals. For urban / rural and rural studies, more generalized mapping may be used.

METHOD OF AGGREGATION

As indicated at the beginning of chapter three, hydrological models are characterized as either lumped or distributed depending on the method of aggregation of parametric information. A lumped hydrological model simulation will usually involve the aggregation of some spatial information. Figure XIV demonstrates the aggregation of soil and land use information for a simulation that uses land use and soil information. Several different polygons representing land use types and soil type are shown to overlap. In the Lumped aggregation method, the shaded area representing a watershed overlaps and intersects several soil and land use polygons. When using a lumped model approach, the numerical values (area, infiltration rates, etc.) for land use and for soil types are weighted by percentage of the basin area, and the weighted average is used in the model as a representation of the characteristics of the basin. In this example the watershed is the smallest reporting unit used in the hydrological model.

A distributed modeling approach to aggregation is also shown. In this approach, the numerical values (area, infiltration rates, etc.) for land use and for soil types are reported on an individual cell by cell basis to the hydrological modeling program.

A hybrid type of hydrological model is suggested here. The ability of GIS software to store and manipulate spatial data includes the ability to generate a unique set of polygons that are the intersection of a series of map layers. By using a unique conditions polygon outline as the reporting frame for a hydrological model, only the minimum number of reporting units needed are used, without compromising the level of parametric detail available in the source maps.. This aggregation method is referred to as the unique conditions method.

Figure XIV Differing Methods of Aggregation for Modeling

TIME TO PEAK

Time to peak is the time that it takes from the start of a rain storm for the flows in a stream channel to reach their highest point. This is a crucial parameter used in hydrological models, especially when linking the effects of several sub-watershed reporting areas. It is a difficult factor to calculate precisely for watersheds that have not been monitored. This is because of the complex nature of a watershed drainage system, including both stream channel flow and overland flow. The theoretical time to peak corresponds to approximately two thirds the longest time it would take for a molecule of water dropped anywhere within the watershed to reach the drainage outlet. Determining precisely which point within a watershed has the greatest travel time to the drainage outlet would entail calculating the path from each location, the length of that path, and the velocity (a function of slope and surface roughness) all along that path, for every location within the watershed. Hydrologists have several methods of estimating the time to peak of a watershed, using measurements of the watershed and drainage network. One method is the overland/channel velocity method.

The overland/channel velocity method relies on an estimation of the longest pathway within the watershed, and is a reasonable representation of the theoretical time to peak. Because the flow rate of runoff varies with surface cover, a distinction is usually made between flow within stream networks and overland flow. The travel time for both types of flow are calculated and added together. The formulation for this approach, as described by Statisticians Wisner & Associates, is:

$$T_p = 0.66 * [f\{MAX(velocity_o * length_o)\} + f\{MAX(velocity_s * length_s)\}]$$

where o = overland flow

s = stream network flow

Figure XV shows one possible combination of channel and overland flow pathways. The point at the boundary of the watershed where the overland flow length is

measured is chosen heuristically. A combination of distance from the stream channel and overall shallow slope should be used to find the greatest travel time (Wisner & Associates, personal communication). In observing the selection of this "farthest" point by hydrologists, it was noted that the point on the watershed boundary that had the greatest distance from the stream network would often be chosen despite being at a higher elevation than other slightly less distant points. The greater slope and increased velocity from this point was often discounted. Note that the point at which the overland flow component meets the stream network component is approximately 15 percent down from the head of the stream channel. A heuristic rule used in selecting the longest (in time) combination of overland and stream network paths is to use only about 85 percent of the stream network.

Figure XV Measuring Overland Flow and Channel Flow Lengths

USING A GIS TO FIND A SUITABLE DRAINAGE PATH FOR TIME TO PEAK CALCULATIONS

An experimental method of locating a reasonable path for calculating time to peak was developed for this thesis, although it is not included in the shell program documented in chapter four.

The time to peak method was developed using the IDRISI GIS modules, and is based on the overland/channel velocity method. The objective was to use a least-cost path routine to identify a path that water would follow down a watershed. The difficulty was in identifying the point at the uphill end of the watershed from which this path would be drawn. Without calculating and recalculating countless pathway variations, a method had to be identified that would highlight a starting point within the watershed that would be at least near the optimal combination of maximum distance and low elevation.

The required inputs for the routine are a digital elevation map, a map outlining the watershed, a map outlining the extent of the stream drainage channel, and a map showing the location of the watershed drainage outlet or lowest point. With these files ready, the following steps are taken:

- Find the minimum elevation within the watershed and subtract this amount from the entire coverage to prepare a "normalized" elevation map of the watershed
- Perform a transformation of the normalized elevation map to obtain a reciprocal map of normalized elevation
- Assign an arbitrarily high value to areas in the reciprocal elevation map that are outside the watershed, to act as a barrier to subsequent cost surface and pathway routines

- **Prepare a cost surface map using the modified reciprocal elevation map as a friction surface, and the watershed outlet as a starting point**
- **Identify the highest value found within the cost surface map, and reclass the cost surface map to isolate only the few highest values (remember they are reciprocal values). The new map will show only those points that are a combination of relatively low and distant from the drainage outlet. This can be called the "farthest time" map**
- **Create a second cost surface using the original elevation model**
- **Perform a least-cost pathway operation using the "farthest time" map as a starting point and the second cost surface. This will find a path from the "farthest time" point down to the drainage outlet, taking the quickest route down the elevation model, as would water.**
- **Using the definition of the stream network, reclass the path into overland and channel flow classes, and measure average slope and length from these two classes.**

While this routine is a preliminary attempt at the time to peak problem, it does appear to produce reasonable results. In testing, the routine isolated a location near the extremities of a watershed that was not the greatest distance from the drainage network, but was low and would likely take a long time to drain to the network. The pathway selected from this "farthest time" point did lead towards the drainage network, but favoured a longer overland flow route than the "15% from the top of the channel" rule would have dictated. Perhaps improvements might be made using the drainage network as the starting point for the delineation of the first cost surface. This might force the pathway routine to favour the network as a pathway down the friction surface.

CHAPTER FOUR: USING A SIMPLE RASTER GIS TO PREPARE WATERSHED PARAMETERS FOR A LUMPED HYDROLOGICAL MODEL

A relatively simple and potentially effective application of GIS technology is to the parameterization of a watershed for hydrological modeling. In this chapter, a description of the program HYDROGIS is provided. The program was developed to aid civil engineers to prepare hydrological model parameters for a study watershed. This program was developed to take advantage of existing relatively inexpensive GIS software and in a user guided fashion to prepare the digital maps and text files needed to run an existing lumped hydrological model.

The current praxis in parameterizing a watershed for modeling is to measure from paper maps the various inputs parameters required. This usually involves considerable use of planimeters, measurements of length and calculations of slope. Delineating sub-watershed boundaries is usually a manual effort and few practitioners use digital methods. By replacing the manual methods with automated GIS methods, the task of parameterizing a watershed and sub-watersheds can be facilitated. However, the potential gains in efficiency may not be of sufficient value to warrant the high software and training costs associated with high-end commercial GIS packages. Therefore, a relatively simple and inexpensive means of providing GIS technology to hydrologists was developed.

The HYDROGIS program is a single purpose, dedicated shell that links the IDRISI (Eastman, 1992) raster geographic information system to the OTTHYMO 89 (Wisner, 1989) hydrological model. The IDRISI geographic information system was developed by the graduate School of Geography at Clark University, and is now marketed on a low-cost non-profit basis as a professional level tool (Eastman, 1992). In comparison to fully functional GIS software costing much more, IDRISI is a relatively simple tool to learn. However, testing of the IDRISI package with a hydrological firm indicated that the steps needed to parameterize a watershed were too complicated for the IDRISI system to be adopted as a regularly used parameterization tool². The OTTHYMO 89 model is a lumped hydrological model for storm water

². Informal testing of the Idrisi package in a working civil engineering environment was undertaken by the author in conjunction with Paul Wisner & Associates, Ottawa, from June to August 1992. Conclusions reached by hydrology staff were: 1) that there were too many small steps involved in

management and flood control. The program evolved out of the HYMO model (Williams and Hann, 1973) and OTTHYMO (Wisner and P'ng, 1983). It is used widely in many countries around the world by practicing engineers, modeling researchers and educators. The current version of this software relies on the preparation of detailed text files for parametric input, although future versions may incorporate user prompts to improve parameter input.

The approach to integrating these two packages was to develop a shell program that manages a limited set of operator choices needed to parameterize a watershed. The shell operates through a menu system designed specifically for the task of parameterization. HYDROGIS is written in C language and compiled as an executable file. To function, the shell selectively calls functions from the IDRISI software package, and must be installed in the same directory as IDRISI. The product of the shell program is a pre-formatted text input file for the OTTHYMO program, and several digital map files. Through choices made with the menu system, an operator can manipulate digital map files with the aid of IDRISI. Menu selections execute IDRISI routines either by single command line method, or through a series of prompted user inputs in guided routine runs.³ Where additional data manipulation other than what can be accomplished by an IDRISI routine is required, the HYDROGIS code takes control and performs database or function routines. Within HYDROGIS is a subroutine that prepares a formatted text input file for OTTHYMO based on the geographic parameters in the maps produced with IDRISI routines. Most of the parameters required by OTTHYMO are extracted automatically from the digital map files produced, while some specific parameters are prompted for during operation.

implementing the Idrisi GIS package in a working environment, 2) that hardware configuration was beyond the scope of the average user, and 3) that a dedicated or expert system would be beneficial.

³ Communications with the Idrisi Project, Clark University, April 22, 1993 indicate that for the next release of the Idrisi software all modules will have command line mode operation capability. If this is occurs, the HydroGis could operate without the need for prompted user inputs.

The routines in HYDROGIS include:

- manipulation of a pair of soil and land use map files to generate a map of soil infiltration capacity,
- smoothing and analyzing a digital elevation model to obtain slope information,
- delineating watersheds from specified drainage channels,
- and preparing an OTTHYMO input command file.

Based on the maps produced by these routines, HYDROGIS determines most of the parameters needed for OTTHYMO, and offers a choice of output types: simple tables or a formatted OTTHYMO command input file. The OTTHYMO model provides many operator choices, some of which are handled by the HYDROGIS program in an automated or user-prompt fashion. The following comparison outlines functions of OTTHYMO that are handled by HYDROGIS.

Table I Comparison of OTTHYMO and HYDROGIS Options

HYDROLOGICAL FEATURES	MANUAL OPTIONS AVAILABLE IN OTTHYMO	AUTOMATIC OPTIONS AVAILABLE IN HYDROGIS
Rain Storm Input Options	Read a Design Storm IDF data file, generate a Chicago storm via seven IDF co-ordinates or three parameters, or read a mass curve storm file	Prompt for all options supported
Rainfall Loss	Horton relation, CN procedure of Proportional loss methods	
Impervious Ratio	Total impervious ratio and ratio of directly connected imperious areas derived from soil and land use maps	Total impervious ratio calculated from curve number map
Watershed Area	Derived from contours, measured by planimeter.	Derived digitally from slope and aspect maps
Slope of Sub-watershed	Average calculated from the difference in elevation for two locations within the watershed	Average measured from all cells within the watershed area on slope map
Time to Peak	Calculated manually	Prompt for Time to Peak
Instantaneous Unit Hydrographs	Design hydrographs of Standard, Nash and SCS type; Calibrated hydrographs of Standard, Nash and Williams type	Design hydrographs only
Operational, Routing and Plotting commands	Inserted in command file manually	Option to insert blank operational, routing, plotting commands

FUNCTIONS PROVIDED BY HYDROGIS

STUDY AREA FILES

The *Study area statistics* option allows the users to document the various files being used for a particular study. HYDROGIS operates on a number of required input maps in the form of IDRISI raster images. The maps that must be prepared before running HYDROGIS are:

A land use map. This land use map must conform to a predetermined land use classification scheme in order to function properly in HYDROGIS. Table II lists the 20 permissible land use classifications and the corresponding attribute value used in the raster image. The array of prescribed land use classes should be sufficient in number and variety to reclassify most land use maps that the user will encounter.

A soil infiltration type map. The soil type map must be compiled so that all areas are classified as one of seven possible Soil Conservation Service infiltration classifications. These soil types are usually labeled from highest infiltration to lowest infiltration rates as A, AB, B, BC, C, CD, D. In preparing such a soil type map, the user will usually have to interpret attribute information provided with the source soil map.

A digital elevation model map. This file may be produced from either a contour map or a point map, depending on the chosen elevation data source. The raw elevation data should be converted into a continuous surface of elevation data in the IDRISI raster image format. Either the Intercon or Interpol routines in IDRISI should be used to convert raw elevation data to a digital elevation model.

An optional drainage pattern map. This map should represent the watershed drainage pattern that will be used to delineate sub-watersheds. Each reach of the drainage pattern should have a unique identification value. These reaches as represented in the input raster

image, will be used to delineate sub-watersheds and the reach identification numbers will be used to identify the resulting sub-watersheds.

An optional watershed map. The watershed delineation procedure incorporated in the HYDROGIS shell need not be the only method of generating watershed areas. It is possible to display either a contour map or a classified digital elevation model on screen with IDRISI and to use an on-screen digitizing technique to delineate watersheds heuristically. An optional watershed map may be generated by rasterizing such digitized watershed boundaries.

Other file names that can be specified by the user include the desired OTTHYMO output file, the file containing a lookup table of curve number and percent impervious values for specific combinations of soil infiltration type and land use class to be used by HYDROGIS. The ability to specify the names of various map and text files allows the user to save files for different modeling scenarios. In order to change either the input land use or soil maps or the curve number matrix file, or to reflect differing land use or infiltration scenarios, the users can choose to change file names to a previously prepared set of files.

CURVE NUMBER INFILTRATION AND IMPERVIOUS RATIO MAPS

To generate infiltration curve number maps, HYDROGIS performs an operation on soil and land use maps that produces a new map representing infiltration capacities. The new map represents the Soil Conservation Service (SCS) infiltration curve number (cn) values specific to combinations of soil infiltration type and land use class. To assign appropriate curve numbers to land use and soil combinations, and to provide some operator control over the curve numbers that are assigned by HYDROGIS, a text file that lists the unique soil / land use / curve number combinations is used. The list of possible combinations is referred to as the curve number matrix, and functions as a lookup table during development of the curve number map. This file can be displayed, and the curve number values for various land use and soil

combinations can be edited during a session. The *Curve Number Matrix Editing* option allows viewing and editing of the curve number matrix. Table II is an example of a curve number matrix developed from various text book curve number values.

Table II Curve Number Matrix

	SOIL CODE	1	2	3	4	5	6	7
	SOIL TYPE	A	AB	B	BC	C	CD	D
LAND CODE	LAND NAME							
1	FALLOW	77	82	86	89	91	93	94
2	CROP GOOD DRAIN	65	70	75	79	82	84	86
3	CROP POOR DRAIN	70	75	79	82	84	86	88
4	SMALL GRAIN CROP	63	69	74	78	82	84	85
5	PASTURE GOOD DRAIN	39	50	61	68	74	77	80
6	PASTURE FAIR DRAIN	49	59	69	74	79	82	84
7	PASTURE POOR DRAIN	68	70	72	78	83	87	90
8	MEADOW	30	44	58	65	71	75	78
9	WOODS GOOD DRAIN	25	40	55	63	70	74	77
10	WOODS POOR DRAIN	45	56	66	72	77	80	83
11	FARMSTEAD	59	67	74	78	82	84	86
12	ROADS - DIRT	99	99	99	99	99	99	99
13	ROADS - PAVED	99	99	99	99	99	99	99
14	COMMERCIAL	80	80	80	80	80	80	80
15	INDUSTRIAL LIGHT	80	80	80	80	80	80	80
16	INDUSTRIAL HEAVY	80	80	80	80	80	80	80
17	RESIDENTIAL LOW	80	80	80	80	80	80	80
18	RESIDENTIAL MEDIUM	80	80	80	80	80	80	80
19	RESIDENTIAL HIGH	80	80	80	80	80	80	80
20	WATER	99	99	99	99	99	99	99

The *Make curve number map* option starts a sequence of IDRISI operations and internal calculations to prepare a curve number map from the soil and land

use maps and the curve number matrix. The first step prepares a map of the intersection of the soil and land use maps, resulting in more, smaller polygons which represent the intersection of individual soil classes with individual land use classes (i.e., the logical AND of two maps). The IDRISI *CrossTab* module is invoked, and because the crosstab module does not currently support command line functions, the user must respond to the IDRISI prompts for this module. HYDROGIS reminds the user of the required responses before the module is invoked. The CrossTab command produces a new image from the land use and soil maps. This new image has ID values for each combination of land use/soil found in the cross-classification, (i.e., each combination found is sequentially numbered) but does not actually contain information of what those combinations are.

To manipulate the information in the land use and soil maps so that infiltration curve number information can be mapped, the land use values and soil type values for each polygon in the cross-classification map must be extracted. The EXTRACT command is invoked, using the cross-classification map as a feature map through which information from the land use and soil maps is extracted. EXTRACT can retrieve through the features of the cross-classification map the minimum, maximum, average, or sum of the attributes found in the land use or soil maps. Minimum values are extracted from the land use or soil codes found in each cross-classification polygon, and the values are written out to a pair of values files. Each file lists the polygon ID number in the first column and the land use or soil code in the second.

IDRISI does not have a database manager as such. To perform the query needed to identify curve number values associated with the land use and soil type values, a query is required. HYDROGIS performs this query function automatically. The result of this query is a list of ID numbers and the CN value for that ID number, which are written out to a text file. The IDRISI ASSIGN command is invoked, and curve number values in the text file are assigned to the cross-classification map, resulting in a map of curve number for the study area.

Impervious ratio editing and *Assign impervious values to a map* are two functions in HYDROGIS that are similar to the *Edit curve number matrix* and

Make curve number map functions. These functions use the land use map and a matrix lookup table to prepare a map showing the percentage of area covered by impervious surfaces, such as parking lots, roads and buildings.

Impervious ratio editing allows the impervious ratio assigned to specific land uses to be edited. ***Assign impervious values to a map*** prepares a map of impervious ratio by reassigning impervious ratio values to the current land use map.

Update land use map is a function that allows alternative land use scenarios to be modeled with a minimum of effort. The function uses the on screen digitizing capabilities of the IDRISI COLOR command to produce a vector map of changes in land use, converts this to raster format and overlays new land use values on the previous land use map. After updating the land use map, new curve number and impervious ratio maps should be generated.

TERRAIN MODELING AND QUERIES

A digital elevation model is needed for watershed delineation, and also to derive a map of slope. Obtaining a raster grid with an elevation value for each grid cell involves the interpolation of values from either a point data set or a line data set (i.e., contours). As with the land use and soil maps, preparation of the initial digital elevation model for a given study area is done outside HYDROGIS. IDRISI provides interpolation routines that are suitable for preparing a DTM from either point or contour data. As indicated in the previous chapter, there are a number of variables that can influence the adequacy of a digital elevation model. To use the IDRISI interpolation models with confidence, it is advisable to use a dense point elevation data set that provides greater elevation detail than the source commonly used for manual parameterization. For example, if 1:50 000 National Topographic Series contours are normally used for watershed delineation, a digital elevation model developed from 1:10 000 Ontario Base Maps point elevation data will produce a digital terrain map of suitable quality. Once a digital terrain map has been prepared, HYDROGIS can perform a set of operations on the DTM that are needed for parameterization of a watershed.

Smooth the raw digital elevation model. A digital elevation model that is a direct product of an interpolation routine may be a suitable data set for watershed delineation and slope calculations. However, small irregularities in the represented surface may limit the area of a watershed that is delineated. The option to run a low pass mean filter on the raw DTM is provided. This function runs without user interaction.

Make slope and aspect maps. This option uses the IDRISI SURFACE routine to prepare slope and aspect maps from the digital elevation model. A slope map is needed for calculating the average slope of a watershed, or for calculating the time of concentration of a watershed, while an aspect map is needed to delineate watersheds. This functions runs without user interaction.

Profiles from a selected transect and Length and slope of a line. These two functions are provided to aid the program user in determining the time to peak of a watershed. The functions are highly interactive, with the user digitizing on screen the line or transect for which length, slope or profile information is desired. Both functions display the current digital elevation model and prompt for on-screen digitizing of a line. Either the length and slope of the line are reported, or the IDRISI PROFILE module is invoked and a profile displayed on the screen. These two functions are not essential for the operation of other functions, but are provided as an aid.

DRAINAGE NETWORKS AND WATERSHED DELINEATION

Prepare existing drainage network vector file. This module will prepare an existing drainage network vector file for use by the watershed routine. The network segment values will be used to create sub watershed ID numbers. If new drainage network segments are needed, use the *Digitize and Prepare Drainage Network* module.

Digitize and prepare drainage network. This function allows the user to digitize the drainage network on-screen, using the digital elevation model as a background display. The module displays the current surface image specified by the study area statistics list, and allows for digitizing of numbered drainage

lines. The module then prepares a drainage raster file in the same manner as the *Prepare exiting drainage network vector file* routine, and then updates the study area statistics list with the specified new drainage file name.

Make watershed map. The watershed routine will determine the extent of drainage for each drainage network segment, then combine these sub-watersheds in one map. This process is slow!

The first step that the watershed function takes is to reclass the raster image of the target drainage network so that each segment of the network is represented by a separate map. Then the IDRISI WATERSHED module is invoked once for each stream segment. This results in one watershed map for each stream segment. The function then reclassifies the results of each watershed map to the value of the stream segment from which it was determined. These maps are then stacked together in one map using the IDRISI OVERLAY module. The lower value (upstream) watershed areas are placed over the higher value (downstream) watershed areas to produce one map showing the sub-watersheds in a nested fashion. This resultant watershed map is used as the spatial framework for extracting data from the curve number, impervious ratio and slope map, as well as deriving the area of sub-watersheds.

OTTHYMO COMMAND FILE AND TABLES OUTPUT

Write tables. Using the IDRISI EXTRACT module, this function uses the resultant watershed map as the spatial framework for extracting data from the curve number, impervious ratio and slope map, as well as deriving the area of sub-watersheds. The data extracted is then written as an ascii file summary (file extension *.tbl) of these values for each watershed.

Make OTTHYMO input file. GIS2OTT (version 2) is a sub-routine within HYDROGIS which uses the watershed map as the spatial framework for extracting data from the curve number, impervious ratio and slope map, as well as deriving the area of sub-watersheds, and then creates a parameter file for the OTTHYMO hydrology model. The routine starts by writing start-up commands to the parameter file, then prompts the user for information on the precipitation records to be used. Then a loop is started which prepares and

writes out information for each sub-watershed. The type of hydrograph used for modeling and some parameters are prompted for, while other parameters are derived from the maps. Only design hydrograph commands are supported. The following outlines the sequence of prompts in the GIS2OTT subroutine:

Measurement units: Imperial or Metric

Input storm type choice:

The read storm choice prompts the user to input a storm file name.

The mass storm choice prompts the user to input total precipitation of the storm, storm time increments in minutes, and the storm file name.

The Chicago storm choice prompts the user to input total duration of storm in hours, ratio of time to peak to storm duration, storm time increments in minutes, and either three constants that describe the slope of a storm hyetograph, or between seven and twenty coordinate values that describe a storm hyetograph.

Choose the design hydrograph method

The **DESIGN NASH HYDROGRAPH** choice prompts the user to input the following:

TIME TO PEAK IN HOURS
SIMULATION TIME INCREMENT
DRY WEATHER FLOW

The **DESIGN SCS HYDROGRAPH** choice prompts the user to input the following:

TIME TO PEAK IN HOURS
SIMULATION TIME INCREMENT
DRY WEATHER FLOW

The **DESIGN STANDARD HYDROGRAPH** choice prompts the user to input the following:

TIME TO PEAK IN HOURS

SIMULATION TIME INCREMENT IN MINUTES

DRY WEATHER FLOW

RATIO OF TOTAL AREA DIRECTLY CONNECTED TO SEWERS

For each of the sub-watersheds in the watershed map, one or more hydrographs may be selected and parameterized. After each pass through the design hydrograph prompts, the **HYDROGIS** program extracts parametric data from the prepared maps and writes out the appropriate command sequence for **OTTHYMO** to interpret.

Also included within the **GIS2OTT** sub-routine are a series of sub-menu options that allow the user to insert a variety of "blank" or "dummy" operational, routing and plotting commands into the **OTTHYMO** command file. These blank commands are inserted without the critical information needed for operation of **OTTHYMO**, and the user must edit the **OTTHYMO** file before running the file through the modeling program.

HARDWARE AND SOFTWARE REQUIREMENTS

HYDROGIS is written in C language and compiled for operation on a DOS system. The program also functions in a DOS window for the Windows operating system or the IBM OS/2 operating system. Minimum memory requirements depend on the size of **IDRISI** files being prepared, but at least 4 megabytes of RAM are recommended. A minimum of 620Kb is required for the shell program and **IDRISI** to function. A color monitor and a mouse are required.

The program requires that the **IDRISI** GIS software be installed in the same directory as **HYDROGIS**, although the data files used by **IDRISI** may be in another directory, as directed by the **IDRISI** environment file settings. The **OTTHYMO** program need not be in the same directory, as the output text file may be moved after creation.

CHAPTER FIVE: CASE STUDY RESULTS

STUDY AREA PARAMETERS AND MODELING RESULTS

The test study area is located just north of the village of Carp, in the Regional Municipality of Ottawa-Carleton, Ontario, Canada. The study area is primarily a rural landscape with predominantly agricultural and open space land uses. This area was chosen because of the variety of terrain features in the area, and is not necessarily representative of the urban/rural transitional landscapes that are normally modeled using the OTTHYMO program, and because digital data was available without cost for this area. Emphasis on the variety of terrain was important during the testing of the watershed delineation functions of HYDROGIS.

Where possible, existing digital mapping was obtained. The use of digitizing from paper maps was avoided as a cost reduction measure. Digitizing of existing maps is a feasible means of obtaining soil, land use and digital elevation data, but it is time consuming. Also, digitizing increases the opportunities for data entry error. For the purposes of this study, existing government produced digital mapping was available, and the conversion of these maps from the source format to IDRISI raster format required some preprocessing or file manipulation in addition to the application of file conversion utilities provided by IDRISI. In the following sections, the conversion of digital source files to IDRISI format is described.

LAND USE SCENARIOS

The study area is primarily a rural landscape, with few urban land use features. The map used in this study was obtained in digital form from the Canadian Soil Information System (CanSIS), Agriculture Canada. Entitled "Agricultural Land use System of the Regional Municipality of Ottawa-Carleton", this map is also available in paper manuscript form. The digital map is available in the Digital Line Graph (DLG) file format, which can be converted to the IDRISI vector format. Some file preprocessing was required before using the IDRISI DLG conversion routine, due to differences in the treatment of DLG major and minor codes between the Agriculture Canada DLG

export file⁴ and the IDRISI conversion routines. Specifically, the DLG files received from Agriculture Canada have a unique value for both the major and minor code for each polygon in the file. IDRISI provides a DLG conversion utility that requires the selection of specific major codes during processing, which would require the operator to enter a unique value for every polygon in the file. To facilitate conversion, a simple DLG modification routine was written which changes all the unique major codes to 1. This makes the use of the IDRISI conversion utility simple. The DLG conversion produces an IDRISI vector map which must be converted to raster format, reclassified into the land use classes listed in Table II - Curve Number Matrix, and appended with legend information.

The following table lists the area and percentage of each land use occurring in the study area as determined by the IDRISI Area module. The area is predominantly fallow or pasture. Map 1: Land Use shows the distribution of land use in the study area.

Table III Land Use Statistics

LAND USE	SQUARE METERS	PERCENT (/100)
1 : Fallow	62590	0.7144
2 : Crop Good Drain	1275	0.0146
3 : Row Crop	9694	0.1106
5 : Pasture	11622	0.1326
8 : Meadow	36	0.0004
10: Woods	1238	0.0141
11: Farmstead	1161	0.0133

⁴Agriculture Canada uses ARCINFO software, which produced the DLG file through a file export routine. This file export routine produces a DLG file with the same Major and Minor codes for every polygon. The Idrisi DLG import routine expects the Major code to be used as a classifier for a group or class of polygons, while the minor code specifically identifies each polygon.

MAP 1: Land Use

↑ N

1:65100

Idris1

SOILS

The study area is dominated by rock, resulting in a large percentage of poorly drained soils (SCS class D). The map used in this study obtained in digital form from CanSIS. Entitled "Soils of the Regional Municipality of Ottawa-Carleton", this map is also available in paper manuscript form. Conversion of the source DIG file to IDRISI format is identical to the conversion of the land use map. Either IBM-PC 3 1/2 inch disks or magnetic tape formats are available. ⁵

The predominant rock outcrop in the study area is described as exposures of Paleozoic or Precambrian bedrock. Other soils in this area include Dalhousie silty clay with poor Paleozoic and Rideau silty clay with poor drainage. Distinct patterns indicating stream beds are visible on the map, and are describe on the original soil map as eroded channels with slopes greater than 15 percent. These areas were assigned poor infiltration characteristics.

The following table lists the area and percentage of each soil infiltration class occurring in the study area. Class AB is the fastest draining soil class in the study area, and most of the area is of the poorest drainage class D.

Table IV Soil Infiltration Statistics

SOIL TYPE	SQUARE METERS	PERCENT (/100)
2 : AB	9907	0.131
3 : B	9694	0.1106
4 : BC	19928	0.274
6 : CD	411	0.047
7 : D	51440	0.5871

⁵ Currently Agriculture Canada releases these files at no cost, but with the agreement that the user acknowledge the source of the data as "Soil Boundaries Supplied by Centre for Land and Biological Resource Research" and not charge a fee for redistribution of the CanSIS data other than for copying of data or for the manipulation and processing of the data to other formats. The Canadian Soil Information System Data Release Agreement, Agriculture Canada.

MAP 2 Soil - SCS Infiltration Classes

a ab B BC C CB D

1:65100

Idrisi

CURVE NUMBER MAP

The cross classification of the soil and land use maps, and assignment of SCS infiltration curve numbers resulted in Map 3 SCS - Curve Number

DIGITAL ELEVATION MODEL

A digital elevation model was prepared from existing digital elevation information. The Ontario Base Map (OBM) series, produced by the Ontario Ministry of Natural Resources, is available for a fee. The actual copy used for this study was obtained from the Carleton University map library for research purposes. The digital files are available directly from the Ontario Ministry of Natural Resources in the Intergraph exchange file format. The copy used in this study was released to Carleton University on a computer tape that required uploading to the mainframe before conversion to IBM-PC media.

The OBM maps are divided into 18 layers containing data on buildings, transportation features, vegetation, drainage features and other cartographic elements. One layer is dedicated to spot elevation data. For the study area, approximately 32,000 elevation points were available. The distribution of data points in the OBM elevation layer is not entirely even. A relatively evenly spaced grid of data points is evident in flatter areas, but the density of data points increases significantly where terrain changes rapidly. According to Mussakowski (1991), the OBM digital topographic data base is produced as follows:

"...fully digital photogrammetric stereo-compilation methods were adapted for the collection of elevation data. Points were digitized along scan lines in a static mode at a density of 2mm at photographic scale. Scan lines are separated by the same distance. This translates to a point...every 60 meters in Southern Ontario. Points are also collected at up to three times the scan density along break lines. These include crowns of hills, bottoms of depressions, water courses, lake edges, roads, railways, etc. Specifications for elevation accuracy required that measurements be accurate to within one quarter of the contour interval or ... 1.25 meters for 1:10 000-scale. Recent tests found that accuracy was well within 1m..."

This makes the OBM elevation data exceptionally well suited for the creation of a digital elevation model for hydrological purposes. The definition of stream banks and channels is improved by the increased density of points at these features. The higher density points function as pseudo-breaklines, as described in chapter three.

MAP 3 SCS Infiltration Curve Numbers

↑ N

1:65 100

Idrisi

MAP 4: Digital Elevation Model with Drainage Pattern

1:65 100

Idrisi

DRAINAGE PATTERN

The Ontario Base Map series includes a layer with arcs representing natural and built drainage channels. Map 5 includes a sample of the many drainage channels that are found in the study area. The predominant drainage pattern is from the south west to the north east.

SLOPE MAP

Conversion of the point data to a continuous surface was accomplished with the IDRISI interpolation routine. Map 6 is a slope map that was derived from the digital elevation model, and Table V and Figure XVII summarize the slope values in the study area. Note that slope is calculated in percentages (100 percent = 45 degrees). The majority of the study area resolves to a slope of between 0 and 5 percent. The mean slope is approximately 2.5 for the whole study area. For a less variable terrain the mean slope could be significantly less. This demonstrates the need for real numbers with precision to at least two decimal places, and preferably more.

Table V Histogram of Slope Values in Percent

Class	Lower Limit	Upper Limit	Frequency	Prop.	Cum. Freq.	Cum. Prop.
0	0.0000	4.9999	72707	0.8298	72707	0.8298
1	5.0000	9.9999	11275	0.1287	83982	0.9585
2	10.0000	14.9999	2333	0.0266	86315	0.9852
3	15.0000	19.9999	815	0.0093	87130	0.9945
4	20.0000	24.9999	289	0.0033	87419	0.9978
5	25.0000	29.9999	138	0.0016	87557	0.9993
6	30.0000	34.9999	44	0.0005	87601	0.9998
7	35.0000	39.9999	11	0.0001	87612	1.0000
8	40.0000	44.9999	4	0.0000	87616	1.0000
Mean	=		2.6847

Figure XVII Histogram of Slope Values in Percent

Ministry of Natural Resources
Ontario

Ministère des Ressources Naturelles
Ontario

Map of the Province of Ontario
Scale 1:100,000

Legend
 (List of symbols and their meanings)

Sheet 10 10 4150 50250
D-6

Map of the Province of Ontario
Scale 1:100,000

Legend
 (List of symbols and their meanings)

Sheet 10 10 4150 50250
D-6

MAP 5: Modified Drainage Pattern

↑ N

1:65 100

MAP 6: PERCENT SLOPE

↑ N

1:65100

Idris1

WATERSHED CONFIGURATION

The modified drainage pattern shown in Map 5 was used as the input to the watershed delineation routine. The drainage pattern includes six stream channels with unique values. These values are assigned by the watershed delineation routine to the resulting watersheds, shown in Map 7.

LAND USE SCENARIO UPDATE

Map 8 shows an artificial land use development scenario of the type that might be modeled using OTTHYMO. A relatively large area of commercial land use has been imposed on the existing land use map. This change in modeled land use represents a potential change in surface water runoff. By preparing this updated land use map and submitting it to the curve number map preparation routines, a new OTTHYMO command file can be generated.

MAP 7: Watershed Configuration

← N

1:65,000

Idrisi

2 of/de 2

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
STANDARD REFERENCE MATERIAL 1010a
(ANSI and ISO TEST CHART No. 2)

MAP & UPDATED LANDUSE MAP

↑ N

Fallow
Rou Crop 1
Rou Crop 2
Crop Small
Pasture 1
Pasture 2
Pasture 3
Meadow
Woods 1
Woods 2
Farmland
Roads - Dirt
Roads - Pave
Commercial

1:65100

Idrisi

OTTHYMO COMMAND INPUT FILE AND MODELING RESULTS

The curve number, slope and watershed configuration maps produced in the steps outlined above were used by the OTTHYMO file preparation routine. Two OTTHYMO command files are included as Appendix A, one for the current land use scenario and one for the updated land use scenario. For simulation of runoff from a summer storm event, rain fall data from a storm that occurred in the Ottawa area on July 1, 1979 were used. This storm had relatively heavy rainfall, and is often used as a standard design storm by hydrologists and engineers in the Ottawa area.

Filename: b:JLY.STM

| Ptotal= 83.99 mm | Comments: JULY 1 1979 STORM

TIME	RAIN	TIME	RAIN	TIME	RAIN	TIME	RAIN
hrs	mm/hr	hrs	mm/hr	hrs	mm/hr	hrs	mm/hr
.08	2.30	.93	38.10	1.58	71.10	2.33	3.80
.17	2.30	.92	38.10	1.67	71.10	2.42	3.80
.25	8.89	1.00	38.10	1.75	30.50	2.50	3.80
.33	8.89	1.08	38.10	1.83	30.50	2.58	3.80
.42	8.89	1.17	50.80	1.92	30.50	2.67	3.80
.50	8.89	1.25	50.80	2.00	30.50	2.75	3.80
.58	38.10	1.33	76.20	2.08	3.80	2.83	3.80
.67	38.10	1.42	106.70	2.17	3.80	2.92	3.80
.75	38.10	1.50	106.70	2.25	3.80	3.00	3.80

The two OTTHYMO files were run through the OTTHYMO program, and the resulting statistics and hydrographs are shown below. It is evident from the two hydrographs shown that the hypothetical development scenario used to test the HYDROGIS/Otthymo interface would result in an increase in storm runoff. Summary statistics obtained from the two OTTHYMO runs show no difference in the peak flow rates and the time to peak of the two scenarios. The future land use scenario does have a greater total flow volume.

EXISTING LAND USE SCENARIO:

AREA	(ha)	171.60
QPEAK	(cms)	1.94
TPEAK	(hrs)	1.67
VOLUME	(mm)	35.69

FUTURE LAND USE SCENARIO:

AREA	(ha)	171.60
QPEAK	(cms)	1.94
TPEAK	(hrs)	1.67
VOLUME	(mm)	38.14

Figure XVIII Hydrograph of Current and Updated Scenario Modeling

CHAPTER SIX: CONCLUSIONS AND RECOMMENDATIONS

The application of the HYDROGIS shell program in conjunction with OTTHYMO and IDRISI demonstrates that at least on a pilot project it is feasible to use an inexpensive geographic information system to parameterize a hydrological model. IDRISI is a relatively inexpensive GIS package, and it is not difficult to learn. However, the parameterization of the OTTHYMO model requires some geographic information processing steps that are not well handled by IDRISI alone. A significant operation which IDRISI does not handle is the preparation of an infiltration curve number map from a pair of land use and soil maps. The procedure required, which in larger more expensive systems is known as an indexed overlay, must be accomplished outside IDRISI. For this purpose, the HYDROGIS shell was prepared. Within the indexed mapping procedure, HYDROGIS code performs the lookup of curve number values corresponding to soil and land use combinations. Other related geographic information processing operations which are feasible with IDRISI, were included in the HYDROGIS shell to reduce the operator skill required.

The preparation of a digital elevation model for use by HYDROGIS is the most demanding operation that an operator will be faced with in parameterizing a watershed, primarily due to the stringent requirements of a hydrologically sound digital elevation model. In this thesis, the potential error in watershed delineation caused by digital elevation model artifacts is reduced by obtaining a satisfactory data source. The Ontario Base Map (OBM) provides much greater detail with a dense grid of point elevations than may actually be required for studies at the scale used here. Other data sources may not be as effective as the OBM's in describing detailed topography, especially when the density of points or distance between contours increases.

With more sophisticated geographic information systems, control of the interpolation routines may be possible, and editing environments may be available, allowing for the correction of interpolation artifacts that would otherwise result in hydrologically unsound models. Alternatively, the use of true breakline technology would improve the ability to control digital elevation model development. As these technologies are not available within the IDRISI package, potential users are advised to obtain the most accurate and detailed digital elevation data that is available to them.

With the limited resources available within the IDRISI package, and assumed limitations to operator knowledge in this application, the effects of different data source density and interpolation routines leave the operator open to potential watershed delineation error. This can only be corrected in this application by ensuring that the operator uses a digital elevation data source with a density of elevation points considerably higher than that which would otherwise be used in manual watershed delineation. In this case, where the manual delineation of watershed boundaries would normally be made using contour lines on a 1:50 000 topographic map, the automated delineation is done using point data from a 1:10 000 base map.

It is essential for successful and reliable application of GIS technology to hydrological problem solving that adequate training of GIS/hydrology scientists is provided to ensure that the soundness of surface models being used is well understood. This is particularly important where the digital terrain model is used to delineate watershed boundaries. In light of this conclusion, the use of the IDRISI watershed delineation routine for civil engineering projects and other hydrological studies, without adequate training in the preparation of hydrologically sound digital elevation models, is suspect and may not be reliable. The delineation of watershed boundaries in the traditional heuristic manner, interpolating contours and drawing the watershed divide, can be incorporated into the HYDROGIS / IDRISI / OTTHYMO using on-screen digitizing of watershed divides.

As stated in the introduction, the objectives for applying GIS technology successfully in any working environment should include the maintenance or improvement of the current levels of accuracy and precision being achieved by manual methods, while providing benefits either in terms of methodological ease, cost effectiveness, or by the creation of by-products of additional value. The HYDROGIS / IDRISI / OTTHYMO software combination may improve the accuracy with which watersheds are delineated by replacing the subjective generalized method of manual contour interpolation with a rigorous digital interpretation, but at the cost of greater complexity. The digital delineation of watersheds functions "accurately" only within the context of the digital elevation model that is supplied, and produces watershed shapes with greater complexity than the manual approach. Because the watershed delineation routines may produce uncharacteristic watershed areas, the maintenance of current levels of accuracy may not be achieved with this component of the overall methodology.

The method of preparing an indexed overlay of land use and soil maps to create an infiltration curve number map is a significant improvement in methodological ease over the manual measurement of areas where land uses and soils intersect.

The methodological advantage of both the delineation of watersheds and the preparation of CN maps is offset somewhat by the increased effort required to prepare the digital input maps. Only where existing digital data is available and easily imported to IDRISI is there a significant potential saving in person/hours using the digital approach.

The benefits of by-products accruing from a shift from a manual to a digital parameterization mode are map products that can be incorporated into desktop publications, and exportable digital maps. Municipalities and government agencies for whom hydrological modeling studies are usually conducted, are increasingly calling for the inclusion of digital export files of watershed areas and other digital mapping products in study deliverables; these files become part of a municipality's corporate GIS database. This in itself is a significant driving force behind the transition from manual to digital watershed parameterization methods.

This application of geographic information technology to a specific task or structured problem involves system and data base development which normally presupposes a relatively high level of operator skill. Professionals within fields that may take advantage of geographic information systems technology do not usually have the skill level required to develop new structured GIS solutions. This may result in an under-utilization of GIS technology. The use of specific GIS operations arranged in a "hard-wired" single application package may make the employment of GIS technology to new fields easier for professionals in those fields to accept. There are definite limitations to the system described in this thesis. The combination of two existing commercial products, IDRISI and OTTHYMO, and a third integrating program, obliges either the user or the developer to ensure that updates in either of the three components are consistent with the other two. Given the limited potential market for specific applications of this sort, multi-party maintenance agreements are not considered likely. The dependence on multiple software vendors is not desirable. A more robust adaptation of GIS technology to "hard-wired" structured problems can be developed by using application development tool kits now available from some GIS vendors. These tool kits allow the development of a specific application using

functions from the geographic information system, and compiling the developed application for resale as a single product.

Several related hydrological / geographical techniques have been explored within this thesis. Rigorous testing was not intended as part of this work. Further work is required before the techniques demonstrated here can be fully accepted by the hydrological modeling profession. Testing of the IDRISI watershed delineation routine against trained hydrologists is recommended. Differences between the IDRISI method and manual delineation should be measured for the following: total area, shape, and inclusions and exclusions of pits and non-draining areas. Further research is also needed into the application of GIS technology to the problem of calculating the time to peak of a given watershed. This thesis described one possible approach, based on the calculation of overland and channel flow velocity, but did not apply that approach in the integrated HYDROGIS program. Finally, further research into the incorporation of proprietary GIS functions and lumped hydrological modeling software into a single executable program, as opposed to the IDRISI / HYDROGIS/ OTTHYMO combination, is highly recommended.

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APPENDIX A: OTTHYMO INPUT FILES FROM HYDROGIS

A:1 Othymo Command Input Produced By HydroGis: Existing Land use Scenario

A:2 Othymo Command Input Produced By HydroGis: Future Land use Scenario

A:3 Othymo Output: Existing Land use Scenario

A:4 Othymo Output: Future Land use Scenario

A:1 Otthymo Command Input Produced By HydroGis: Existing Land use Scenario

2 (1=Imperial Units, 2= Metric Units)

*

*

* HYDROGIS (version 2) is a program which reads IDRISI Geographic

* Information System files and creates a command input

* file for the OTTHYMO hydrology model. This file is the product

* of HYDROGIS.

*

*

*

*

START AT TIME = 0.0 hrs

*

*

*

READ STORM b:jly.stm

*

*

*

*#####

** SUBAREA 1

*#####

*

DESIGN STANDHYD ID=1 NHYD=150 DT=5 min AREA=6.40 ha

XIMP=0.15 TIMP=0.05 BASEFLOW (DWF)= 0.00

LOSS=2 (CN Procedure)

CN=94 SLOPE=2.201 percent

END= -1

*

*

SUBAREA 2

DESIGN NASHYD ID=2 NHYD=250 DT=5 min AREA=35.84 ha
 BASEFLOW(DWF)= 0.00 CN=94 TP=7 hrs
 END= -1

*

*

ADD HYD ID=3 NHYD=300 IDONE=1 IDTWO=2

*

*

SUBAREA 3

DESIGN SCSHYD ID=1 NHYD=350 DT=5 min AREA=49.00 ha
 BASEFLOW (DWF)= 0.00 CN=61 TP=7 hrs
 END= -1

*

*

ADD HYD ID=2 NHYD=400 IDONE=1 IDTWO=3

*

*

*

SUBAREA 4

*

DESIGN STANDHYD ID=1 NHYD=450 DT=5 min AREA=4.40 ha
 XIMP=0.15 TIMP=0.05 BASEFLOW (DWF)= 0.00
 LOSS=2 (CN Procedure)
 CN=75 SLOPE=1.159 percent
 END= -1

*

*

ADD HYD ID=3 NHYD=500 IDONE=1 IDTWO=2

*

```

*
*****
** SUBAREA 5
*****
DESIGN NASHYD      ID=1 NHYD=550 DT=5 min  AREA=51.50 ha
                   BASEFLOW(DWF)= 0.00  CN=75 TP=7 hrs
                   END= -1

*
*
ADD HYD            ID=2 NHYD=600  IDONE=1  IDTWO=3
*
**
*****
** SUBAREA 6
*****
DESIGN SCSHYD      ID=1 NHYD=650  DT=5 min  AREA=24.40 ha
                   BASEFLOW (DWF)= 0.00  CN=61  TP=7 hrs
                   END= -1

*
*
ADD HYD            ID=3 NHYD=700  IDONE=1  IDTWO=2
*
*
PRINT HYD          ID=3  NPCYC=1
*
*
*
FINISH
*
*

```


A:2 Otthymo Command Input Produced By HydroGis: Future Land use Scenario

```

2 (1=Imperial Units, 2= Metric Units)
*
*
* HYDROGIS (version 2) is a program which reads IDRISI Geographic
* Information System files and creates a command input
* file for the OTTHYMO hydrology model. This file is the product
* of HYDROGIS.
*
*
*
*
START                AT TIME = 0.0 hrs
*
*
*
READ STORM           b:JLY.STM
*
*
*
*****
** SUBAREA 1
*****
*
DESIGN STANDHYD      ID=1 NHYD=150 DT=5 min AREA=6.40 ha
                     XIMP=0.15 TIMP=0.05 BASEFLOW (DWF)= 0.00
                     LOSS=2 (CN Procedure)
                     CN=94 SLOPE=2.201 percent
                     END= -1
*
*
*****

```

** SUBAREA 2

DESIGN NASHYD ID=2 NHYD=250 DT=5 min AREA=35.84 ha
 BASEFLOW(DWF)= 0.00 CN=94 TP=7 hrs
 END= -1

*

*

ADD HYD ID=3 NHYD=300 IDONE=1 IDTWO=2

*

**

** SUBAREA 3

DESIGN SCSHYD ID=1 NHYD=350 DT=5 mi AREA=49.00 ha
 BASEFLOW (DWF)= 0.00 CN=61 TP=7 hrs
 END= -1

*

*

ADD HYD ID=2 NHYD=400 IDONE=1 IDTWO=3

*

*

*

** SUBAREA 4

*

DESIGN STANDHYD ID=1 NHYD=450 DT=5 min AREA=4.40 ha
 XIMP=0.15 TIMP=0.05 BASEFLOW (DWF)= 0.00
 LOSS=2 (CN Procedure)
 CN=75 SLOPE=1.159 percent
 END= -1

*

*

ADD HYD ID=3 NHYD=500 IDONE=1 IDTWO=2

*

*

*# SUBAREA 5

DESIGN NASHYD ID=1 NHYD=550 DT=5 min AREA=51.56 ha
 BASEFLOW(DWF)= 0.00 CN=75 TP=7 hrs
 END= -1

*

*

ADD HYD ID=2 NHYD=600 IDONE=1 IDTWO=3

*

**

*# SUBAREA 6

DESIGN SCSHYD ID=1 NHYD=650 DT=5 min AREA=24.40 ha
 BASEFLOW (DWF)= 0.00 CN=75 TP=7 hrs
 END= -1

*

*

ADD HYD ID=3 NHYD=700 IDONE=1 IDTWO=2

*

*

PRINT HYD ID=3 NPCYC=1

*

*

*

FINISH

*

*

A:3 Otthymo Output: Existing Land use Scenario

=====

```

OOO  TTTT  TTTT  H  H  Y  Y  M  M  OOO  I N T E R H Y M O
O  O  T    T    H  H  Y Y  M M M M O  O  * * * 1989b * * *
O  O  T    T    S H H H H    Y    M M M O  O
O  O  T    T    H  H    Y    M  M O  O
OOO  T    T    H  H    Y    M  M  OOO  cH-106251400339

```

Distributed by the INTERHYMO Centre. Copyright (c), 1989. Paul Wisner & Assoc.

EXCLUSIVE USE TO : PAUL WISNER AND ASSOCIATES I

Input filename: b:land use.txt

Output filename: b:land use.out

Summary filename: b:land use.sum

DATE: 04-05-1993

TIME: 14:07:04

NC., OTTAWA Simulation for EXISTING LAND USE

Produced with HYDROGIS command file

Mike Ballard 4/5/93

•

•

- HYDROGIS (version 2) is a program which reads IDRISI Geographic
- Information System files and creates a command input
- file for the OTTHYMO hydrology model. This file is the product
- of HYDROGIS.

•
•
•
•

** SIMULATION NUMBER: 1 **

•
•
•

| READ STORM | Filename: b:jly.stm
| Ptotal= 83.99 mm | Comments: JULY 1 1979 STORM

TIME	RAIN	TIME	RAIN	TIME	RAIN	TIME	RAIN
hrs	mm/hr	hrs	mm/hr	hrs	mm/hr	hrs	mm/hr
.08	2.30	.83	38.10	1.58	71.10	2.33	3.80
.17	2.30	.92	38.10	1.67	71.10	2.42	3.80
.25	8.89	1.00	38.10	1.75	30.50	2.50	3.80
.33	8.89	1.08	38.10	1.83	30.50	2.58	3.80
.42	8.89	1.17	50.80	1.92	30.50	2.67	3.80
.50	8.89	1.25	50.80	2.00	30.50	2.75	3.80
.58	38.10	1.33	76.20	2.08	3.80	2.83	3.80
.67	38.10	1.42	106.70	2.17	3.80	2.92	3.80
.75	38.10	1.50	106.70	2.25	3.80	3.00	3.80

•
•

•

** SUBAREA 1

•

! DESIGN |

! STANDHYD (0150) | Area (ha)= 6.40

! ID= 1 DT= 5.0 min | Total Imp(%)= 5.00 Dir. Conn.(%)= 15.00

	IMPERVIOUS	PERVIOUS (1)
Surface Area (ha)=	.32	6.08
Dep. Storage (mm)=	.80	1.50
Average Slope (%)=	2.20	2.20
Length (m)=	206.56	40.00
Mannings n =	.013	.250

Max. eff. Inten. (mm/hr)=	106.70	88.08
over (min)	5.00	15.00
Storage Coeff. (min)=	3.04 (11)	10.25 (11)
Unit Hyd. Tpeak (min)=	5.00	15.00
Unit Hyd. peak (cms)=	.27	.09

TOTALS

PEAK FLOW (cms)=	.28	1.15	1.35 (111)
TIME TO PEAK (hrs)=	1.50	1.67	1.67
RUNOFF VOLUME (mm)=	83.19	67.46	69.82
TOTAL RAINFALL (mm)=	83.99	83.99	83.99
RUNOFF COEFFICIENT =	.99	.80	.83

***** WARNING: STORAGE COEFF. IS SMALLER THAN TIME STEP!

***** WARNING: FOR AREAS WITH IMPERVIOUS RATIOS BELOW 20%

YOU SHOULD CONSIDER SPLITTING THE AREA.

(1) CN PROCEDURE SELECTED FOR PERVIOUS LOSSES:

CN* = 94.0 Ia = Dep. Storage (Above)

(11) TIME STEP (DT) SHOULD BE SMALLER OR EQUAL

THAN THE STORAGE COEFFICIENT.

(111) PEAK FLOW DOES NOT INCLUDE BASEFLOW IF ANY.

 *
 *

*# SUBAREA 2

 | DESIGN |

| NASHYD (0250) | Area (ha)= 35.84 Curve Number (CN)= 94.0

| ID= 2 DT= 5.0 min | Ia (mm)= 1.50 # of Linear Res.(N)= 3.00

----- U.H. T_p(hrs)= 7.00

Unit Hyd Qpeak (cms)= .196

PEAK FLOW (cms)= .529 (1)

TIME TO PEAK (hrs)= 8.417

RUNOFF VOLUME (mm)= 68.935

TOTAL RAINFALL (mm)= 83.988

RUNOFF COEFFICIENT = .821

(1) PEAK FLOW DOES NOT INCLUDE BASEFLOW IF ANY.

 *
 *

 | ADD HYD (0300) |

| 1 + 2 = 3 |

----- AREA QPEAK TPEAK R.V.

(ha) (cms) (hrs) (mm)

ID1= 1 (0150): 6.40 1.35 1.67 69.82

+ ID2= 2 (0250): 35.84 .53 8.42 68.93

=====

ID = 3 (0300): 42.24 1.36 1.67 69.07

NOTE: PEAK FLOWS DO NOT INCLUDE BASEFLOWS IF ANY.

•

•

*#####

*# SUBAREA 3

*#####

 | DESIGN SCS(0350) | Area (ha)= 49.00 Curve Number (CN) : 61.0
 | ID= 1 DT= 5.0 min | Ia (mm)= 0.2 S # of Linear Res.(N)= 5.00

 U.H. Tp(hrs)= 7.00

Ia as 0.2xS (mm)= 32.479

Unit Hyd Qpeak (cms)= .386

PEAK FLOW (cms)= .187 (1)

TIME TO PEAK (hrs)= 8.667

RUNOFF VOLUME (mm)= 12.402

TOTAL RAINFALL (mm)= 83.988

RUNOFF COEFFICIENT = .148

(1) PEAK FLOW DOES NOT INCLUDE BASEFLOW IF ANY.

•

•

 | ADD HYD (0400) |

| 1 + 3 = 2 |

	AREA	QPEAK	TPEAK	R.V.
	(ha)	(cms)	(hrs)	(mm)
ID1= 1 (0350):	49.00	.19	8.67	12.40
+ ID2= 3 (0300):	42.24	1.36	1.67	69.07

=====

ID = 2 (0400): 91.24 1.36 1.67 38.64

NOTE: PEAK FLOWS DO NOT INCLUDE BASEFLOWS IF ANY.

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* SUBAREA 4

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| DESIGN |

| STANDHYD (0450) | Area (ha)= 4.40

| ID= 1 DT= 5.0 min | Total Imp(%)= 5.00 Dir. Conn.(%)= 15.00

		IMPERVIOUS	PERVIOUS (1)
Surface Area	(ha)=	.22	4.18
Dep. Storage	(mm)=	.80	1.50
Average Slope	(%)=	1.16	1.16
Length	(m)=	171.27	40.00
Mannings n	=	.013	.250

Max.eff.Inten.(mm/hr)=	106.70	48.57
over (min)	5.00	15.00
Storage Coeff. (min)=	3.29 (11)	14.39 (11)
Unit Hyd. Tpeak (min)=	5.00	15.00
Unit Hyd. peak (cms)=	.27	.08

TOTALS

PEAK FLOW	(cms)=	.19	.43	.56 (111)
TIME TO PEAK	(hrs)=	1.50	1.67	1.67
RUNOFF VOLUME	(mm)=	83.19	38.29	45.02
TOTAL RAINFALL	(mm)=	83.99	83.99	83.99
RUNOFF COEFFICIENT	=	.99	.46	.54

***** WARNING: STORAGE COEFF. IS SMALLER THAN TIME STEP!

***** WARNING: FOR AREAS WITH IMPERVIOUS RATIOS BELOW 20%

YOU SHOULD CONSIDER SPLITTING THE AREA.

(i) CN PROCEDURE SELECTED FOR PERVIOUS LOSSES:

CN* = 75.0 Ia = Dep. Storage (Above)

(ii) TIME STEP (DT) SHOULD BE SMALLER OR EQUAL

THAN THE STORAGE COEFFICIENT.

(iii) PEAK FLOW DOES NOT INCLUDE BASEFLOW IF ANY.

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*

| ADD HYD (0500) |

1 + 2 = 3	AREA	QPEAK	TPEAK	R.V.
	(ha)	(cms)	(hrs)	(mm)
ID1= 1 (0450):	4.40	.56	1.67	45.02
+ ID2= 2 (0400):	91.24	1.36	1.67	38.64

ID = 3 (0500):	95.64	1.93	1.67	38.93

NOTE: PEAK FLOWS DO NOT INCLUDE BASEFLOWS IF ANY.

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** SUBAREA 5

| DESIGN |

NASHYD (0550)	Area	(ha)= 51.56	Curve Number	(CN)= 75.0
ID= 1 DT= 5.0 min	Ia	(mm)= 1.50	# of Linear Res. (N)=	3.00

----- U.H. Tp(hrs)= 7.00

Unit Hyd Qpeak (cms)= .281

PEAK FLOW (cms)= .449 (1)

TIME TO PEAK (hrs)= 8.500

RUNOFF VOLUME (mm)= 40.704

TOTAL RAINFALL (mm)= 83.988

RUNOFF COEFFICIENT = .485

(1) PEAK FLOW DOES NOT INCLUDE BASEFLOW IF ANY.

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*

| ADD HYD (0600) |

| 1 + 3 = 2 |

	AREA	QPEAK	TPEAK	R.V.
	(ha)	(cms)	(hrs)	(mm)
ID1= 1 (0550):	51.56	.45	8.50	40.70
+ ID2= 3 (0500):	95.64	1.93	1.67	38.93

ID = 2 (0600):	147.20	1.94	1.67	39.55

NOTE: PEAK FLOWS DO NOT INCLUDE BASEFLOWS IF ANY.

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*0 SUBAREA 6

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| DESIGN SCS(0650) | Area (ha)= 24.40 Curve Number (CN) = 61.0

| ID= 1 DT= 5.0 min | Ia (mm)= 0.2 S # of Linear Res. (N)= 5.00

----- U.H. Tp(hrs)= 7.00

Ia as 0.2xS (mm)= 32.479

Unit Hyd Qpeak (cms)= .192

PEAK FLOW (cms)= .093 (1)

TIME TO PEAK (hrs)= 8.667

RUNOFF VOLUME (mm)= 12.401

TOTAL RAINFALL (mm)= 83.982

RUNOFF COEFFICIENT = .148

(1) PEAK FLOW DOES NOT INCLUDE BASEFLOW IF ANY.

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| ADD HYD (0700) |

1 + 2 = 3	AREA	QPEAK	TPEAK	R.V.
	(ha)	(cms)	(hrs)	(mm)
ID1= 1 (0650):	24.40	.09	8.67	12.40
+ ID2= 2 (0600):	147.20	1.94	1.67	39.55
=====				
ID = 3 (0700):	171.60	1.94	1.67	35.69

NOTE: PEAK FLOWS DO NOT INCLUDE BASEFLOWS IF ANY.

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| PRINT HYD (0700) | AREA (ha)= 171.60
| ID= 3 PCYC= 1 | QPEAK (cms)= 1.94 (1)
| DT= 5.0 min | TPEAK (hrs)= 1.67
----- VOLUME (mm)= 35.69

(1) PEAK FLOW DOES NOT INCLUDE BASEFLOW IF ANY.

TIME	FLOW	TIME	FLOW	TIME	FLOW	TIME	FLOW	TIME	FLOW
hrs	cms	hrs	cms	hrs	cms	hrs	cms	hrs	cms
.00	.00	10.50	1.16	21.00	.23	31.50	.02	42.00	.00
.08	.00	10.58	1.15	21.08	.22	31.58	.02	42.08	.00
.17	.00	10.67	1.14	21.17	.22	31.67	.02	42.17	.00
.25	.01	10.75	1.14	21.25	.21	31.75	.02	42.25	.00
.33	.03	10.83	1.13	21.33	.21	31.83	.02	42.33	.00
.42	.04	10.92	1.12	21.42	.21	31.92	.02	42.42	.00
.50	.04	11.00	1.11	21.50	.20	32.00	.02	42.50	.00
.58	.17	11.08	1.10	21.58	.20	32.08	.02	42.58	.00
.67	.23	11.17	1.10	21.67	.20	32.17	.02	42.67	.00
.75	.32	11.25	1.09	21.75	.19	32.25	.02	42.75	.00
.83	.40	11.33	1.08	21.83	.19	32.33	.02	42.83	.00
.92	.48	11.42	1.07	21.92	.19	32.42	.02	42.92	.00
1.00	.55	11.50	1.06	22.00	.19	32.50	.02	43.00	.00
1.08	.62	11.58	1.05	22.08	.18	32.58	.02	43.08	.00
1.17	.73	11.67	1.04	22.17	.18	32.67	.02	43.17	.00
1.25	.83	11.75	1.03	22.25	.18	32.75	.02	43.25	.00
1.33	1.06	11.83	1.02	22.33	.17	32.83	.02	43.33	.00
1.42	1.41	11.92	1.01	22.42	.17	32.92	.02	43.42	.00
1.50	1.74	12.00	1.00	22.50	.17	33.00	.02	43.50	.00
1.58	1.87	12.08	1.00	22.58	.16	33.08	.02	43.58	.00
1.67	1.94	12.17	.99	22.67	.16	33.17	.02	43.67	.00
1.75	1.68	12.25	.98	22.75	.16	33.25	.02	43.75	.00
1.83	1.49	12.33	.97	22.83	.16	33.33	.02	43.83	.00
1.92	1.26	12.42	.96	22.92	.15	33.42	.02	43.92	.00
2.00	1.12	12.50	.95	23.00	.15	33.50	.02	44.00	.00
2.08	.89	12.58	.94	23.08	.15	33.58	.02	44.08	.00
2.17	.73	12.67	.93	23.17	.15	33.67	.02	44.17	.00
2.25	.55	12.75	.92	23.25	.14	33.75	.02	44.25	.00
2.33	.44	12.83	.91	23.33	.14	33.83	.01	44.33	.00
2.42	.37	12.92	.90	23.42	.14	33.92	.01	44.42	.00
2.50	.34	13.00	.89	23.50	.14	34.00	.01	44.50	.00

2.58	.32 13.08	.88 23.58	.13 34.08	.01 44.58	.00
2.67	.32 13.17	.87 23.67	.13 34.17	.01 44.67	.00
2.75	.32 13.25	.86 23.75	.13 34.25	.01 44.75	.00
2.83	.33 13.33	.85 23.83	.13 34.33	.01 44.83	.00
2.92	.35 13.42	.84 23.92	.13 34.42	.01 44.92	.00
3.00	.36 13.50	.83 24.00	.12 34.50	.01 45.00	.00
3.08	.36 13.58	.82 24.08	.12 34.58	.01 45.08	.00
3.17	.36 13.67	.81 24.17	.12 34.67	.01 45.17	.00
3.25	.36 13.75	.80 24.25	.12 34.75	.01 45.25	.00
3.33	.37 13.83	.79 24.33	.12 34.83	.01 45.33	.00
3.42	.38 13.92	.78 24.42	.11 34.92	.01 45.42	.00
3.50	.40 14.00	.77 24.50	.11 35.00	.01 45.50	.00
3.58	.42 14.08	.76 24.58	.11 35.08	.01 45.58	.00
3.67	.44 14.17	.75 24.67	.11 35.17	.01 45.67	.00
3.75	.46 14.25	.74 24.75	.11 35.25	.01 45.75	.00
3.83	.48 14.33	.74 24.83	.10 35.33	.01 45.83	.00
3.92	.50 14.42	.73 24.92	.10 35.42	.01 45.92	.00
4.00	.53 14.50	.72 25.00	.10 35.50	.01 46.00	.00
4.08	.55 14.58	.71 25.08	.10 35.58	.01 46.08	.00
4.17	.57 14.67	.70 25.17	.10 35.67	.01 46.17	.00
4.25	.60 14.75	.69 25.25	.10 35.75	.01 46.25	.00
4.33	.62 14.83	.68 25.33	.09 35.83	.01 46.33	.00
4.42	.64 14.92	.67 25.42	.09 35.92	.01 46.42	.00
4.50	.66 15.00	.66 25.50	.09 36.00	.01 46.50	.00
4.58	.69 15.08	.65 25.58	.09 36.08	.01 46.58	.00
4.67	.71 15.17	.65 25.67	.09 36.17	.01 46.67	.00
4.75	.73 15.25	.64 25.75	.09 36.25	.01 46.75	.00
4.83	.75 15.33	.63 25.83	.08 36.33	.01 46.83	.00
4.92	.78 15.42	.62 25.92	.08 36.42	.01 46.92	.00
5.00	.80 15.50	.61 26.00	.08 36.50	.01 47.00	.00
5.08	.82 15.58	.60 26.08	.08 36.58	.01 47.08	.00
5.17	.84 15.67	.60 26.17	.08 36.67	.01 47.17	.00
5.25	.86 15.75	.59 26.25	.08 36.75	.01 47.25	.00
5.33	.88 15.83	.58 26.33	.08 36.83	.01 47.33	.00
5.42	.90 15.92	.57 26.42	.07 36.92	.01 47.42	.00
5.50	.92 16.00	.56 26.50	.07 37.00	.01 47.50	.00

5.58	.94	16.08	.56	26.58	.07	37.08	.01	47.58	.00
5.67	.96	16.17	.55	26.67	.07	37.17	.01	47.67	.00
5.75	.97	16.25	.54	26.75	.07	37.25	.01	47.75	.00
5.83	.99	16.33	.53	26.83	.07	37.33	.01	47.83	.00
5.92	1.01	16.42	.53	26.92	.07	37.42	.01	47.92	.00
6.00	1.02	16.50	.52	27.00	.07	37.50	.01	48.00	.00
6.08	1.04	16.58	.51	27.08	.07	37.58	.01	48.08	.00
6.17	1.05	16.67	.50	27.17	.06	37.67	.01	48.17	.00
6.25	1.07	16.75	.50	27.25	.06	37.75	.01	48.25	.00
6.33	1.08	16.83	.49	27.33	.06	37.83	.01	48.33	.00
6.42	1.10	16.92	.48	27.42	.06	37.92	.01	48.42	.00
6.50	1.11	17.00	.47	27.50	.06	38.00	.01	48.50	.00
6.58	1.12	17.08	.47	27.58	.06	38.08	.01	48.58	.00
6.67	1.13	17.17	.46	27.67	.06	38.17	.01	48.67	.00
6.75	1.15	17.25	.45	27.75	.06	38.25	.01	48.75	.00
6.83	1.16	17.33	.45	27.83	.06	38.33	.01	48.83	.00
6.92	1.17	17.42	.44	27.92	.05	38.42	.01	48.92	.00
7.00	1.18	17.50	.43	28.00	.05	38.50	.01	49.00	.00
7.08	1.19	17.58	.43	28.08	.05	38.58	.01	49.08	.00
7.17	1.19	17.67	.42	28.17	.05	38.67	.00	49.17	.00
7.25	1.20	17.75	.42	28.25	.05	38.75	.00	49.25	.00
7.33	1.21	17.83	.41	28.33	.05	38.83	.00	49.33	.00
7.42	1.22	17.92	.40	28.42	.05	38.92	.00	49.42	.00
7.50	1.22	18.00	.40	28.50	.05	39.00	.00	49.50	.00
7.58	1.23	18.08	.39	28.58	.05	39.08	.00	49.58	.00
7.67	1.23	18.17	.39	28.67	.05	39.17	.00	49.67	.00
7.75	1.24	18.25	.38	28.75	.05	39.25	.00	49.75	.00
7.83	1.24	18.33	.37	28.83	.04	39.33	.00	49.83	.00
7.92	1.25	18.42	.37	28.92	.04	39.42	.00	49.92	.00
8.00	1.25	18.50	.36	29.00	.04	39.50	.00	50.00	.00
8.08	1.25	18.58	.36	29.08	.04	39.58	.00	50.08	.00
8.17	1.25	18.67	.35	29.17	.04	39.67	.00	50.17	.00
8.25	1.26	18.75	.35	29.25	.04	39.75	.00	50.25	.00
8.33	1.26	18.83	.34	29.33	.04	39.83	.00	50.33	.00
8.42	1.26	18.92	.34	29.42	.04	39.92	.00	50.42	.00
8.50	1.26	19.00	.33	29.50	.04	40.00	.00	50.50	.00

8.58	1.26	19.08	.33	29.58	.04	40.08	.00	50.58	.00
8.67	1.26	19.17	.32	29.67	.04	40.17	.00	50.67	.00
8.75	1.26	19.25	.32	29.75	.04	40.25	.00	50.75	.00
8.83	1.26	19.33	.31	29.83	.04	40.33	.00	50.83	.00
8.92	1.25	19.42	.31	29.92	.04	40.42	.00	50.92	.00
9.00	1.25	19.50	.30	30.00	.03	40.50	.00	51.00	.00
9.08	1.25	19.58	.30	30.08	.03	40.58	.00	51.08	.00
9.17	1.25	19.67	.29	30.17	.03	40.67	.00	51.17	.00
9.25	1.24	19.75	.29	30.25	.03	40.75	.00	51.25	.00
9.33	1.24	19.83	.28	30.33	.03	40.83	.00	51.33	.00
9.42	1.24	19.92	.28	30.42	.03	40.92	.00	51.42	.00
9.50	1.23	20.00	.27	30.50	.03	41.00	.00	51.50	.00
9.58	1.23	20.08	.27	30.58	.03	41.08	.00	51.58	.00
9.67	1.22	20.17	.26	30.67	.03	41.17	.00	51.67	.00
9.75	1.22	20.25	.26	30.75	.03	41.25	.00	51.75	.00
9.83	1.21	20.33	.26	30.83	.03	41.33	.00	51.83	.00
9.92	1.21	20.42	.25	30.92	.03	41.42	.00	51.92	.00
10.00	1.20	20.50	.25	31.00	.03	41.50	.00	52.00	.00
10.08	1.19	20.58	.24	31.08	.03	41.58	.00	52.08	.00
10.17	1.19	20.67	.24	31.17	.03	41.67	.00	52.17	.00
10.25	1.18	20.75	.24	31.25	.03	41.75	.00	52.25	.00
10.33	1.17	20.83	.23	31.33	.03	41.83	.00		
10.42	1.17	20.92	.23	31.42	.03	41.92	.00		

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FINISH

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A:4 Otthymo Output: Future Land use Scenario

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OOO  TTTT  TTTT  H  H  Y  Y  M  M  OOO  I N T E R H Y M O
O  O  T    T  H  H  Y Y  M M M M  O  O  * * * 1989b * * *
O  O  T    T  H H H H  Y  M M M  O  O
O  O  T    T  H  H  Y  M  M  O  O
OOO  T    T  H  H  Y  M  M  OOO  cH-106251400340

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Input filename: b:newland.txt

Output filename: b:newland.out

Summary filename: b:newland.sum

DATE: 04-05-1993

TIME: 14:08:53

NC., OTTAWA

Simulation for Hypothetical FUTURE LAND USE

Produced with HYDROGIS command file

Mike Ballard 4/5/93

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- HYDROGIS (version 2) is a program which reads IDRISI Geographic
- Information System files and creates a command input
- file for the OTTHYMO hydrology model. This file is the product
- of HYDROGIS.

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** SIMULATION NUMBER: 1 **

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| READ STORM | Filename: b:JLY.STM
| Ptotal= 83.99 mm | Comments: JULY 1 1979 STORM

TIME	RAIN	TIME	RAIN	TIME	RAIN	TIME	RAIN
hrs	mm/hr	hrs	mm/hr	hrs	mm/hr	hrs	mm/hr
.08	2.30	.83	38.10	1.58	71.10	2.33	3.80
.17	2.30	.92	38.10	1.67	71.10	2.42	3.80
.25	8.89	1.00	38.10	1.75	30.50	2.50	3.80
.33	8.89	1.08	38.10	1.83	30.50	2.58	3.80
.42	8.89	1.17	50.80	1.92	30.50	2.67	3.80
.50	8.89	1.25	50.80	2.00	30.50	2.75	3.80
.58	38.10	1.33	76.20	2.08	3.80	2.83	3.80
.67	38.10	1.42	106.70	2.17	3.80	2.92	3.80
.75	38.10	1.50	106.70	2.25	3.80	3.00	3.80

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** SUBAREA 1

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| DESIGN |

| STANDHYD (0150) | Area (ha)= 6.40

| ID= 1 DT= 5.0 min | Total Imp(%)= 5.00 Dir. Conn.(%)= 15.00

		IMPERVIOUS	PERVIOUS (i)
Surface Area	(ha)=	.32	6.08
Dep. Storage	(mm)=	.80	1.50
Average Slope	(%)=	2.20	2.20
Length	(m)=	206.56	40.00
Mannings n	=	.013	.250

Max.eff.Inten.(mm/hr)=	106.70	88.08
over (min)	5.00	15.00
Storage Coeff. (min)=	3.04 (ii)	10.25 (ii)
Unit Hyd. Tpeak (min)=	5.00	15.00
Unit Hyd. peak (cms)=	.27	.09

TOTALS

PEAK FLOW	(cms)=	.28	1.15	1.35 (iii)
TIME TO PEAK	(hrs)=	1.50	1.67	1.67
RUNOFF VOLUME	(mm)=	83.19	67.46	69.82
TOTAL RAINFALL	(mm)=	83.99	83.99	83.99
RUNOFF COEFFICIENT	=	.99	.80	.83

***** WARNING: STORAGE COEFF. IS SMALLER THAN TIME STEP!

***** WARNING:FOR AREAS WITH IMPERVIOUS RATIOS BELOW 20%

YOU SHOULD CONSIDER SPLITTING THE AREA.

(i) CN PROCEDURE SELECTED FOR PERVIOUS LOSSES:

CN* = 94.0 Ia = Dep. Storage (Above)

(ii) TIME STEP (DT) SHOULD BE SMALLER OR EQUAL

THAN THE STORAGE COEFFICIENT.

(111) PEAK FLOW DOES NOT INCLUDE BASEFLOW IF ANY.

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*****
** SUBAREA 2
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| DESIGN          |
| NASHYD   (0250) | Area   (ha)= 35.84   Curve Number   (CN)= 94.0
| ID= 2 DT= 5.0 min | Ia     (mm)=  1.50   # of Linear Res. (N)= 3.00
-----          U.H.   Tp(hrs)=  7.00

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Unit Hyd Qpeak (cms)= .196

PEAK FLOW (cms)= .529 (1)

TIME TO PEAK (hrs)= 8.417

RUNOFF VOLUME (mm)= 68.935

TOTAL RAINFALL (mm)= 83.988

RUNOFF COEFFICIENT = .821

(1) PEAK FLOW DOES NOT INCLUDE BASEFLOW IF ANY.

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| ADD HYD   (0300) |
| 1 + 2 = 3 | AREA   QPEAK   TPEAK   R.V.
-----          (ha)   (cms)   (hrs)   (mm)
      ID1= 1 (0150):    6.40    1.35    1.67    69.82
      + ID2= 2 (0250):  35.84    .53    8.42    68.93
      =====

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ID = 3 (0300): 42.24 1.36 1.67 69.07

NOTE: PEAK FLOWS DO NOT INCLUDE BASEFLOWS IF ANY.

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*# SUBAREA 3

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 | DESIGN SCS(0350) | Area (ha)= 49.00 Curve Number (CN) = 61.0
 | ID= 1 DT= 5.0 min | Ia (mm)= 0.2 S # of Linear Res. (N)= 5.00

 U.H. Tp(hrs)= 7.00

Ia as 0.2xS (mm)= 32.479

Unit Hyd Qpeak (cms)= .386

PEAK FLOW (cms)= .187 (i)

TIME TO PEAK (hrs)= 8.667

RUNOFF VOLUME (mm)= 12.402

TOTAL RAINFALL (mm)= 83.988

RUNOFF COEFFICIENT = .148

(i) PEAK FLOW DOES NOT INCLUDE BASEFLOW IF ANY.

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 | ADD HYD (0400) |

| 1 + 3 = 2 |

	AREA	QPEAK	TPEAK	R.V.
	(ha)	(cms)	(hrs)	(mm)
ID1= 1 (0350):	49.00	.19	8.67	12.40
+ ID2= 3 (0300):	42.24	1.36	1.67	69.07

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=====
ID = 2 (0400):    91.24    1.36    1.67    38.64
```

NOTE: PEAK FLOWS DO NOT INCLUDE BASEFLOWS IF ANY.

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*****
** SUBAREA 4
*****
*
-----
| DESIGN          |
| STANDHYD (0450) | Area    (ha)=  4.40
| ID= 1 DT= 5.0 min | Total Imp(%)=  5.00 Dir. Conn.(%)= 15.00
-----
```

		IMPERVIOUS	PERVIOUS (i)	
Surface Area	(ha)=	.22	4.18	
Dep. Storage	(mm)=	.80	1.50	
Average Slope	(%)=	1.16	1.16	
Length	(m)=	171.27	40.00	
Mannings n	=	.013	.250	
Max.eff.Inten.(mm/hr)=		106.70	48.57	
over (min)		5.00	15.00	
Storage Coeff. (min)=		3.29 (ii)	14.39 (ii)	
Unit Hyd. Tpeak (min)=		5.00	15.00	
Unit Hyd. peak (cms)=		.27	.08	
				TOTALS
PEAK FLOW	(cms)=	.19	.43	.56 (iii)
TIME TO PEAK	(hrs)=	1.50	1.67	1.67
RUNOFF VOLUME	(mm)=	83.19	38.29	45.02
TOTAL RAINFALL	(mm)=	83.99	83.99	83.99
RUNOFF COEFFICIENT	=	.99	.46	.54

***** WARNING: STORAGE COEFF. IS SMALLER THAN TIME STEP!

***** WARNING: FOR AREAS WITH IMPERVIOUS RATIOS BELOW 20%

YOU SHOULD CONSIDER SPLITTING THE AREA.

(i) CN PROCEDURE SELECTED FOR PERVIOUS LOSSES:

CN* = 75.0 Ia = Dep. Storage (Above)

(ii) TIME STEP (DT) SHOULD BE SMALLER OR EQUAL

THAN THE STORAGE COEFFICIENT.

(iii) PEAK FLOW DOES NOT INCLUDE BASEFLOW IF ANY.

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| ADD HYD (0500) |

| 1 + 2 = 3 |

	AREA	QPEAK	TPEAK	R.V.
	(ha)	(cms)	(hrs)	(mm)
ID1= 1 (0450):	4.40	.56	1.67	45.02
+ ID2= 2 (0400):	91.24	1.36	1.67	38.64
=====				
ID = 3 (0500):	95.64	1.93	1.67	38.93

NOTE: PEAK FLOWS DO NOT INCLUDE BASEFLOWS IF ANY.

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*# SUBAREA 5

| DESIGN |

| NASHYD (0550) | Area (ha)= 51.56 Curve Number (CN)= 75.0

| ID= 1 DT= 5.0 min | Ia (mm)= 1.50 # of Linear Res. (N)= 3.00

----- U.H. Tp(hrs)= 7.00

Unit Hyd Qpeak (cms)= .281

PEAK FLOW (cms)= .449 (1)

TIME TO PEAK (hrs)= 8.500

RUNOFF VOLUME (mm)= 40.704

TOTAL RAINFALL (mm)= 83.988

RUNOFF COEFFICIENT = .485

(1) PEAK FLOW DOES NOT INCLUDE BASEFLOW IF ANY.

*
*

I ADD HYD (0600) I

I 1 + 3 = 2 I	AREA (ha)	QPEAK (cms)	TPEAK (hrs)	R.V. (mm)
ID1= 1 (0550):	51.56	.45	8.50	40.70
+ ID2= 3 (0500):	95.64	1.93	1.67	38.93
=====				
ID = 2 (0600):	147.20	1.94	1.67	39.55

NOTE: PEAK FLOWS DO NOT INCLUDE BASEFLOWS IF ANY.

*
**

*# SUBAREA 6

I DESIGN SCS(0650) I Area (ha)= 24.40 Curve Number (CN) = 75.0
ID= 1 DT= 5.0 min I Ia (mm)= 0.2 S # of Linear Res. (N)= 5.00

----- U.H. Tp(hrs)= 7.00

Ia as 0.2xS (mm)= 16.933

Unit Hyd Qpeak (cms)= .192

PEAK FLOW (cms)= .223 (1)

TIME TO PEAK (hrs)= 8.583

RUNOFF VOLUME (mm)= 29.632

TOTAL RAINFALL (mm)= 83.988

RUNOFF COEFFICIENT = .353

(1) PEAK FLOW DOES NOT INCLUDE BASEFLOW IF ANY.

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| ADD HYD (0700) |

1 + 2 = 3	AREA	QPEAK	TPEAK	R.V.
	(ha)	(cms)	(hrs)	(mm)
ID1= 1 (0650):	24.40	.22	8.58	29.63
+ ID2= 2 (0600):	147.20	1.94	1.67	39.55
=====				
ID = 3 (0700):	171.60	1.94	1.67	38.14

NOTE: PEAK FLOWS DO NOT INCLUDE BASEFLOWS IF ANY.

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| PRINT HYD (0700) | AREA (ha)= 171.60
| ID= 3 PCYC= 1 | QPEAK (cms)= 1.94 (1)
| DT= 5.0 min | TPEAK (hrs)= 1.67
----- VOLUME (mm)= 38.14

(1) PEAK FLOW DOES NOT INCLUDE BASEFLOW IF ANY.

TIME	FLOW	TIME	FLOW	TIME	FLOW	TIME	FLOW	TIME	FLOW
hrs	cms	hrs	cms	hrs	cms	hrs	cms	hrs	cms
.00	.00	10.50	1.27	21.00	.23	31.50	.03	42.00	.00
.08	.00	10.58	1.26	21.08	.23	31.58	.02	42.08	.00
.17	.00	10.67	1.26	21.17	.22	31.67	.02	42.17	.00
.25	.01	10.75	1.25	21.25	.22	31.75	.02	42.25	.00
.33	.03	10.83	1.24	21.33	.22	31.83	.02	42.33	.00
.42	.04	10.92	1.23	21.42	.21	31.92	.02	42.42	.00
.50	.04	11.00	1.22	21.50	.21	32.00	.02	42.50	.00
.58	.17	11.08	1.21	21.58	.21	32.08	.02	42.58	.00
.67	.23	11.17	1.20	21.67	.20	32.17	.02	42.67	.00
.75	.32	11.25	1.19	21.75	.20	32.25	.02	42.75	.00
.83	.40	11.33	1.18	21.83	.20	32.33	.02	42.83	.00
.92	.48	11.42	1.17	21.92	.19	32.42	.02	42.92	.00
1.00	.55	11.50	1.16	22.00	.19	32.50	.02	43.00	.00
1.08	.62	11.58	1.15	22.08	.19	32.58	.02	43.08	.00
1.17	.73	11.67	1.14	22.17	.18	32.67	.02	43.17	.00
1.25	.83	11.75	1.13	22.25	.18	32.75	.02	43.25	.00
1.33	1.06	11.83	1.12	22.33	.18	32.83	.02	43.33	.00
1.42	1.41	11.92	1.10	22.42	.17	32.92	.02	43.42	.00
1.50	1.74	12.00	1.09	22.50	.17	33.00	.02	43.50	.00
1.58	1.87	12.08	1.08	22.58	.17	33.08	.02	43.58	.00
1.67	1.94	12.17	1.07	22.67	.17	33.17	.02	43.67	.00
1.75	1.68	12.25	1.06	22.75	.16	33.25	.02	43.75	.00
1.83	1.49	12.33	1.05	22.83	.16	33.33	.02	43.83	.00
1.92	1.26	12.42	1.04	22.92	.16	33.42	.02	43.92	.00
2.00	1.12	12.50	1.03	23.00	.15	33.50	.02	44.00	.00
2.08	.89	12.58	1.02	23.08	.15	33.58	.02	44.08	.00
2.17	.73	12.67	1.01	23.17	.15	33.67	.02	44.17	.00
2.25	.55	12.75	.99	23.25	.15	33.75	.02	44.25	.00
2.33	.44	12.83	.98	23.33	.14	33.83	.01	44.33	.00
2.42	.38	12.92	.97	23.42	.14	33.92	.01	44.42	.00
2.50	.34	13.00	.96	23.50	.14	34.00	.01	44.50	.00

2.58	.33 13.08	.95 23.58	.14 34.08	.01 44.58	.00
2.67	.32 13.17	.94 23.67	.13 34.17	.01 44.67	.00
2.75	.33 13.25	.93 23.75	.13 34.25	.01 44.75	.00
2.83	.34 13.33	.92 23.83	.13 34.33	.01 44.83	.00
2.92	.35 13.42	.91 23.92	.13 34.42	.01 44.92	.00
3.00	.37 13.50	.89 24.00	.13 34.50	.01 45.00	.00
3.08	.37 13.58	.88 24.08	.12 34.58	.01 45.08	.00
3.17	.37 13.67	.87 24.17	.12 34.67	.01 45.17	.00
3.25	.37 13.75	.86 24.25	.12 34.75	.01 45.25	.00
3.33	.38 13.83	.85 24.33	.12 34.83	.01 45.33	.00
3.42	.40 13.92	.84 24.42	.12 34.92	.01 45.42	.00
3.50	.41 14.00	.83 24.50	.11 35.00	.01 45.50	.00
3.58	.43 14.08	.82 24.58	.11 35.08	.01 45.58	.00
3.67	.46 14.17	.81 24.67	.11 35.17	.01 45.67	.00
3.75	.48 14.25	.80 24.75	.11 35.25	.01 45.75	.00
3.83	.50 14.33	.79 24.83	.11 35.33	.01 45.83	.00
3.92	.53 14.42	.78 24.92	.10 35.42	.01 45.92	.00
4.00	.55 14.50	.77 25.00	.10 35.50	.01 46.00	.00
4.08	.58 14.58	.76 25.08	.10 35.58	.01 46.08	.00
4.17	.61 14.67	.75 25.17	.10 35.67	.01 46.17	.00
4.25	.63 14.75	.74 25.25	.10 35.75	.01 46.25	.00
4.33	.66 14.83	.73 25.33	.10 35.83	.01 46.33	.00
4.42	.68 14.92	.72 25.42	.09 35.92	.01 46.42	.00
4.50	.71 15.00	.71 25.50	.09 36.00	.01 46.50	.00
4.58	.73 15.08	.70 25.58	.09 36.08	.01 46.58	.00
4.67	.76 15.17	.69 25.67	.09 36.17	.01 46.67	.00
4.75	.78 15.25	.68 25.75	.09 36.25	.01 46.75	.00
4.83	.81 15.33	.67 25.83	.09 36.33	.01 46.83	.00
4.92	.83 15.42	.66 25.92	.08 36.42	.01 46.92	.00
5.00	.86 15.50	.65 26.00	.08 36.50	.01 47.00	.00
5.08	.88 15.58	.64 26.08	.08 36.58	.01 47.08	.00
5.17	.91 15.67	.63 26.17	.08 36.67	.01 47.17	.00
5.25	.93 15.75	.62 26.25	.08 36.75	.01 47.25	.00
5.33	.95 15.83	.61 26.33	.08 36.83	.01 47.33	.00
5.42	.97 15.92	.61 26.42	.08 36.92	.01 47.42	.00
5.50	1.00 16.00	.60 26.50	.07 37.00	.01 47.50	.00

5.58	1.02	16.08	.59	26.58	.07	37.08	.01	47.58	.00
5.67	1.04	16.17	.58	26.67	.07	37.17	.01	47.67	.00
5.75	1.06	16.25	.57	26.75	.07	37.25	.01	47.75	.00
5.83	1.08	16.33	.56	26.83	.07	37.33	.01	47.83	.00
5.92	1.10	16.42	.55	26.92	.07	37.42	.01	47.92	.00
6.00	1.12	16.50	.55	27.00	.07	37.50	.01	48.00	.00
6.08	1.14	16.58	.54	27.08	.07	37.58	.01	48.08	.00
6.17	1.15	16.67	.53	27.17	.06	37.67	.01	48.17	.00
6.25	1.17	16.75	.52	27.25	.06	37.75	.01	48.25	.00
6.33	1.19	16.83	.51	27.33	.06	37.83	.01	48.33	.00
6.42	1.20	16.92	.51	27.42	.06	37.92	.01	48.42	.00
6.50	1.22	17.00	.50	27.50	.06	38.00	.01	48.50	.00
6.58	1.23	17.08	.49	27.58	.06	38.08	.01	48.58	.00
6.67	1.24	17.17	.48	27.67	.06	38.17	.01	48.67	.00
6.75	1.26	17.25	.48	27.75	.06	38.25	.01	48.75	.00
6.83	1.27	17.33	.47	27.83	.06	38.33	.01	48.83	.00
6.92	1.28	17.42	.46	27.92	.05	38.42	.01	48.92	.00
7.00	1.29	17.50	.46	28.00	.05	38.50	.01	49.00	.00
7.08	1.30	17.58	.45	28.08	.05	38.58	.01	49.08	.00
7.17	1.31	17.67	.44	28.17	.05	38.67	.00	49.17	.00
7.25	1.32	17.75	.43	28.25	.05	38.75	.00	49.25	.00
7.33	1.33	17.83	.43	28.33	.05	38.83	.00	49.33	.00
7.42	1.34	17.92	.42	28.42	.05	38.92	.00	49.42	.00
7.50	1.35	18.00	.41	28.50	.05	39.00	.00	49.50	.00
7.58	1.35	18.08	.41	28.58	.05	39.08	.00	49.58	.00
7.67	1.36	18.17	.40	28.67	.05	39.17	.00	49.67	.00
7.75	1.36	18.25	.40	28.75	.05	39.25	.00	49.75	.00
7.83	1.37	18.33	.39	28.83	.05	39.33	.00	49.83	.00
7.92	1.37	18.42	.38	28.92	.04	39.42	.00	49.92	.00
8.00	1.38	18.50	.38	29.00	.04	39.50	.00	50.00	.00
8.08	1.38	18.58	.37	29.08	.04	39.58	.00	50.08	.00
8.17	1.38	18.67	.37	29.17	.04	39.67	.00	50.17	.00
8.25	1.39	18.75	.36	29.25	.04	39.75	.00	50.25	.00
8.33	1.39	18.83	.35	29.33	.04	39.83	.00	50.33	.00
8.42	1.39	18.92	.35	29.42	.04	39.92	.00	50.42	.00
8.50	1.39	19.00	.34	29.50	.04	40.00	.00	50.50	.00

8.58	1.39	19.08	.34	29.58	.04	40.08	.00	50.58	.00
8.67	1.39	19.17	.33	29.67	.04	40.17	.00	50.67	.00
8.75	1.39	19.25	.33	29.75	.04	40.25	.00	50.75	.00
8.83	1.38	19.33	.32	29.83	.04	40.33	.00	50.83	.00
8.92	1.38	19.42	.32	29.92	.04	40.42	.00	50.92	.00
9.00	1.38	19.50	.31	30.00	.03	40.50	.00	51.00	.00
9.08	1.38	19.58	.31	30.08	.03	40.58	.00	51.08	.00
9.17	1.37	19.67	.30	30.17	.03	40.67	.00	51.17	.00
9.25	1.37	19.75	.30	30.25	.03	40.75	.00	51.25	.00
9.33	1.37	19.83	.29	30.33	.03	40.83	.00	51.33	.00
9.42	1.36	19.92	.29	30.42	.03	40.92	.00	51.42	.00
9.50	1.36	20.00	.28	30.50	.03	41.00	.00	51.50	.00
9.58	1.35	20.08	.28	30.58	.03	41.08	.00	51.58	.00
9.67	1.35	20.17	.27	30.67	.03	41.17	.00	51.67	.00
9.75	1.34	20.25	.27	30.75	.03	41.25	.00	51.75	.00
9.83	1.33	20.33	.26	30.83	.03	41.33	.00	51.83	.00
9.92	1.33	20.42	.26	30.92	.03	41.42	.00	51.92	.00
10.00	1.32	20.50	.26	31.00	.03	41.50	.00	52.00	.00
10.08	1.31	20.58	.25	31.08	.03	41.58	.00	52.08	.00
10.17	1.31	20.67	.25	31.17	.03	41.67	.00	52.17	.00
10.25	1.30	20.75	.24	31.25	.03	41.75	.00	52.25	.00
10.33	1.29	20.83	.24	31.33	.03	41.83	.00		
10.42	1.28	20.92	.24	31.42	.03	41.92	.00		

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FINISH

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APPENDIX B: MACHINE READABLE COPY OF HYDROGIS. 3.5 in, High Density.

**UNABLE TO FILM MATERIAL ACCOMPANYING THIS THESIS (I.E.
DISKETTE(S), SLIDES, MICROFICHE, ETC...).**

PLEASE CONTACT THE UNIVERSITY LIBRARY.

**INCAPABLE DE MICROFILMER LE MATERIEL QUI ACCOMPAGNE CETTE THESE
(EX. DISQUETTES, DIAPOSITIVES, MICROFICHE (S), ETC...).**

VEUILLEZ CONTACTER LA BIBLIOTHEQUE DE L'UNIVERSITE.

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CANADIAN THESES SERVICE**

**BIBLIOTHEQUE NATIONALE DU CANADA
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