THE QUANTIFICATION OF UPLAND RUNOFF FOR SUBSURFACE DRAINAGE DESIGN

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ABSTRACT

Accurate upland runoff and peak flow estimates are crucial for successful subsurface drainage design in adjacent lowland agricultural regions. Three techniques used in drainage design, namely the SCS Curve Number approach for runoff estimation, and the SCS unit hydrograph procedure and the Rational formula for peak flow estimation were evaluated. A small upland research watershed was established at Agriculture Canada's Agassiz Research Station, Farm #2, in the eastern end of the Lower Fraser Valley of British Columbia. The use of digital elevation models to assist in watershed analysis was reviewed through the development of a model for the Research watershed.

Findings showed that the SCS Curve Number approach underestimated runoff. The Rational formula provided the best estimates of peak flow. The use of a digital elevation model provided required parameters for the various methods tested, and showed high potential for further use in watershed quantification.
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A. INTRODUCTION

Adequate land drainage has long been recognized as the most significant limiting factor to agricultural development in the Lower Fraser Valley. Although this is a relatively small agricultural area, it is intensively farmed and accounts for about 50% of the Province's agricultural revenues (Baehr 1980).

There are two basic drainage conditions in the Lower Fraser Valley: 1) flat lands (slope less than 0.5%) such as in Richmond, Delta, and parts of Pitt Meadow and Chilliwack, and 2) upland areas producing runoff onto agricultural lowlands such as Surrey, Port Langley, Matsqui Prairie, and parts of Pitt Meadow and Chilliwack. Due to expansion of agricultural production into the fringes of the lowland and into the upland, it is important to consider the potential effects of upland runoff on lowland agricultural drainage systems.

There are many runoff estimation techniques with varying complexity, ease of use, accuracy, applicability, cost, as well as form: deterministic, stochastic, conceptual, theoretical, black-box, and continuous or event based. In drainage design one is concerned that a model can provide an accurate estimate of upland runoff within a reasonable time and budget. One such model that shows potential for fulfilling these criteria is the Soil Conservation Service Curve Number Method.

Recent research in runoff estimation has been in the direction of physically based deterministic modelling, where the
runoff, time to peak, and peak discharge are dependent on the geomorphology of the basin. TOPMODEL (topography based hydrologic model) (Beven and Kirkby 1976; Beven 1977; Beven and Kirkby 1979; Beven and Wood 1983; Beven et al. 1984; Hornberger et al. 1985) may provide an operational approach in drainage design.

Peak discharge estimation is required for surface drainage system design as well as the design of outlet ditches for subsurface systems. Two commonly used techniques are the Soil Conservation Service Unit Hydrograph method, and the Rational Formula.

The objectives of this research are:

1) to explore the feasibility of using a digital elevation model for watershed quantification in drainage design procedures,
2) to evaluate the soil conservation service curve number method of runoff estimation in a small upland watershed with a large degree of forest cover in the Lower Fraser Valley,
3) to evaluate the rational formula and soil conservation unit hydrograph procedure for peak discharge estimation in same watershed,
4) to evaluate a physically-based deterministic runoff model: TOPMODEL.

This thesis addresses the above objectives by verifying the methods and techniques commonly used in runoff and peak flow estimation with field data collected at Agriculture Canada farm #2 near Agassiz, British Columbia. The problem of watershed
quantification is addressed through the creation and use of a digital elevation model (DEM). The use of digital elevation models is fast becoming an integral component of Geographic Information Systems (GIS), as well as provincial and federal mapping programs; thereby a topical approach for the agricultural community to consider.
B. OVERVIEW OF THEORY AND PROCEDURES

B.1. Watershed quantification – conventional approaches

One of the first steps in preparing a farm water management scheme is to become acquainted with the field and watershed characteristics, namely the topography. The conventional approach involves field inspection, surveying of the field area, plus review of available map sheets for general watershed information such as area, slope, and hydraulic distances. The most common map available for this purpose is the 1:50 000 National Topographic Series (NTS) map sheet, unless special interest maps have been produced. For a small watershed under study for an on-farm subsurface drainage system, often the accuracy of the NTS map sheet is not adequate (a 1:50 000 map sheet is not intended for detailed feature extraction). The map is not produced with the same precision as a large scale map, thus the contour level or location may be inaccurate. A contour interval of 40 meters does not allow for identification of small depressions and seepage zones which are important in runoff estimation. Any measurements of area from a two dimensional map sheet do not incorporate slope, therefore in a mountainous watershed the area can be highly underestimated. The same is true of distances measured.

The study of topographic map sheets may be augmented with aerial photo interpretation, using standard provincial Ministry of Environment black and white aerial photography. This additional analysis (dependent upon the scale of the photography)
can add important information missing from the small scale maps. Measurements can still not be taken directly from the photographs, especially in areas of extreme terrain due to the severe relief displacement (the shift in the photographic position of an image caused by the relief of the object under study, i.e. it's elevation with respect to a selected datum). An orthophoto (a photograph showing images in their true orthographic positions i.e. planimetrically correct) takes out this displacement to allow direct measurement of terrain features, but they are not widely available in the Province. If a high profile resource project has been developed in the area of interest for drainage work, orthophotos may have been produced.

B.2. Digital elevation modelling

Another avenue for determining watershed characteristics is the use of a Digital Terrain Model (DTM), also referred to as a Digital Elevation Model (DEM).

A digital terrain model (DTM) consists of a set of numbers that represents the spatial distribution of a property of the terrain (Collins 1975). This may include coded information on any sort of terrain features (soil type, forest cover, geology, etc.) as long as this information is referenced to specific horizontal coordinates, and is in numerical form. The type of DTM developed and applied in this thesis is one in which the elevation \( Z \) is given as a function of the horizontal coordinates \( X \) and \( Y \), consequently often referred to as a digital elevation model (DEM).
The widespread acceptance of the advantages of map data in digital form is due to numerous reasons including:

1) with digital technology, computational processing, drafting and scribing, changes of scale and projections can be achieved at a fraction of the manual cost,

2) advances in computer technology and the decrease in hardware cost make it possible to design integrated, multifunctional systems that can efficiently do a large volume of work in one operation,

3) producers of digital mapping data are building data bases, primarily to support their own purposes, and secondly to allow for the exchange of data between various groups according to a standardized digital data base structure,

4) digital mapping technology provides the means for achieving a higher degree of accuracy throughout all stages from data acquisition by computer-aided photogrammetric compilation to representation by automated drafting/scribing (Allam 1982).

B.2.a. types of digital elevation models

Different types of DEMs may be distinguished by the regularity of the coordinate spacings:

B.2.a.i. the irregular DEM

In this type none of the coordinates occur in regularly spaced values. A common example is the product of a transit and stadia survey in which the rodman selects ground points at which there is a change in slope or some distinct feature. This type of DEM gives an adequate description of the topography with the
smallest number of points. It also requires the greatest number of decisions by humans in its production. Irregular DEM's can also be derived photogrammetrically (with a stereoplotter), but it is not a common practice to do so.

B.2.a.ii. the contour DEM

In this type the values of Z are equally spaced and the model is created in the contour mode (i.e. each contour level is traced individually). The points to be recorded can be chosen by inspection, thereby may be placed more closely in hilly or rough terrain, and far apart in flat areas. This may be done manually using a digitizer with a large scale map of the watershed (in point mode as described above) or in run mode which accepts a continuous stream of data along the contour at equal distances or equal time intervals. The contour DEM may also be created when the actual stereoplotting of the aerial photos takes place. A digital output is sent to a computer rather than direct plotting of the contour map using a mechanical pantograph. This eliminates one generation of map production.

B.2.a.iii. the profile DEM

In this type the values of either X or Y are equally spaced. The model is generated by tracing transects along a contour map, or scanning a photogrammetric model along equally spaced profiles. Profile DEMs are commonly used in civil engineering for the computation of volumes of earth-work. They may equally well be applied in agricultural engineering for calculating earth-work volumes for surface drainage systems.
The single regular DEMs produced by profiling and by contouring seem to be equally rapid in production and equally accurate in their representation of the terrain. The growth of interest in orthophotography will probably increase interest in profile DEMs because most existing orthophotoscopes are designed for orthophoto production in the profile mode (DEM's are by-products of off-line orthoproduction). However, increased interest and use of automated systems will lead towards adoption of the grid DEM below.

B.2.a.iv. the grid DEM

This is a special case of the profile DEM in which the spacing of the horizontal coordinate values along the profile are constant.

For a model that is limited to a given number of points, the grid DEM is inherently further removed from the real terrain surface than either the contour or profile DEM, just as these are further removed than the irregular DEM. In terms of computer storage, the grid DEM is most economical because it consists only of a list of Z values.

When using a contour map and digitizer to manually input Z values for an entire watershed into the computer, it is much preferred to use the contour method. Operator fatigue is much less as compared to tracing transects or profiles which may be spaced at intervals as little as 1mm on a base map. This again results in higher accuracy of the data base (Collins 1975).

The accuracy of the inverse process of reconstructing the
terrain, or the accuracy of deriving numerical values from the DEM, depends upon the DEM density; the closeness of spacing of the contours, profiles, or grid points. Once the data base is formed, it must be considered as true. No smoothing algorithms should be applied to alter contours, although editing capability is a definite advantage for the correction of incorrect data entry or artifacts.

With the increasing use of computer-based digitizing units (especially with micro-computers), there has been a strong and welcome trend towards the production of digital topographic data by means of: 1) digitizing photogrammetrically-produced graphic plots using manual digitizing tables, semi-automatic line following systems or automated raster scanning systems, and 2) direct photogrammetric instruments interfaced to digital computers (Allam 1982).

Once the data has been collected, a workable format must be created. For example, the data collected from digitizing contour lines will be in the form of a listing of X and Y co-ordinates for specified Z levels. There are various schools of thought on this matter: creation of a triangulated irregular network (TIN), creation of a grid, or creation of a TIN then converting it to a grid.

The TIN was developed by Dr. T. Poiker in the early 1970's at Simon Fraser University in British Columbia. The method involves triangulation between data points to create a triangular network. Advantages of the triangular subdivision are:
1) reproduction of the greatest possible number of fine details from a continuous surface,
2) since original data are used directly, the ground surface is better approximated as compared to using a square-grid interpolation,
3) computing time is much lower than in square grid methods which evaluate breaklines (i.e. watershed dividing lines) (Huegli et al. 1984).

A grid model (regular DTM) is built of meshes which form a square shaped grid in planimetry. The heights of the grid points are interpolated from the heights of given reference points. In photogrammetry, grid models are more frequently applied than triangle models. Their main advantage is the regular structure of the data, which makes the use of the DEM easier and more efficient (Ebner and Reiss 1984; Collins 1979). The square grid is particularly useful for fast computation of areas and volumes. The grid must have a density sufficient to represent the terrain adequately. This density depends on the nature of the features to be represented, and on the precision that is required for depicting the terrain surface or for calculating elevation-dependent quantities. The grid resolution should be maintained for all subsequent analysis using the DEM. It is predicted that geographic data bases will follow the grid format (Collins 1979).

B.2.b. application of digital elevation models

The increased appreciation of the advantages of map data in digital form is accelerating the application of digital mapping
and automated cartography. Numerous government mapping and resource agencies (at various levels), institutions, and private industry throughout the world are actively engaged in computer-aided map compilation and production. The advantages are to obtain a higher level of efficiency, cost effectiveness and improved responsiveness in the production of maps, charts and related information.

The Federal Government of Canada (Department of Energy, Mines & Resources) is involved in developing and implementing hardware and software systems, recommending standards, and providing DEM data bases on a national scale. The Federal Government has produced DEM base maps for nearly all of Southern Ontario, and a large portion of Labrador, Quebec, Northwest Ontario, and the Northwest Territories (at various grid sizes). The standard map scale they are converting to digital format (DEM's) is 1:50 000 (Wong 1985).

The Water Management Systems Division of the Inland Waters Directorate, Environment Canada, have utilized digital terrain data in river system monitoring in the Peace-Athabasca Delta modelling studies. The hydrodynamic approach to modelling as opposed to the hydrological routing approach requires the additional model input of surveyed cross sections, both for the channel and flood plains. In complex river networks subject to considerable overbank flooding, digital terrain data provide the most efficient and reliable means of adequately representing topographic features in a hydrodynamic model (Farley 1985).
The Alberta provincial government has embarked on a ten year program to implement a Geographic Information System: coverage of the entire province with DEMs at a 1:20 000 scale (grid format) providing base maps, as well as developing thematic overlays for resource information such as minerals, soil type, forest cover, public lands etc (Langford 1986). They are now in their fourth year of the project. Government directives have been issued to private industry regarding the format and standards required in DEM production, and submitted DEMs are currently being reviewed. It is their intention to make the system accessible on micro-computers, and a prototype study using a base sheet (DEM) and thematic overlays is being tested on an IBM-PCXT.

The Inventory Branch of the British Columbia Forest Service have developed and are successfully implementing a province-wide digital data base of forest stand information (at 1:20 000 scale). They plan to complete their Geographic Information System (GIS) by obtaining digital elevation data. This has most commonly been done through photogrammetric procedures, but the Ministry hopes to use high resolution imagery (ten meter ground resolution) from the French satellite SPOT (Hedgey 1986). The GIS is to be based on an IBM-PC image analysis system, eventually with one per district office.

The Provincial Ministry of the Environment in British Columbia are also involved in reviewing software and proposing a system for the conversion of the province's topographic maps into
digital format for the eventual adoption of a mini- and micro-based computer system. The proposed program is called TRIM, Terrain Resource Inventory Mapping, a three year, 15 million dollar program funded by the BC government to produce 1:20 000 digital maps (10 m contour interval) containing topography, planimetry, and cadastre. The work is to be carried out through the private sector, with specifications, data storage and dissemination, and administration the responsibility of the Surveys and Resource Mapping Branch, Ministry of Environment (Sondheim 1986). The start date is scheduled for the beginning of the 1986 fiscal year.

Raw DTM data will be collected from stereo aerial photographs (1:60 000 scale) using an analogue or analytical stereoplotter operated by a photogrammetrist. The Ministry has recently completed an accuracy evaluation project of the vertical mapping accuracy obtained with commercially available hardware and software in the production of digital elevation models. It was undertaken to determine whether proposed 1:20 000 topographic accuracy standards in British Columbia are realistic using present photogrammetric technology applied to 1:60 000 black and white photography. The study showed that the proposed accuracy standards for spot and interpolated relief data are realistic for gentle topography, but may frequently not be met for mountainous terrain. The present standards may not adequately address the problem of extreme errors (Sondheim 1986). It should be noted that this study only evaluated two procedures of data collection:
a regular grid pattern, and irregular points converted to a triangulated irregular network. All variables were not held constant in comparison of the methods, so recommendations of one method over an other are not absolute. Also, accuracies obtainable from large scale photography, say 1:20 000 or 1:10 000 going to a 1:10 000, or 1:5 000 scale DEM with the same 10 m contour interval were not evaluated (a more reasonable procedure for mountainous regions and watershed analysis for drainage design, but too large of a scale for complete provincial coverage). It is anticipated that one may be able to purchase a tape or floppy diskette from the Provincial Government containing a DEM equivalent to a 1:20 000 map sheet (a positional file containing XYZ values, possibly in grid format) (Sawayama 1985).

In the United States, the U.S. Geological Survey (USGS) through its National Mapping Program has provided a major program of digital mapping and technical assistance. The DEM is a by-product of the USGS orthophoto mapping program that transforms photo coordinates into model coordinates through automatic correlation by the Gestalt Photo Mapper II (a Canadian product) (Allder et al. 1982). DEM files may be purchased as standard 7.5-minute quadrangles at 30-meter intervals from the National Center in Virginia (White 1981).

As illustrated above, the concept and use of digital elevation models is not new, but has gained enormous development efforts and funding commitment over the past few years. With the rapid improvements in computer technology and software systems,
plus the increased awareness of potential benefits, DEMs are bound to become standard tools of resource managers and planners. For these reasons, the feasibility of using a DEM in agricultural hydrology for watershed quantification was evaluated in this thesis.
C. RUNOFF ESTIMATION PROCEDURES

C.1. Hydrograph analysis

The hydrograph can be regarded as an integral expression of the physiographic and climatic characteristics that govern the relations between rainfall and runoff of a particular drainage basin (Chow 1964). The water which constitutes streamflow and creates the discharge hydrograph may reach the stream channel by several paths from the point where it first reaches the ground as precipitation.

The three main routes of travel traditionally described are overland flow, interflow, and groundwater flow:

1) overland flow or surface runoff: overland flow is that water which travels over the ground surface to a channel (any depression which may carry a small rivulet of water in turbulent flow during a rain and for a short time afterwards). Such channels are numerous, and the distance water must travel overland is generally small. Overland flow therefore reaches the channel in a short time period, and may be an important element in the formation of flood peaks when existing in reasonable amounts.

2) interflow or subsurface flow: some of the water which infiltrates the soil surface may move laterally through the upper soil layers until it enters a stream channel, thus called subsurface flow. Subsurface flow moves much more slowly than the surface runoff.
3) groundwater flow or base flow: precipitation that percolates down to the groundwater table may eventually discharge into the streams as groundwater flow if the water table intersects the stream channels of the basin.

The hydrograph analysis technique relies on the separation of the hydrograph into at least two components, and this is at its best an empirical separation (Raudkivi 1979). These two components are base flow and storm or direct runoff. Either may contain a certain amount of the subsurface flow (Linsley et al. 1982).

A typical simple hydrograph resulting from an isolated period of rainfall consists of a rising limb, crest segment, and fall or recession limb. The shape of the rising limb is influenced mainly by the storm characteristics. The shape of the recession is largely independent of the characteristics of the storm causing the rise. The point of inflection on the falling side of the hydrograph is commonly assumed to mark the time at which surface inflow to the channel system ceases. Thereafter, the recession curve represents withdrawal of water from storage within the basin. If there is no surface inflow into the channel system, the recession curve represents subsurface and base flow contributions.

Since there is no ready basis for distinguishing between direct and groundwater flow in a stream at any instant, and since definitions of these components are relatively arbitrary, the method of separation is equally arbitrary (Linsley et al. 1982).
If the base flow is assumed either to include or to exclude the entire portion of the subsurface flow, several forms of recession curve analysis may be used for base flow determination and for base flow separation from the direct runoff of a hydrograph (Chow 1964). Barnes (Linsley et al. 1982) suggests that the recession can be approximated by three straight lines on a semilogarithmic plot. The transition from one line to the next is often so gradual that it is difficult to select the points of change in slope (due to the heterogeneity of the typical catchment). The slope of the last portion of the recession should represent the characteristic recession constant for groundwater since, presumably, both interflow and surface runoff have ceased. By projecting this slope backward in time (fig. 1) and reploting the difference between the projected line and the total hydrograph, a recession which consists largely of interflow is obtained. A slope applicable to interflow is now determined, and the process can be repeated to establish the recession characteristics of surface runoff.
Figure 1: Barnes method - logarithmic plotting of a hydrograph showing method of recession analysis (Linsley et al. 1982)

The above technique represents a degree of refinement rarely used for engineering problems. The base-flow recession curve is most frequently used. One method to construct this curve is to piece together sections of recessions from various storms until a composite curve is obtained which covers the necessary range of flow rates. The recession curve may also be developed by plotting values of the initial flow ($q_0$) against flow ($q_t$) at some fixed time ($t$) later.

However, as runoff is normally considered to be divided into only two parts: direct runoff and base flow, and both parts may contain a certain amount of the subsurface runoff; base-flow
separation is usually made in an arbitrary manner and it is not significant to even consider the exact amount (which is unknown anyway) to be included in or excluded from the base flow (Chow 1964).

For application of the unit hydrograph concept, the method of separation should be such that the time base of direct runoff remains relatively constant from storm to storm. This may be achieved by terminating the direct runoff at a fixed time after the peak of the hydrograph. The fixed time in days $N$ may be approximated by

\[ N = bA^{0.2} \]  

[1]

where $A$ is the drainage area and $b$ is a coefficient. The value of $b$ is 0.8 when $A$ is in square kilometers and unity when $A$ is in square miles. The fixed time, $N$, may be better estimated by evaluating storm hydrographs, maintaining the total time at a reasonable length (Linsley et al. 1982; Chow 1964).

The most widely used separation procedure consists of extending the recession existing before the storm to a point under the peak of the hydrograph (AB, Fig. 2). From this point a straight line is drawn to the hydrograph at a point $N$ days after the peak (as defined above). The reasoning given for this procedure is that as the stream rises, there is flow from the stream into the banks; therefore, base flow should decrease until stages in the stream begin to drop and bank storage returns to the channel.

The simple way to make a base-flow separation is to draw a
straight line from the point of rise to an arbitrary point (N days) on the lower portion of the recession segment of the hydrograph (AC, Fig. 2).

A third method of separation is illustrated by line ADE (Fig. 2). This line is constructed by projecting the recession of the groundwater after the storm back under the hydrograph to a point under the inflection point of the falling limb. An arbitrary rising limb is sketched from the point of rise of the hydrograph to connect with the projected base-flow recession (Linsley et al. 1958).

![Diagram of hydrograph with points A, B, C, D, E, and line ADE](image)

Figure 2: Some simple baseflow separation procedures (Linsley et al. 1982)
Complex hydrographs resulting from two or more closely spaced bursts of rainfall are more difficult to analyse. It is necessary to separate the runoff caused by individual bursts of rainfall in addition to separating direct runoff from base flow.

If a base-flow separation such as line ABC of Figure [2] is used, bursts of rainfall are divided by projecting the small segment of recession between peaks using a total-flow recession curve for the basin (line AB, Fig. 3). Direct runoff for the two periods of rain is given by areas I and II. There must be two clearly defined peaks with a short segment of recession following the first in order to do this type of separation.

![Figure 3: Separation of complex hydrograph using recession curve (Linsley et al. 1982)](image-url)
Area under a discharge hydrograph represents volume of runoff (Q):

$$\text{vol} = \int Q dt$$

[2]

The area under the curve may be calculated by integrating the hydrograph curve. It may also be determined by manually determining the enclosed area below the hydrograph and baseflow separation line.
C.2. Soil Conservation Service curve number method

The United States Soil Conservation Service (SCS) has developed a set of empirical curves to relate storm precipitation to direct runoff (see figure 16). The procedure was developed in the early 1950's and has become a widely used and accepted means for estimating stormflow volumes for design and natural events in small ungauged watersheds (Hope and Schulze 1982).

The primary input parameter of the SCS model is the runoff curve number (CN). The curve number is a weighting factor which reflects the importance of three major parameters: the land use and treatment class, the soil hydrologic group, and the antecedent moisture condition.

C.2.a. land use and treatment classes

In the SCS method of runoff evaluation, the effects of surface conditions are evaluated by means of land use and treatment classes. Land use is the watershed cover and it includes every kind of vegetation, litter and mulch, and fallow (bare soil) as well as non-agricultural uses such as water surfaces (lakes, swamps, etc.) and impervious surfaces (roads, roofs, etc.).

Land treatment applies mainly to agricultural land uses and it includes mechanical practices such as contouring or terracing, and management practices such as grazing control or crop rotation.

Land use and treatment classes are obtained either by observation or by measurement of plant and litter density and
extent on sample areas. In areas where commercial forest covers a large part of the watershed, U.S. Forest Service procedures for determining forest hydrologic conditions are used (USDA 1972).

C.2.b. hydrologic soil groups

The hydrologic soil group measures the ability of soils to absorb water through infiltration. The greater the infiltration, the less the direct runoff.

The premise in assigning soils to a particular hydrologic group is that soils with comparable depth, organic matter content, structure, and degree of swelling when saturated, will respond essentially the same during a rainstorm with excessive intensities.

The four hydrologic groups outlined are:

A. (low runoff potential - overland flow). Soils having high infiltration rates even when thoroughly wetted and consisting chiefly of deep, well to excessively drained sands or gravels. These soils have a high rate of water transmission (e.g. deep sand, deep loess, aggregated silts), thus overland flow rarely occurs.

B. Soils having moderate infiltration rates when thoroughly wetted and consisting chiefly of moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission (e.g. shallow loess, sandy loam) and generally do not produce overland flow.

C. Soils having slow infiltration rates when thoroughly wetted
and consisting chiefly of soils with a layer that impedes downward movement of water, or soils with moderately fine to fine texture. These soils have a slow rate of water transmission (e.g. clay loams, shallow sandy loam, soils low in organic content, and soils usually high in clay) thereby prone to producing overland flow.

D. (high runoff potential) Soils having very slow infiltration rates when thoroughly wetted and consisting chiefly of clay soils with high swelling potential, soils with a permanent high water table, soils with a claypan or clay layer at or near the surface, and shallow soils over nearly impervious material. These soils have a very slow rate of water transmission (e.g. heavy plastic clays, and certain saline soils) thereby causing overland flow.

The SCS soil group can be identified at a site using one of three ways:

1) soil characteristics
2) soil maps
3) minimum infiltration rate

The minimum rate of infiltration (as obtained for a bare soil after prolonged wetting) incorporates the influences of both the surface and the horizons of a soil. Table 1 below outlines the minimum infiltration rates for the four hydrologic soil groups.
<table>
<thead>
<tr>
<th>Group</th>
<th>Minimum Infiltration Rate (in/hr)</th>
<th>Minimum Infiltration Rate (cm/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.30 - 0.45</td>
<td>0.762 - 1.143</td>
</tr>
<tr>
<td>B</td>
<td>0.15 - 0.30</td>
<td>0.381 - 0.762</td>
</tr>
<tr>
<td>C</td>
<td>0.05 - 0.15</td>
<td>0.127 - 0.381</td>
</tr>
<tr>
<td>D</td>
<td>0.00 - 0.05</td>
<td>0.00 - 0.127</td>
</tr>
</tbody>
</table>

Table 1: Minimum Infiltration rates for soil hydrologic groups (McCuen 1982)

Areal extent for different soil groups must be determined through procedures such as planimetering, or ideally if available from a digital elevation model of the watershed. When delineating the soil groups, a general rule is recommended: two groups are combined only if one of them covers less than about 3 percent of the hydrologic unit. Impervious surfaces should always be handled separately because they produce runoff even if there is none from D soils.

C.2.c. antecedent moisture condition

The antecedent moisture condition (AMC) measures the dryness of the soil and its readiness to absorb further water through infiltration. Three antecedent moisture conditions are recognized:

1) AMC I - the soil is dry and has the ability to absorb large quantities of water through infiltration,
2) AMC II - an average condition in which the soil is moist but still has the capacity to absorb considerable water, and
3) AMC III - the soil is nearly saturated and has negligible
ability to absorb further water.

The AMC is determined on the basis of the total precipitation from the five days preceding the storm as outlined in Table 2 below:

<table>
<thead>
<tr>
<th>Preceding 5 day precipitation (mm)</th>
<th>AMC I</th>
<th>AMC II</th>
<th>AMC III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Growing Season</td>
<td>&lt; 35</td>
<td>35.0 - 52.5</td>
<td>&gt; 52.5</td>
</tr>
<tr>
<td>Dormant Season</td>
<td>&lt; 12.5</td>
<td>12.5 - 27.5</td>
<td>&gt; 27.5</td>
</tr>
</tbody>
</table>

Table 2: Available Moisture Condition classification (Smedema and Rycroft 1983)

The growing season in the Lower Fraser Valley is considered to be March 1 to November 1, and the dormant season November 1 to March 1. In design procedures the antecedent soil moisture condition is often a policy decision rather than a statement of actual soil conditions at the site. (i.e. AMC II is assumed in the growing season, and AMCIII in the dormant season).

C.2.d. runoff estimation

Appropriate curve numbers are chosen for a given watershed to reflect the above characteristics. The related runoff is then calculated using relationships established by the Soil Conservation Service (USDA 1972; McCuen 1982).
C.3. Physically based rainfall-runoff models

Since the 1930's the Horton (1933) infiltration approach to runoff production has dominated hydrology and its applications to the prediction of river discharges and in land management (Dunne et al. 1975). The hydrological response of catchments to storm rainfall has traditionally been viewed as predominantly controlled at the soil surface. Where the infiltration capacity of the soil is exceeded, the excess rainfall will generate the surface runoff that was assumed to provide the bulk of the storm hydrograph. The Horton model of overland flow has been confirmed by repeated field observation and hydraulic study in semiarid regions and on agricultural lands such as those of the Midwestern United States.

Since the infiltration capacities of soils on a catchment are rarely uniform, the production of Horton overland flow varies spatially. Hewlett (1961) developed the partial-area model of storm runoff based on the original Horton analysis of overland flow, but suggesting that only a small portion of some catchments contributes storm runoff. This led to further research efforts by Betson (1964).

In humid regions, the infiltration capacity of the soil remains high unless the dense vegetation cover is disturbed. Hence, Horton overland flow is confined to locations such as roads, skid trails in forests, some ploughed fields, artificial fills, and other areas that have been denuded of their vegetation. Overland flow can also occur under snowpacks in
areas where the infiltration capacity is lowered by the presence of concrete frost in the soil.

In humid regions that have not been severely disturbed, Horton overland flow does not occur (Dunne et al. 1975). Under these conditions, the storm hydrograph may either be generated almost entirely by subsurface flows, or saturation overland flow (Beven and Wood 1983). Subsurface stormflow occurs where rainwater enters some zone of a permeable soil and displaces soil water to the stream (referred to as translatory flow (Hewlett and Hibbert 1967)). Subsurface stormflow may also include some of the storm rainfall. When subsurface stormflow is unable to remove all the incoming rainwater, the consequent increase in the amount of water stored in the soil raises the water table to the soil surface in swales and on the lower parts of hillslopes. Subsurface water can then emerge from the soil surface as return flow, and run overland at much greater velocities than are possible for subsurface stormflow. Rain falling directly on the saturated area also runs off as overland flow. These last two processes may be grouped together as saturation overland flow. Such areas of saturated soil have been shown to expand and contract both seasonally and within individual storm events.

A choice is available between an infiltration rate approach to the prediction of overland flow (as originally described by Hewlett (1961) and used in the model of Engman & Rogowski (1974)), and a soil storage based approach in which the infiltration rate is essentially considered to be non-limiting
such that overland flow is predicted when storage capacity is exceeded (Beven and Kirkby 1979). The different views of how catchments respond becomes largely a question of semantics, but the important points to recognize are that catchment storm response may involve significant subsurface contributions, while runoff contributing areas may be highly dynamic (Beven and Wood 1983).

A number of physically based deterministic models of the variable contributing area concept of basin response are reported in the literature (Beven and Kirkby 1979). These models, of varying degrees of sophistication and methodological rigour, have been essentially based on distributed moisture accounting for soil elements within segments of hillslope. The data and computing requirements of these models are so great that they restrict their practical application to research projects where economic criteria are less dominant. Also, none of the models make little use of topographic and soil information, even though both are important in determining source areas. In developing a simpler model, Beven and Kirkby (1976) presented a simple physically-based hydrograph model, TOPMODEL, that attempts to combine the advantages of a lumped representation of average soil water response with the distributed effects of a variable contributing area. The model has since existed in many forms and has been expanded to include flow routing through the channel network.
C.3.a. model structure

TOPMODEL (topography-based hydrological model), is based on the combination of several linear storage components organized in a series chain (i.e. output from one storage level becomes input into the next). A fundamental assumption of the model is that the catchment under study may be subdivided into several subcatchment units which are relatively homogeneous in their hydrologic response and which should therefore be modelled separately. The sub-basin model has been formulated from the components as illustrated in Figure 4:

![Diagram](image)

Figure 4: A schematic representation of the sub-basin model

C.3.a.i. interception/depression store

The interception/depression store, $S_1$, has a maximum value $S_D$ which must be filled before any infiltration takes place into the lower stores. Evaporation is allowed from this store at the
estimated potential rate until it is empty.

C.3.a.ii. near-surface (infiltration) store

The near-surface (infiltration) store, $S_2$, receives water from the interception store, $S_1$, when the latter is full, at a rate $i$ equal to the excess rainfall, unless the infiltration capacity is exceeded.

\[ i > i_{\text{max}} = i_o + b/S_2 \]  

[3]

where $i_o$ is the constant leakage rate allowed from $S_2$ to the exponential subsurface store within the area that is not considered saturated.

In this case excess rainfall $(i - i_{\text{max}})$ is considered to reach the basin outlet by a surface route (infiltration excess overland flow). If under extreme conditions a maximum value of near surface storage (infiltration store), $S_c$, is exceeded then again excess water is considered to reach the sub-basin outlet by a surface route (saturation excess overland flow).

Further losses due to evapotranspiration are allowed from this store at a decreasing rate depending on the level of the infiltration store, $S_2$. Thus

\[ e_a = e_r S_2 / S_c \]  

[4]

where $e_r$ is the potential evapotranspiration remaining once the interception store $S_1$ is depleted, and $e_a$ is the actual loss from the infiltration store.
C.3.a.iii. variable contributing area component related to subsurface soil water storage

Rain falling on the contributing saturated area will immediately become overland flow. For a given saturated zone storage level, \( S_3 \), the saturated area is that for which

\[
\ln\left(\frac{a}{\tan\beta}\right) > \frac{S_T}{m} - \frac{S_3}{m} + \lambda \tag{5}
\]

\[
\lambda = A^{-1} \int \ln \left(\frac{a}{\tan\beta}\right) \, dA \tag{6}
\]

where:
- \( a \) = area drained /unit contour length at a point
- \( \tan\beta \) = slope gradient at that point
- \( m \) = a parameter of the exponential relationship between storage and lateral flow
- \( \lambda \) = a constant for the subcatchment representing the average areas for \( (a/\tan\beta) \) given by the above equation.
- \( A \) = total subcatchment area
- \( S_T \) = the local saturated storage (assumed spatially constant)
- \( S_3 \) = negative moisture deficit, at complete saturation \( S_3 = 0 \) and \( S_3 < 0 \) for less than full saturation.

The contributing area is also required to calculate the overland flow discharge \( Q_{OF} \):

\[
Q_{OF} = \frac{i}{A_c} \tag{7}
\]

where \( i \) = instantaneous rainfall intensity

\( A_c \) = contributing area

C.3.a.iv. delayed subsurface flow

Delayed subsurface flow from the non-linear saturation store is represented as an exponential store for which
\[ q_b = q_o \exp\left(\frac{S_3}{m}\right) \]  

where:  

- \( q_b \) = the flow reaching the channel from the store  
- \( q_o \) = the flow when \( S_3 = 0 \) (soil is completely saturated)  

(\( q_o \) has the primary function of adjusting the outflow from the exponential store as calculated using average storage and the estimated value of \( m \), to be equivalent to the subsurface outflow from the basin as a whole.)  

- \( m \) = a constant which controls the slope of the recession limb of the hydrograph  

This sequence of storage elements is assumed to represent the average response of the soil water in a homogeneous sub-basin unit. In this respect, each sub-basin is treated as a lumped system. It is assumed that the dominant source of quick return or surface flow is an area of surface saturation, or variable contributing area, the extent of which varies with the average level of subsurface soil water storage as represented by the store \( S_3 \) (Beven and Kirkby 1979).  

C.3.a.v. overland flow  

The overland flow component may be estimated as  

\[ q_{of} = iA_c \]  

where \( i \) is the instantaneous rainfall intensity and \( A_c \) is the saturated area. Early modelling in the Crimple Beck catchment in England (Beven 1977) suggested that even for small sub-basin areas, overland flow travel times were causing a significant delay in the timing of sub-basin discharge. A simple overland flow routing routine was thus included in the model based on the
expected spread of contributing area in relation to the
topography and a constant overland flow velocity OFV. Overland
flow within the contributing area is routed at a velocity
proportional to local gradient, with the parameter OFV as the
constant of proportionality. The time taken to reach the sub-
basin outlet from any point within the predicted contributing
area is given by
\[
\sum_{i=1}^{N} \frac{x_i}{\text{OPV} \tan \theta_i}
\]
where \(x_i\) is the length of the \(i\)th flow path segment of slope
\(\tan \theta_i\), and \(N\) is the number of segments between the point and the
outflow. For a given value of \(A_c\), a unique time-delay histogram
can be derived from the basin topography which allows overland
flow to be routed to the outlet (Beven and Kirkby 1979).

In Beven et al. (1984), a new routing procedure was used; a
simple non-linear convolution routing algorithm based on the at-
a-station velocity relationship:
\[
c(t) = CHA \cdot Q(t)^{CHB}
\]
where \(Q(t)\) is the outflow discharge for the whole catchment at
time \(t\); \(CHA\) and \(CHB\) are constants; and \(c(t)\) is an average
kinematic wave velocity for the channel network which is assumed
to be spatially constant. The routing procedure accounts for the
distribution of predicted subcatchment inflows with distance
along the channel network (Beven et al. 1984).

C.3.b. model theory

TOPMODEL uses readily available topographic data in
conjunction with a limited amount of soil information so that
not only can the variation in basin topography and channel topology be readily described, but physically-based soil parameters can be measured in any catchment. Since all the model parameters can be obtained by direct measurement for a particular area, the model should be applicable to ungauged catchments of up to 500 km$^2$, where only rainfall and evaporation data are available. The model has been designed specifically for unforested catchments with a humid-temperate climate (this restriction is mainly based on the procedures used to incorporate evapotranspiration) (Beven et al. 1984).

As per Beven and Kirkby (1979), it is assumed that at any point in the catchment, downslope flow per unit width of slope, $q$, is related to saturation deficit, $S$, by:

$$q = K_0 \exp(-S/m) \tan \theta$$

[12]

where $K_0$ is the saturated conductivity at the soil surface, and $m$ is a parameter of the recession curve (subsurface flow parameter). Return flow as well as subsurface flow are governed by this equation (Beven 1985).

Saturation deficit ($S$) is defined as the storage deficit below full saturation due to soil drainage alone and excluding the additional deficits that would result from evapotranspiration. Thus $K_0 \tan \theta$ is the transmission capacity of the soil profile at full saturation, where $\tan \theta$ is the local surface slope angle. This relationship allows soil hydraulic conductivity to vary with depth but assumes that the local hydraulic gradient is equal to the surface slope angle.
Assuming steady state input rate, $R$, at any point

$$q = Ra \tag{13}$$

where $a$ is the upslope area drained per unit width of slope or contour length.

Combining equations [12] and [13] above,

$$S = -\ln(aR/K \tan \beta) \tag{14}$$

The saturated area may then be defined as the area which

$$S < 0$$

or

$$a/\tan \beta < k_o/R \tag{15}$$

(notating that deficits are $+ve$)

The average storage deficit in the catchment is given by:

$$\bar{S} = A^{-1} \int_0^A S \, da = A^{-1} \int_0^A -\ln(aR/K_o \tan \beta) \, da \tag{16}$$

It is further assumed that $K_o$ and $m$ are constant, i.e. that the soil is homogeneous and of a uniform depth then

$$\bar{S} = -m \lambda - m \ln(R/K_o) \tag{17}$$

where:

$$\lambda = A^{-1} \int_0^A \ln(a/\tan \beta) \, da \tag{18}$$

is a constant for the catchment dependent on topography.

From equation [17]:

$$\ln(R/k_o) = -S/m - \ln(a/\tan \beta) \tag{19}$$

so that

$$\bar{S} = -m \lambda + S + m \ln(\tan \beta) \tag{20}$$

It is also assumed that subsurface drainage from the complete
basin $Q_B$ is described by a similar exponential function to equation [12], involving the average deficit $\bar{S}$:

$$Q_B = Q_o \exp(-\bar{S}/m)$$

or also expressed as:

$$q_B = q_o \exp(S_3/m)$$

where $S_3$ is the saturated zone storage, and $m$ is a parameter of the recession curve of the catchment and can easily be estimated from a minimum of discharge measurements.

The model of Beven and Kirkby (1979) involved continuous accounting for the subsurface storage deficit $\bar{S}$, so that at any time, given $\bar{S}$ and the distribution of $\ln(a/\tan\theta)$ in the catchment, equation [14] based on steady-state assumptions, was used to predict the dynamic response of the contributing area for which $S < 0$ or:

$$\ln(a/\tan\theta) > \bar{S}/m + \lambda$$

This approach was modified somewhat by Beven and Wood (1983) where their interest was directed to predicting the response to individual large storms. Equation [14] not only gives a relationship for predicting saturated areas for any value of $\bar{S}$ but also for predicting the saturation deficits anywhere in the catchment. If a value of initial catchment discharge, $Q_i$ is available prior to the storm, then equations [14] and [15] may be combined to give:

$$S = m \lambda - m\ln(a/\tan\theta) - m\ln(Q_i/Q_o)$$

Values of $S < 0$ indicate an initial saturated area, while elsewhere the deficit must be filled before saturation is
predicted for each value of \( \ln(a/\tan\theta) \).

The saturation deficit approach to predicting variable contributing areas neglects the dynamic response of the subsurface flow system (Beven and Wood 1983). One of the failings of the earlier Beven and Kirkby (1979) model was in its treatment of the delays in the unsaturated zone in affecting the subsurface response. The use of the initial saturation deficit approach outlined above also suggests a convenient way to allow for the effect of the unsaturated zone.

For any area of soil at or near saturation, the unsaturated zone delay will be minimal, and will increase upslope for points of higher initial deficit (lower \( \ln(a/\tan\theta) \)). If it is assumed that the delay in the unsaturated zone is directly proportional to deficit at a point, then the input to the saturated zone at that point \( q_v \) may be described by:

\[
q_v = \frac{S_{uz}}{(t_d S)}
\]

where \( S \) is the predicted saturation deficit, \( t_d \) is a time delay per unit of deficit; and \( S_{uz} \) is storage in the unsaturated zone in excess of some field capacity value below which vertical flows may be neglected on the time scale of the storm hydrograph. The average residence of the unsaturated zone is effectively \( t_d S \). Given the different values of \( S \) associated with different values of \( \ln(a/\tan\theta) \), an areally weighted reduction in the catchment average deficit \( S \) can be calculated during a time period. Subsurface output in the same time period can be calculated from equation [17] allowing continuous accounting for \( S \).
Recalculation of the saturation deficits predicted from $S$ at each time step makes allowance for downslope flows and, during drainage, the recovery of saturation deficits between closely spaced events. In this way both surface and subsurface responses can be predicted, thereby avoiding any arbitrary hydrograph separation prior to analysis (Beven and Wood 1983).

The model has also been modified to account for the spatial variability of soil hydraulic characteristics (Beven 1985).

$$S = S_i - m \gamma + m \ln \left( \frac{a}{K_i \tan \beta_i} \right)$$  \[26\]

where $\gamma$ is a basin constant:

$$\gamma = \frac{1}{A} \int_A \ln \left( \frac{a}{K_i \tan \beta_i} \right)$$  \[27\]

The use of equation [26] in a continuous accounting model assumes that the steady state relationships used in the development are a good approximation to storage relationships under transient conditions. If this is a reasonable assumption, equation [26] allows for prediction of the pattern of soil moisture deficit within the catchment, and particularly the saturated contributing area ($S_i < 0$), from knowledge of topography and soil characteristics. The basin constant $\gamma$ can be divided into a topographic part and a soil part where the first integral is the topographic constant $\lambda$ of Beven and Kirkby (1979):

$$\gamma = \frac{1}{A} \int_A \ln \left( \frac{A}{\tan \beta} \right) - \frac{1}{A} \int_A \ln (K_i)$$  \[28\]
C.3.c. model calibration

C.3.c.i. overland flow, interception and infiltration parameters

Model calibration for overland flow, interception, and infiltration parameters ($S_D$, $S_o$, $i_o$, and OPV) in TOPMODEL requires field experimentation using a sprinkling infiltrometer. A single or double ring infiltrometer could not be used for the calibration. A ground plot with a sufficient area for generating surface runoff, and a means of collecting and measuring this runoff is imperative for parameter determination. A sprinkling infiltrometer allows native vegetation to remain intact giving a more representative estimation of interception store near the ground surface. Simulating rainfall on the ground instead of flooding with a constant head as in using a ring set-up is more realistic, especially in the upland soils where ponding does not usually occur (unless in small depressions).

The sprinkling infiltrometer used by Beven (1977) is shown in figure 5 below where:

a. one wheeled trolley with motor, pump, pressure gauge and two 5-gallon water reservoirs
b. sprinkler nozzle
c. sprinkler bar
d. height adjustment for sprinkler bar
e. polyethylene wind shield
f. runoff plot boundary
g. splash cover over runoff collection tube
h. runoff collection tube - in trench
The above apparatus was relatively portable, with reasonably even ground cover and minimal wind effects (Beven 1977). The rates of application that could be achieved (30 to >200 mm/hr equivalent) were, however, high in relation to the range of recorded rainfall rates in the Crimple Beck watershed under study.

Beven found that the sprinkling infiltrometer could be much improved, in particular to allow lower rates of application, more realistic drop sizes, and vehicle mounted water reservoirs.

At least one sprinkler test is recommended on each major soil and vegetation type (Beven and Wood 1983). Calibration is performed as follows:

a) One or more soil cores are taken adjacent to the chosen
site, for analysis of near surface soil water storage \( (M_1) \) prior to the experiment.

b) Infiltrometer apparatus is set up at the chosen site, and when proper head has been attained in the infiltrometer for desired sprinkling rate, time is started and water is allowed to reach soil.

c) Once overland flow has begun on the plot, the runoff is collected at given time periods (to calculate the rate of runoff/unit area) until a constant runoff rate is obtained.

d) When constant runoff is reached, an estimate of velocity of surface runoff is obtained by applying dye at the upslope end of the plot and estimating the travelling time to the opposite end of the plot by eye. This may be more accurately determined by the analysis of runoff samples taken at known times on a fluorimeter.

e) A measurement of surface slope, \( \tan \beta \), at the site allows the parameter OFV to be calculated from:

\[
\text{OFV} = \frac{x}{\bar{t} \tan \beta}
\]

where \( \bar{t} \) = the average time of travel
\( x \) = the length of the plot
\( \beta \) = plot slope

f) Rainfall is stopped, and when runoff has ceased a soil core is taken from the centre of the plot \( (M_2) \).

g) Once all rates of flow and soil moisture values have been calculated, a graph of runoff rate and infiltration rate \( (i_0 \) as
calculated from sprinkler application rate - runoff rate) is drawn (similar to that in figure 6). In the simplest form of analysis the parameter $i_o$ is taken as the final constant infiltration rate. The maximum value of interception store $S_D$ is taken as the amount of water applied before the constant runoff is achieved minus the change in near surface soil water storage ($M_2 - M_1$).

![Figure 6: Results from a sprinkling infiltrometer experiment, Landshaw sub-basin (Beven and Kirkby 1979).](image)

If infiltration rates are greater than the input (artificial precipitation rate), the parameter $S_2$ (infiltration store) is inoperative. When measured values of $i_o$ (final constant infiltration rate) are used in the model, the infiltration store as a whole has little or no effect on the predicted discharges and does not provide a delay before flow reaches the subsurface store.

If infiltration rates are less than the sprinkling input rate, the linear infiltration store, ($S_2$), serves to model the
delay before infiltrated water reaches the subsurface saturated soil water store. Estimation of the parameters \( b \) and \( S_c \) requires a more complex procedure involving several spray tests carried out at different application rates. Under a constant rate of input, \( i \), to the near surface store \( S_2 \) (as in the sprinkler test) surface flow may occur either as a result of the infiltration capacity, \( i_{\text{max}} \), or the total storage capacity, \( S_c \), being exceeded. If \( T \) is the time from the start of the test to the onset of overland flow and \( T' \) is the time required to fill the depression storage \( S_D \), (that is \( T' = S_D/i \)) then for infiltration excess overland flow

\[
i_{\text{max}} \leq i
\]

or from equation [3]

\[
i_o + \frac{b}{S_2} \leq i \quad \text{when} \quad S_2 = (T-T')(i-i_o)
\]

This assumes that the depression storage \( S_D \) is satisfied first, or

\[
i_0 + b(i-i_o)(T-T')
\]

or

\[
T-T' = \left( \frac{b}{i-i_o} \right)^2
\]

For saturation excess overland flow, the storage \( S_2 \) at the onset of overland flow is equal to \( S_c \):

\[
S_c = (T-T')(i-i_o)
\]

or

\[
T-T' = \frac{S_c}{i-i_o}
\]

Plotting \((i-i_o)\) against \(\log(T-T')\) for tests at different
application rates should distinguish the two mechanisms of overland flow generation, and enable the parameters \( b \) and \( S_c \) to be determined from the intercepts on the \((i-i_0)\) axis (figure 7):

![Diagram](image)

Figure 7: Expected nature of results from infiltrometer experiments interpreted in terms of the storage based infiltration component of the model (Beven and Kirkby 1979).

C.3.c.ii. subsurface storage parameters

The parameter \( m \) of the exponential subsurface store is estimated by making discharge measurements at the subsurface catchment outflow during a recession period of zero rainfall. Any existing discharge measurements within the catchment can be incorporated in the analysis. The discharge measurements are converted to mm per unit area equivalent from which an estimate of change in average storage level in the sub-catchment during the period of measurement can be calculated. The use of a winter recession period is recommended to minimise the effect of evaporation on the change in storage which otherwise must be taken into account.
If the subsurface contribution to drainage from the catchment conforms to the exponential store that is assumed in the model, then a graph of calculated relative storage level (as the abcissa) versus \( \log_e (\text{measured discharge}) \) (as the ordinate) should plot as a straight line with a slope of \( 1/m \). Given a value of \( m \) for a subcatchment, the subsurface parameter \( Q_o \), can be calculated from measurements of average soil water storage obtained from soil cores taken throughout the soil profile at a number of locations in the subcatchment, at a known value of discharge (\( q_b \)) per unit area from the catchment. Substitution into the following equation yields a value of \( q_o \).

\[
q_b = q_o e^{S_3/m} \quad [36]
\]

The value of the final subcatchment parameter \( S_o \), the initial value of \( S_3 \) at the start of a simulation run, can be found by substituting a known or estimated value of actual discharge from the catchment into equation [22], given \( q_o \) and \( m \). This procedure is only satisfactory if the simulation run starts during a recession period such that all subcatchment discharge is derived from subsurface drainage and both the interception and infiltration stores may be assumed to be dry provided that the model is a suitable representation of subcatchment behaviour. Errors in the initial conditions are quickly damped out and have been found to have little effect on the simulations (Beven 1977).

**C.3.c.iii. channel routing parameters**

Channel routing is expressed by the flow velocity relationship of the following equation:
\[ C(t) = C_A Q(t)^{C_B} \]  

where \( Q(t) \) is the discharge at the outflow of the whole catchment at time \( t \) and \( C(t) \) is an average kinematic wave velocity for the network which is assumed to be spatially constant. The parameters \( C_A \) and \( C_B \) can be obtained by non-linear regression calculations.

C.3.d. analyzing catchment topography

The derivation of \( \ln(a/\tan\beta) \) distributions for real catchments will always involve some degree of subjective generalization and abstraction (Beven and Wood 1983). Beven and Kirkby (1979) used a computerized procedure based on flow lines orthogonal to the contours on large-scale topographic maps as drawn by hand after preliminary evaluation of air photographs and field inspection. This procedure was very time-consuming. With the increasing availability of data banks of digitized topographic maps at a scale of 1:24 000 or better, this part of the analysis is handled automatically using a digitizer tablet and digital elevation model (Beven and Wood 1983). Beven and Wood (1983) have also explored the possibility of subdividing a catchment into a number of idealized flow planes for which distributions of \( \ln(a/\tan\beta) \) and the parameter \( \lambda \) could be derived analytically.

The analytical derivation of topographic characteristics involves subdividing a catchment into three different types of idealized subcatchments; namely, rectangular planes, rectangular curved, and radially convergent surfaces. The analytical results for these idealized flow surfaces are given below.
C.3.d.i. rectangular planes

The catchment can be represented by a V-shaped rectangular plane with overland flow length L, and stream length x; 0≤x≤L. The derived functions are as follows:

\[
a / \tan \beta = (L - x) / \tan \beta \quad [38]
\]

\[
\lambda = A^{-1} \int_A a / (a / \tan \beta) \, dA = \ln (L / \tan \beta) - 1 \quad [39]
\]

\[
A_c / a = 1 - (\tan \beta / L)(a / \tan \beta)^s \quad [40]
\]

where \(a\) is the upslope area draining past that point per unit width of slope or contour length, and \(A_c\) is the contributing area for this subcatchment where \((a / \tan \beta)^s\) exceeds the critical \((a / \tan \beta)\) for saturation. This linear relationship for \(A_c / A\) can be transformed into \(A_c / A\) vs. \(\ln(a / \tan \beta)\).

C.3.d.ii. rectangular curved flow surface

Assuming that the overland flow surface can be approximated by the quadratic equation:

\[
Y = jx^2 + bx \quad [41]
\]

where \(j\) and \(b\) can easily be estimated from topographic map data and \(x\) is measured from the stream. The derived functions are:

\[
a / \tan \beta = (L - x) / (2jx + b) \quad [42]
\]

\[
\lambda = \ln \left( \frac{Lb / 2jL}{(2jK + b)^{k+b, 2jK}} \right) \quad [43]
\]

\[
A_c / A = \frac{[1 - (b / L)(a / \tan \beta)]}{[1 - 2j(a / \tan \beta)]} \quad [44]
\]
C.3.d.iii. convergent plane section

Assuming a headwater catchment can be modeled as a convergent plane with angle $\theta$ and overland flow length $L$, the derived functions are:

\[
a / \tan \theta = (L^2 - x^2) / 2xtan\theta \quad \text{[45]}
\]

\[
\lambda = \ln(L/2\tan \theta) - 0.5 \quad \text{[46]}
\]

\[
A_c / A = L^{-2} \{L^2 + \tan^2 \theta (a / \tan \theta)^2\}^{0.5} - \tan \theta (a / \tan \theta) \quad \text{[47]}
\]

Assuming $N$-such idealized flow surfaces ($i = 1, \ldots, N$), the corresponding values for the whole catchment are:

\[
\lambda = (\sum_{i=1}^{N} A_i)^{-1} \sum_{i=1}^{N} A_i \lambda_i \quad \text{[48]}
\]

and

\[
A_c / A = (\sum_{i=1}^{N} A_i)^{-1} \sum_{i=1}^{N} A_i (A_{ci} / A_i)(a / \tan \theta) \quad \text{[49]}
\]
Figure 8 below plots the $A_c/A$ vs. $(a/tan\theta)$ for the three types of idealized planes.

Figure 8: $A_c/A$ vs. $a/tan\theta$ for idealized side slopes (Beven and Wood 1983).
D. PEAK FLOW ESTIMATION

D.1. Time of concentration

Time of concentration \( (t_c) \) is defined as the time required for runoff to travel from the hydraulically most distant part of the watershed, to the watershed outlet or some other point of reference downstream (hydraulic length) (Luthin 1978). In hydrograph analysis, the time of concentration is the time from the end of excessive rainfall to the inflection point on the falling limb of the hydrograph where the recession curve begins (runoff ceases).

The Soil Conservation Service presents the following relationships related to the time of concentration:

\[
t_p = 0.7 \ t_c \quad \text{[50]}
\]

with excess duration of precipitation \( = 0.133 \ t_c \) \quad \text{[51]}

These are augmented with a review by Smedema and Rycroft (1983):

\[
t_p = 0.7 \ t_c \quad \text{[52]}
\]

\[
t_l = 0.6 \ t_c \quad \text{[53]}
\]

\[
t_r = 1.67 \ t_p \quad \text{[54]}
\]

Therefore, \( t_l \) should be 10% lower than \( t_p \).

where: \( t_p \) = time to peak

\( t_r \) = recession time

\( t_l \) = lag time

As observed values of \( t_c \) are rarely available, the designer normally has to make do with estimates of \( t_c \). Many formulas and nomographs have been developed for estimating \( t_c \). Almost all
methods of estimating the time of concentration use the slope, hydraulic length, and some measure of land use.

The following methods were selected from the literature to test their accuracy in $t_c$ estimates as compared to observed $t_p$ values and $t_c$ estimates: nomograph (Chow 1964), Kerby formula (Chow 1964), flow velocity method (McCuen 1982), Kirpich formula (Smedema and Rycroft 1985; Raudkivi 1979), and the lag method (McCuen 1982).

D.2. Soil Conservation Service unit hydrograph method

A unit hydrograph is the hydrograph that results from one inch of precipitation excess generated uniformly over the watershed at a uniform rate during a specified period of time. The SCS methods use dimensionless unit hydrographs which are based on extensive analysis of measured data (a dimensionless unit hydrograph is a graph of $q/q_p$ versus $t/t_p$ in which $q$ is the discharge at any time $t$). Unit hydrographs were evaluated for a large number of actual watersheds and then made dimensionless. An average of these dimensionless unit hydrographs was developed with the following characteristics:

1) the time base of the dimensionless unit hydrograph was approximately five times the time-to-peak,

2) approximately $3/8$ of the total volume occurred before the time-to-peak,

3) the inflection point on the recession limb occurs at approximately 1.7 time the time-to-peak,

4) the unit hydrograph had a curvilinear shape.
The curvilinear unit hydrograph can be approximated by a triangular UH that has similar characteristics. The area under the rising limb of the two unit hydrographs are the same (37.5%) but the time base of the triangular unit hydrograph is only 8/3 of the time-to-peak (as compared to 5 for the curvilinear unit hydrograph).

D.2.a. peak discharge of the unit hydrograph

The area under the unit hydrograph equates the volume of direct runoff \( Q \) as estimated by the SCS CN approach. Runoff can also be expressed in terms of time-to-peak \( (t_p) \), recession time \( (t_r) \), and peak discharge \( (q_p) \):

\[
Q = \frac{1}{2} q_p (t_p + t_r) \tag{55}
\]

solving for \( q_p \) and rearranging gives

\[
q_p = \frac{Q t_p}{t_p} \cdot \frac{2}{1 + t_r/t_p} \tag{56}
\]

replacing the second term in the above equation yields:

\[
q_p = \frac{KQ}{t_p} \tag{57}
\]

In order to have \( q_p \) in cfs, \( t_p \) in hours, and \( Q \) in inches, it is necessary to divide by the area \( A \) in square miles and to multiply by the constant 645.3; also because \( t_r = 1.67 t_p \), equation [57] above becomes:

\[
q_p = \frac{484 AQ}{t_p} \tag{58}
\]

The constant 484 reflects a unit hydrograph with 3/8 of its area under the rising limb. In mountainous areas, the fraction
could be expected to be greater thus reflecting a constant near 600 (assuming increased overland flow).

The time-to-peak in the above equation [58] can be expressed in terms of the duration of unit precipitation excess and the time of concentration:

\[ t_c + D = 1.7 \, t_p \]  \[59\]

and \[ D/2 + 0.6 \, t_c = t_p \]  \[60\]

The above two equations are expressed in figure 9 below. Solving equations [59] and [60] for D gives:

\[ D = 0.133 \, t_c \]  \[61\]

Therefore, \( t_p \) can be expressed in terms of \( t_c \):

\[ t_p = D/2 + 0.6 \, t_c = 2/3 \, t \]  \[62\]

Equation [62] then be expressed in terms of \( t_c \) rather than \( t_p \):

\[ q_p = \frac{726 \, AQ}{t_c} \]  \[63\]
Figure 9: Dimensionless curvilinear unit hydrograph and equivalent triangular hydrograph (McCuen 1982).

D.3. Rational formula

D.3.a. overview of use and development

The rational formula had its beginning about 130 years ago. The first paper published containing the underlying principles was in 1851, but was largely ignored until 1889 when the method was presented to the American Society of Civil Engineers. In the next few decades, attempts were made to estimate time of concentration, runoff coefficient, and rainfall intensity more accurately. The development of the intensity-duration-frequency curves provided improved rainfall intensity estimates, however work on the time of concentration and runoff coefficient were
less successful, as still is the case.

The past forty years have provided few if any improvements in the use of the rational formula, rather a proliferation of methods to estimate the various factors in the form of equations, graphs, and tables. This attempt at simplification has resulted in some widespread misconceptions in the use of this formula (Rossmiller 1982).

The basic principle underlying the rational formula is that the highest discharge from the basin occurs in response to a storm with a duration equal to the time of concentration ($t_c$). The rational formula is based on the following assumptions:

1) the recurrence interval of the peak flow is the same as that of the rainfall intensity,

2) the rainfall is uniform in space over the drainage area being considered,

3) the rainfall intensity is uniform throughout the duration of the storm,

4) the coefficient of runoff is the same for storms of various frequencies,

5) the coefficient of runoff is the same for all storms on a given watershed.

The assumptions of uniform rainfall in space and uniform rainfall intensity are true only for small drainage basins and short duration storms respectively. Therefore, in agricultural drainage system design, the rational formula is best applied to responsive types of field drainage where very little
transformation occurs in the field drainage system (the field drainage hydrograph resembles the hyetograph) (Smedema and Rycroft 1983). For example, groundwater drainage (subsurface drainage) usually results in more attenuated hydrographs than shallow flow or surface drainage. The rational formula was originally developed to estimate peak discharge from small urban basins (with a discharge (runoff) coefficient close to 1.0 representing the large percentage of impervious area). Its application in agricultural drainage system design is most appropriate for basins not exceeding 100 - 200 ha.

Therefore, for a small drainage basin (100 - 200 ha), with conditions promoting overland flow/or rapid interflow (sloping land, less permeable soils, development creating impervious surfaces, grazing lands with reduced infiltration, swampy or poorly drained lowlands, etc.), the rational formula may be quite successfully used to estimate design runoff for surface drainage systems.

Use of the rational formula should be accompanied by the awareness of various reported shortcomings of the method:

1) Time of concentration estimates must include overland flow plus time of flow in open and/or closed channels (where significant) to the point of design.

2) The various equations developed to estimate time of concentration may vary over a wide range, therefore a weak variable.

3) The runoff coefficient, C, is usually estimated from a
table of values for C. Some tables only consider one variable (landuse), and other tables consider five variables (land use, soil type, slope, antecedent moisture conditions, and recurrence interval). Different users with different tables can easily select values of C which differ by 100%, therefore $t_c$ is a very weak component of the formula (Rossmiller 1982).

4) The runoff coefficient (C) is not constant; rainfall runoff curves are reported to converge at the rarer frequency rainfall events. This implies C should be increased for greater recurrence intervals (Rossmiller 1982).
E. WATERSHED DESCRIPTION

All field research was carried out at the Agriculture Canada Research Farm #2 which is located at 49.2744°N and 121.7472°W (NTS map sheet 92H/5) in the eastern end of the Lower Fraser Valley of British Columbia. It will hereinafter be referred to as the Agassiz Research Watershed.

Located to the west of Bear Mountain, the Agassiz Research watershed has an area of 474 ha, with a 790 m range of elevation. The watershed is distinctly divided into an upland and lowland region with a 7:1 upland to lowland ratio. Upland slopes vary between approximately 50% to 70%. Less than 1% of the lowland has been reclaimed and cultivated for future crop growth. A subsurface drainage system was installed in 1982 on half of the cultivated field. The outlet consists of a small channel in the lowland which has been cleared and maintained. This leads to Maria Slough and eventually to the Fraser River.

E.1. Historical landuse

A historical review of provincial aerial photography dating back to 1939 shows the site area under cultivation with clearly defined tree-lined drainage ditches traversing the lowland field. Over the years through to the early 1960's there appeared to be reasonable attempts at farming the field area, with varied success. It is obvious that poor drainage in the lowland field has always posed a management challenge. In the late 1960's two new interception ditches were excavated, but appeared to fall into limited use due to poor maintenance by the next series of
aerial coverage in the late 1970's. By 1979, a bridge had been constructed over the outlet channel, and by 1983, a new drainage ditch was excavated.

Evidence of the first logging of the upland since 1939 was noticed in the 1965 aerial coverage, on parts of the west slope of Bear Mountain. Prior to this, the only clearing in the upland was for the original power line as seen in the 1952 photos. A new clearing for a powerline right-of-way was evident in 1961, and two new powerlines had been constructed by 1979 (note - there is a gap in photo coverage between 1969 and 1979). The site logged in 1965 had considerable regrowth (mainly deciduous) by 1979. In July of 1983, part of the area logged in 1965 had been relogged in the vicinity of the power line. During the research period logging in the saddle of the upland commenced.

E.2. Native vegetation

The Agassiz Research Watershed is included in the Pacific Coast Section of the Coast Forest Region. In the upland areas prior to logging, the forest cover was dominated by Douglas fir, western hemlock and western red cedar with the hemlock and cedar predominating on moist slopes and seepage areas. The logged areas support dense deciduous cover dominated by red alder, vine and broadleaf maple interspersed with second-growth Douglas fir and western hemlock.

In the lowland, the alluvial valley bottom originally supported stands of black cottonwood, red alder, broadleaf maple, western white birch as well as western red cedar, sitka spruce,
and grand fir. Most of these stands have been cleared, and remnants of the original forest only occur as scattered pockets on Seabird and some of the islands.

E3. General climate

The inshore maritime climate of the area is strongly influenced by the Coast Mountains. Winters are dominated by a large number of low pressure systems which move onshore from the Pacific Ocean producing dull, mild, long duration, low intensity rains. Except for recharging ground water reservoirs, the high rainfall has little benefit and water tables in many areas are raised sufficiently to cause severe drainage problems. Occasionally, polar air masses drain into the Lower Fraser Valley from the interior of the province and produce heavy snow falls or freezing rain when the cold interior and damp maritime air meet.

High pressure systems producing warm, sunny weather are common in the summer. Rainfall is sharply curtailed and soil moisture deficiencies frequently develop, particularly during the important crop growing months of July and August.

E.4. Soils

The soils in the Agassiz area have developed from unconsolidated geologic deposits of Pleistocene or Recent Age. Deposits vary in depth from less than a meter in parts of the mountains to at least 305 meters in the valley bottom.

With reference to the Soil survey of Agassiz area (Luttmerding and Sprout 1967), the Research watershed can be subdivided into the following soil series (as illustrated on the
air photo in Appendix A):

SOIL CLASS

1) \( \frac{SO - RO}{GH, S_{4-5}} \) Slollicum-Rock outcrop soil complex

2) \( \frac{PT - RO}{HG S_{4-5}} \) Poignant-Rock outcrop soil complex

3) \( \frac{IS - HR}{D - CaS} \) Isar - Harrison

4) \( \frac{RD - RD_{sp}}{fg} \) Ryder

5) \( \frac{GN}{b} \) Gibson

6) \( \frac{AN - BD}{A} \) Annis/Banford

7) \( \frac{H^2}{b} \) Hatzic

8) Hj Hj sp. Hjorth

9) \( \frac{RD - RD; s_{p-PT}}{q; S_{o-2}} \) Ryder-Poignant

Further details on the above soil classes are found in table 3.
<table>
<thead>
<tr>
<th>SOIL CLASS</th>
<th>CLASSIFICATION</th>
<th>PARENT MATERIAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1)</td>
<td>degraded acid brown wooded</td>
<td>Aeolian dep. mix with colluvial slopewash deposits</td>
</tr>
<tr>
<td>2)</td>
<td>orthic acid brown wooded</td>
<td>Aeolian dep. mix with colluvial slopewash deposits</td>
</tr>
<tr>
<td>3)</td>
<td>orthic regosol, degraded acid brown</td>
<td>Alluvial-colluvial fan deposits</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Alluvial-colluvial fan deposits</td>
</tr>
<tr>
<td>4)</td>
<td>orthic acid brown wooded</td>
<td>shallow aeolian deposits over glacial till or bedrock</td>
</tr>
<tr>
<td>5)</td>
<td>deep muck</td>
<td>organic deposits</td>
</tr>
<tr>
<td>6)</td>
<td>rego gleysol shallow muck</td>
<td>Fraser floodplain deposits</td>
</tr>
<tr>
<td></td>
<td></td>
<td>organic deposits</td>
</tr>
<tr>
<td>7)</td>
<td>orthic humic gleysol</td>
<td>Fraser floodplain deposits</td>
</tr>
<tr>
<td>8)</td>
<td>rego humic gleysol</td>
<td>Fraser floodplain deposit</td>
</tr>
<tr>
<td>9)</td>
<td>orthic acid brown wooded</td>
<td>Aeolian dep. mix with colluvial slopewash deposits</td>
</tr>
</tbody>
</table>

Table 3: Soil series classification

E.4.a. upland soils

E.4.a.i. Slolicicum Series

Slolicicum Series are found between elevations of 305 and 762 meters. Topography is very steeply to extremely sloping; most gradients between 60 - 90 %.

Slolicicum soils have developed from unstable, coarse textured colluvial deposits into which a shallow aeolian overlay has been mixed by windthrow and soil creep. Textures, both surface and
subsurface, are coarse and vary from gravelly sandy loam to gravelly loamy sand. Profiles are extremely stony and bedrock usually occurs within 91 cm of the soil surface. Rooting depth and moisture permeability is good until the underlying bedrock is reached then decreases abruptly (as seen by root mat development and occasional weak gleying and mottling).

Most profiles are well drained although seepage occurs above and through the upper part of the fractured bedrock.

These soils developed under Douglas fir, cedar and hemlock vegetation, now mostly logged. The soils also support: small hemlock, Douglas fir, fireweed, willow, birch, alder, big leaf maple, thimbleberry, false azalea, vaccinium species, moss, and other regrowth vegetation.

None of the Slollicum soils are suitable for agricultural use due to steep topography and stoniness.

E.4.a.ii. Poignant Series (orthic brown wooded)

Poignant soils are common between 30 and 457 meter elevations. They are very steeply to extremely sloping with gradients generally over 50 and commonly ranging to 90 per cent.

These soils have developed on steep, unstable slopes. The colluvial parent material includes aeolian and minor glacial till deposits and rock fragments which have been mixed by soil creep and windthrow. Surface textures vary from gravelly sandy loam to loam and generally become coarser with depth. Stone content is very high, occupying 50 - 80 % of the soil volume and range in size from gravel to over one meter in diameter. Bedrock is
usually encountered within 91 cm of the surface and frequently outcrops.

Drainage ranges from well to moderately well and varies with the depth of the solum and the amount of seepage from higher elevations.

Original vegetation was mainly coniferous and has mostly been removed by logging. Present vegetation consists of alder, vine maple, willow, thimbleberry, dogwood, second growth Douglas fir and hemlock.

E.4.a.iii. Isar Series (orthic regosol)

Regosol soils are well and imperfectly drained soils that lack discernible horizons or in which development is limited to slight organic accumulation in the surface.

The Isar soil occurs on the uplands of the map area between 152 and 304 meter elevations. They have developed from relatively recent alluvial and occasionally alluvial - colluvial fan deposits eroded from the mountains. Surface and subsurface textures vary from sandy loam to gravelly sand and sand and are sometimes weakly stratified. Cobbles and stones frequently occupy a large part of the solum. Fan apexes are steeper and coarser textured than the fan aprons which sometimes have a thin, finer textured capping mantling the coarse underlay.

Isar soils are well to rapidly drained. Profile development is negligible. Original vegetation was mainly coniferous, but logged areas are presently dominated by a variety of deciduous species.
Adverse topography and stoniness make the Isar soils unsuitable for arable agriculture on the uplands, but some areas may produce small amounts of browse.

E.4.a.iv. Harrison series (degraded acid brown)

The Harrison series is a degraded acid brown wooded soil. This implies well to moderately well drained soils, which, under native conditions, are characterized by organic surface L-H horizons, a light coloured, eluviated Ae horizon not more than one inch thick and one or more reddish-brown Bf or Bm horizons.

The Harrison soils occupy a minor acreage on the uplands of the map area between 15 and 45 meter elevations. This series developed from alluvial and occasionally alluvial-colluvial fan deposits originating from the mountains. Most fans have shallow aeolian deposits mixed into the surface horizons by the action of windthrow, and surface textures generally vary from gravelly sandy loam to loam. Cobbles and stones are mixed throughout the profile, but are most abundant in the coarse sub-soil.

Drainage is well to rapid. The Harrison series developed under coniferous vegetation dominated by Douglas fir. Most areas have been logged, and regrowth includes Douglas fir, vine; maple, red alder, cedar, birch, huckleberry, trailing blackberry, wild strawberry, thimbleberry, soapberry, bracken and moss.

On the uplands, the Harrison soils are generally unsuitable for agriculture due to steep topography, stoniness and low moisture holding capacity. Forest growth is fair to good.
E.4.a.v. Ryder series (orthic acid brown wooded soil)

Ryder soils are mainly restricted to the northeast upland of the Agassiz experimental farm and occur between 23 and 305 meter elevations. The topography is strongly to very steeply sloping and rolling with most gradients between 10 and 40 percent.

The parent material of the Ryder series consists of silty aeolian material which overlies glacial till or bedrock. Surface textures are usually silt loam; subsoil textures are similar, but vary to loam. The underlying glacial till when present, is usually gravelly sandy loam in texture. The depth of the aeolian overlay is generally three or more feet. Occasionally stones and gravels occur in the profile from windthrow, underlaying glacial till or scattered rock outcrops. Roots and moisture penetration is good.

The Ryder series is well to moderately well drained. Dense deciduous cover has developed since the original coniferous vegetation was logged. Earthworm activity is evident in the upper portions of some profiles. Common vegetation includes Douglas fir, vine and big leaf maple, stinging nettle, deer fern, bracken, alder, thimbleberry, salmonberry, and trailing blackberry.

Adverse topography renders most of the Ryder soils unsuitable for arable agriculture, but do have some use as permanent grazing and browse. Ryder soils are friable and easily cultivated but become droughty during dry summers.
E.4.b. lowland soils

E.4.b.i. Gibson Muck (organic soil)

Organic soils contain 30 percent or more organic matter and have a depth of at least 31 cm of consolidated or 46 cm of unconsolidated organic material. They are very poorly drained and the water table is at or near the surface for substantial parts of the year.

Muck soils are the only organic soils occurring in the lowlands of the Agassiz map area.

Gibson muck occupies several areas on the lowlands between 14 and 21 meter elevations. The topography is slightly depressional to very gently sloping with gradients below two percent.

These soils have developed from organic accumulations of sedges, reeds, mosses, and other organic material which exceed 61 cm in depth and overlie heavy textured floodplain sediments. The surface horizons are well to moderately well decomposed while underlying horizons are at various stages of decomposition. The mineral subsoil is strongly gleyed. Profile reaction is moderately to extremely acidic.

Drainage is very poor and the water table is at or near the surface for large parts of the year. Runoff and seepage from higher surrounding areas and seepage from the Fraser River during its freshet stage cause the high water conditions.

Gibson muck is classified as a deep muck with the organic material usually between two and six feet in depth. Native vegetation is swamp forest consisting of scattered cedar,
hemlock, bog birch, hardhack, sweet gale, sedge, skunk cabbage, various grasses and other hydrophytic species.

Areas of gibson muck which have been reclaimed in other regions in the Agassiz area are used for hay and pasture production. Sedge content of the forage is usually high and the feed value low. If well managed, these soils are highly productive, especially for such specialized crops as blueberry and vegetables.

Seepage from higher areas can often be reduced by intercepting tile drains and ditches. Tile drains or open ditches are satisfactory for drainage within the bog, but the water table should not be lowered more than is required for good crop growth. Overdraining causes excessive subsidence of the organic deposits and often results in droughty conditions during the latter part of the growing season.

E.4.b.ii. Banford muck (organic soils)

Banford muck occurs in scattered areas on the Fraser floodplain between 12 and 21 meter elevations. As with Gibson muck, it varies from depressional to very gently sloping with slopes below two percent. Usually this series is associated with the Annis series or Gibson muck with no distinguishing surface or topographic features between them. Separation is based on the depth of the organic deposit.

Banford muck has developed from accumulations of sedges, reeds and other organic material 31 to 61 cm deep, which overlie heavy textured Fraser floodplain sediments. The surface horizon
is well decomposed, while the subsurface organic horizons are usually intermediate in decomposition.

The Banford soil developed under very poorly drained conditions. The water table is at or near the soil surface for most of the year, with runoff and seepage from surrounding higher land contributing large amounts of water.

The Banford soil (a shallow muck), developed under swampy vegetation consisting of sedges, reeds, hardhack, sweet gale, skunk cabbage, various grasses, scattered willow, cottonwood, cedar and bog birch.

Land use is similar to that on Gibson muck.

E.4.b.iii. Annis (rego gleysol)

Gleysol soils are poorly to very poorly drained soils. The rego gleysol may have a dark coloured Al surface horizon not more than three inches thick, and when cultivated, the plow layer (Ap) is light in colour. Up to 31 cm of consolidated or 46 cm of unconsolidated peat or muck may be present on the surface.

The Annis soils occupy small, scattered areas between 9 and 17 meter elevations. The topography is level to very gently undulating and often is depressional in relation to the surrounding land.

Fifteen to thirty-one cm of well decomposed organic material overlaying silty clay loam to silty clay textured floodplain deposits forms the parent material of these soils. Sand is usually encountered at depth. Annis soils often form a transition zone between mineral and organic soils. Surface
Textures are muck.

Drainage is very poor. Flooding frequently occurs after heavy rainfall and the water table is near the surface most of the year. Depressional areas of Annis muck serve as catchment basins for runoff from higher land. Water percolation and rooting depth is severely restricted by the heavy massive nature of the subsoils.

Profile development is restricted to organic accumulation on the surface and strong gleying in the subsoil. Native vegetation consists of cedar, willow, sedge reeds, hardhack, and other hydrophytic species.

A large portion of Annis soils are used for hay and pasture production. These soils are friable and fertile, but yields are usually poor due to poor drainage which destroys the legumes and some of the domestic grasses. Drainage is required in these soils.

E.4.b.iv. Hatzic (orthic humic gleysol soil)

Orthic humic gleysol soils are distinguished by poor drainage, a dark coloured Ah horizon greater than 8 cm thick and weakly developed eluvial and/or illuvial horizons which are strongly gleved and mottled. There may be up to 31 cm of consolidated or 46 cm of unconsolidated peat or muck on the surface.

The Hatzic series occupies minor acreage between 12 and 15 meter elevations and has very level to very gently sloping topography with gradients less than two percent.
These soils have developed from heavy textured sediments deposited by the Fraser River in quiet shallow ponds. Silty clay and silty clay loam are the dominant surface texture, with underlying horizons somewhat heavier. Cracking occurs during drying, but when wet, the soil expands thereby restricting moisture and root penetration.

Internal and external drainage are poor due to slow surface runoff and restricted internal moisture movement. The water table is at or near the surface most of the winter and during high water on the Fraser River. Prior to clearing, original vegetation consisted of sedge, various grasses, hardhack, willow, and other species tolerant to poor drainage.

Hatzic soils are mostly cleared and utilized for hay and pasture production. Clover-grass mixtures are used, however clovers tend to die rapidly due to the poor drainage. Drainage is required on this soil.

E.4.b.v. Hjorth series

These soils are found in similar topographic areas as hatzic soils. The parent material is silty lateral accretion deposits of the Fraser River. In the ridge-and-swale topography these soils occupy the swales and lower slopes of the ridges. Surface textures range from silt loam to silty clay loam and are underlain by sand and occasional gravel.

These soils are poorly drained, ponding frequently occurs.

Native vegetation is mainly deciduous and includes cottonwood, willow, and alder with occasional cedar. Shrub
cover is dense and a light ground cover of sedge and moss exists. Most areas of Hjorth soils are cleared and used for hay and pasture production. Drainage is required.

For a convenient reference, one can turn to the Soil Management Handbook for the Fraser Valley (Bertrand and Wood 1983) where soil series are listed, and divided into soil management groups. Soil limitations are presented along with a classification of crop groups based on the level of management required to achieve an acceptable level of production.

Soil Mapping for Farm #2 was also performed for Agriculture Canada. The upland soils have been classified as CUNNINGHAM fine sandy loam: well drained soils developed on a medium-textured outwash material.

The lowland at the base of the upland area has been classified as HICKS muck and thin peat: poorly-drained-to very poorly drained soils. The field area (fields 8 & 9) have a mixture of MARIA silty clay loam and MARIA silty clay.

The pocket of well drained Isar-Harrison series soils identified in the 1967 Soil Survey of Agassiz Area was not described. This area may serve as a recharge zone for the adjacent lowlands - reducing surface runoff onto the poorly drained muck in the adjacent lowland fields.
F. PROCEDURES

F.1. Watershed quantification

The standard procedures of watershed quantification were performed for the Agassiz Research Watershed. A 1:50 000 NTS map sheet was used to delineate the watershed boundaries (with reference to 1:10 000 and 1:20 000 scale aerial photography), and this region was then planimetered to determine watershed area.

To improved accuracy and allow delineation of the characteristic regions of the watershed, a large scale 1:5 000 map was stereoplotted from 1:20 000, 1983 panchromatic aerial photography by Ackerfeldt Inc. in Vancouver (aerial photography in Appendix A). The contour interval at this scale for a forested region was 10 meters. Elevations in the lowland were cross-referenced to 1:10 000 scale photography. Vegetation boundaries and major landmarks such as the powerlines, and bridge over the ditch were indicated.

This large scale map served two purposes in data collection: 1) direct measurement of watershed areas (using a digital planimeter as seen in figure [10] below) plus measurement of hydraulic length, and 2) creation of a digital data base.
Figure 10: Digital planimeter and 1:5 000 stereoplotted map

F.1.a. creation of a digital data base

From this large-scale map of the Agassiz Research Watershed, a digital format was created by manually digitizing the map using the contour method. A Talos digitizer located at the computer centre of the University of British Columbia was used. Software provided by the centre was modified to allow labels to be set for each contour level. The Talos digitizer and Formica workboard measures 1.21 meters in X and 0.91 meters in Y (48 inches by 36 inches). The digitizer is set in point mode, and returns positive x and y coordinate measurements in thousandths of an inch reflecting the position of the cursor crosshairs on the worktable when the button on the cursor pad is pressed. The digitizer is
connected to a Tektronix 4010 terminal, which enables the user to simultaneously view an image of the map being digitized. Figure [11] below illustrates the digitizer set-up used.

Figure 11: Digitizer set-up at the UBC Computing Centre

The end product of digitizing was a set of 7000 data points consisting of X,Y,Z coordinates for each digitized point. These points were chosen to best reflect changes in topography; namely being relatively dense along curves and important characteristics.

In order to make the digitizer output useful, some type of efficient data format and referencing system had to be adopted. A triangulation program for creating a triangulated irregular network (TIN) written by Dr. J. Little (currently of MIT) was run
on a VAX 11/780 minicomputer to create a network of triangles between all 7000 data points for the Research Watershed. At this stage, the TIN was converted to a raster or grid to allow for program development and more efficient manipulation of the data base.

Access to an image display system allowed image files of the DEM to be displayed. Elevations were represented by 255 grey levels, and displayed in pixel format on a raster display screen with a resolution of 512 X 512 pixels. Different sun angles of azimuth and elevation above the horizon could be specified for any time of day, or day of the year, to create shadows in the model. A synthetic image was created which highlights terrain features and gives some indication of sun exposure times and intensity which could be significant in understanding such processes as spring snowmelt. Contours could be created for any given interval (based on pixel grey scale interval) then either displayed as a map on their own or overlaid on the synthetic image. The raster display system allowed visual checking for any artifacts or problems in creation of the TIN and grid DEM.

A grid data base was thus created with the origin in the upper left corner of the map (NW), and co-ordinates expressed as (row,column) pairs. To check the integrity of the digital data, a contour map was re-created from the DEM. A graphics package available on the mainframe system at UBC, DISSPLA, was used to create a contour map. Plotting was done by transporting the plot file to the IBM-PC (equipped with a Hercules graphics board),
then using a tektronix terminal emulator package to plot the map on a ROLAND DXY-880 plotter (map in Appendix B).

**F.1.b. analytical software**

The development of a digital elevation model for the Agassiz Research Watershed required not only acquiring a digital database for the site, but creating the model and developing analytical software. Commercial digital elevation modelling software does exist, most based on mini-computers and Integraph work stations. Some software is available commercially for the micro-computer market, but was not accessible for this research. In watershed analysis for the purpose of runoff estimation, it is important to know the watershed area, and be able to create profiles across areas of interest to calculate distance and slope. In this research two procedures were developed:

1) area determination
2) profile determination.

**F.1.b.i. area**

As described earlier, DEMs allow the slope of the terrain to be accounted for in area determination. A grid of cosθ for each data point was created. The theory behind using cosθ in area determination follows:
\[ \cos(\theta) = \frac{p}{z} \quad [72] \]

\[ z = \frac{p}{\cos \theta} \quad [73] \]

\[ \text{Area} = p \times z \]
\[ = \frac{p \times p}{\cos \theta} \]
\[ \quad = \frac{p^2}{\cos \theta} \quad [75] \]

\[ \text{Area} = \frac{1}{\cos \theta} \quad [76] \]

Area for pixels \((p = 1)\) is calculated as \(\frac{1}{\cos \theta}\) \[77\]

Area calculation is a two-step process. First, a polygon outlining the chosen area must be created on a grid file the same size as the database (in terms of rows and columns). This process is performed using the program POLY.C in Appendix C. The polygon must then be filled, highlighting the pixels included in the calculations (area is calculated for each pixel individually then totalled). The edges of the polygon often cut through a pixel with only a portion of it included in the area. To
accommodate for this, only half the area of all perimeter pixels was used. Reference may be made to program AREA.C in Appendix C for program particulars.

F.1.b.ii. profiles

Profiles can be created between any two points in the digital elevation model. The program NEWPROFI.C requires the following information: DEM size (number of rows and columns), starting and ending point of the profile, plus either the sampling interval or the number of points to sample along the profile. Output is a list of elevations for all the sampled points. This was imported into a spreadsheet program on the IBM-PC, and made into a graph file for plotting. Reference may be made to NEWPROFI.C in Appendix C for program particulars.
F.2. Runoff estimation

F.2.a. field instrumentation

The Agassiz Research watershed (Agriculture Canada Farm #2) was chosen for this research project since it provided a small contained watershed with a high percentage of forested upland area, a condition common for agriculture development in the lowland fringes of the Lower Fraser Valley. The lowland area had been farmed in the past as evidenced by historical aerial photography, but drainage problems have always posed a management problem. Subsurface drainage had been installed in a portion of the lowland in 1982 before this research began. The thesis research was in conjunction with a contract project with Agriculture Canada.

At the onset of this project, there were no discharge measurements for the watershed. A rectangular sharp crested weir had been previously installed, but was in need of repair. In the summer of 1984, a waterlevel recorder was installed approximately 16 m upstream from the weir in a straight uniform section of the ditch. The waterlevel recorder was supported by a polyethylene tube mounted in the ditch bed. Holes were drilled into the tube to allow water levels to equalize with the ditch level. A platform extending to the recorder was built to allow access to the equipment. The tube was secured to the banks of the ditch by four adjustable guy-wires to prevent shifting or ice damage as occurred the previous winter to the weir.

The rectangular crested weir was repaired, and the stream
channel cleaned of weeds with a back-hoe for a distance of approximately seven meters upstream. The following two photographs illustrate the weir and water level recorder setup.

Figure 12: Weir and water level recorder (looking north)
A Sierra-Misco tipping bucket raingage was installed in the lowland region of the watershed suspended by a platform from the bridge downstream of the weir. A Campbell Scientific 21x micrologger was connected to the raingage to provide a continuous precipitation record. The Campbell Scientific micro-computer in the Soil Science Department at UBC was used to interpret field tapes.

In addition to the above instrumentation, two existing groundwater level recorders in the drained and undrained field were monitored.

The data collection period for this project was August 1, 1984 to October 1985.

Analysis of the weekly stage data charts was done manually.
(to retain full resolution and accuracy due to the small scale of
the recording charts) on an event basis, and transferred to
spreadsheets on the IBM-PC. Precipitation totals and groundwater
levels for both the drained and undrained fields were also
transferred from field graphs to computer spreadsheets. For
comparison purposes, the hyetograph, stream discharge hydrograph,
and field groundwater hydrographs were re-plotted on a Roland-DXY
880 at the same time interval to allow for time to peak
determination and comparison between the stream and field
hydrographs.

F.2.b. Hydrograph separation

In order to compare runoff estimates from the SCS CN
procedures to those measured from the stream hydrographs, the
base flow had to be removed (the SCS CN procedures estimates
direct flow only, excluding base flow). It was not necessary to
determine the volume of base flow for the analysis procedures.
Hydrograph separation was performed on all storm hydrographs by
extending the recession before the storm to a point under the
peak, then joining the hydrograph recession one day after the
peak (as determined by the relationship $N = bA$ where $A$ is the
drainage area and $b$ is a coefficient ($b = 0.8$ when $A$ is in $km^2$ and
unity when $A$ is $mi^2$).

In multi-event storms, the recession limbs of the hydrograph
had to be extended in some cases to allow for the separation of
base flow for a period of one day after the peak. This was
accomplished by creating a composite total storm recession curve.
Six single event storm hydrographs without complicating factors such as freezing conditions with rain on snow or snowfall were chosen. The log of the discharge was calculated and plotted for each of these storms, with an identical time scale for each storm. Characteristic segments of the recession curve were chosen for each storm (straight line segments when possible), from different discharge levels. These segments were then pieced together to form a composite total storm recession curve (refer to appendix D for the composite total storm recession curve and hydrographs analysed to derive this, and appendix E for the hydrograph separation of all storms).

F.2.c. runoff measurement from hydrographs

Once baseflow was separated from the hydrograph, the area above baseflow and under the curve was measured to determine the direct runoff. This was accomplished using a digital planimeter. The computed volume of runoff was divided by the watershed area to give runoff depth in millimeters.

F.2.d. Soil Conservation Service Curve Number method

The Agassiz Research Watershed, as indicated in earlier sections, displays extreme contrasts of slope, elevation, landuse, and soil condition. The SCS (USDA 1972) recommends that if a watershed displays heterogeneous soils, land use or treatment classes, it should be subdivided into appropriate sections and analysed by one of two methods:

1) determine the CN for each section, then calculate a weighted CN for the watershed, or
2) determine the CN and related runoff for each section, then calculate a weighted runoff value for the watershed.

The method of weighted runoff \((Q)\) gives a more accurate result, but requires more work than the weighted Curve Number procedure. When there are large differences in CN for a watershed, the weighted CN will either under or over estimate \(Q\), depending on the size of the storm rainfall. Weighted \(Q\) is preferred when small rainfalls are used and there are two or more widely differing CNs on the watershed. For conditions other than these, the method of weighted CN is less time consuming and almost as accurate (USDA 1972).

It was therefore considered advisable to perform a weighted runoff estimation rather than follow a weighted CN approach. The watershed was subdivided into the following characteristic regions: forested fan A (soil hydrologic condition A), forested upland B (soil hydrologic condition B), lowland scrub/marsh, undrained fallow, and drained fallow (Appendix A).

Curve numbers for the lowland regions of the watershed were estimated using table 4 below (based on AMC II).
## Land Use Description/Treatment/Hydrologic Condition

<table>
<thead>
<tr>
<th>Residential: 1/</th>
<th>Hydrologic Soil Group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
</tr>
<tr>
<td><strong>Average lot size</strong></td>
<td><strong>Average % Impervious</strong></td>
</tr>
<tr>
<td>1/8 acre or less</td>
<td>65</td>
</tr>
<tr>
<td>1/4 acre</td>
<td>58</td>
</tr>
<tr>
<td>1/3 acre</td>
<td>50</td>
</tr>
<tr>
<td>1/2 acre</td>
<td>25</td>
</tr>
<tr>
<td>1 acre</td>
<td>20</td>
</tr>
</tbody>
</table>

| **Paved parking lots, roofs, driveways, etc.** | 98 | 98 | 98 | 98 |

<table>
<thead>
<tr>
<th><strong>Streets and roads:</strong></th>
<th>98</th>
<th>98</th>
<th>98</th>
<th>98</th>
</tr>
</thead>
<tbody>
<tr>
<td>paved with curbs and storm sewers</td>
<td>76</td>
<td>85</td>
<td>89</td>
<td>91</td>
</tr>
<tr>
<td>gravel</td>
<td>72</td>
<td>82</td>
<td>87</td>
<td>89</td>
</tr>
</tbody>
</table>

| **Commercial and business areas (85% impervious)** | 89 | 92 | 94 | 95 |

| **Industrial districts (72% impervious)** | 81 | 88 | 91 | 93 |

| **Open Spaces, lawns, parks, golf courses, cemeteries, etc.** |
| **good condition:** grass cover on 75% or more of the area | 39 | 61 | 74 | 80 |
| **fair condition:** grass cover on 50% to 75% of the area  | 49 | 69 | 79 | 84 |

| **Fallow** | Straight row | --- | 77 | 86 | 91 | 94 |
| **Row crops** | Straight row | Poor | 72 | 81 | 88 | 91 |
|             | Good | 67 | 78 | 85 | 89 |
|             | Contoured Poor | 70 | 79 | 84 | 88 |
|             | Contoured Good | 65 | 75 | 82 | 86 |
|             | Contoured & terraced Poor | 66 | 74 | 80 | 82 |
|             | Contoured & terraced Good | 62 | 71 | 78 | 81 |

| **Small grain** | Straight row | Poor | 65 | 76 | 84 | 88 |
|                | Contoured Poor | 63 | 74 | 82 | 85 |
|                | Contoured & terraced Poor | 61 | 72 | 79 | 82 |
|                | Contoured & terraced Good | 59 | 70 | 78 | 81 |

| **Close-seeded legumes** |
| **Straw** | Poor | 66 | 77 | 85 | 89 |
| Contoured Poor | 58 | 72 | 81 | 85 |
| Contoured Poor | 64 | 75 | 83 | 85 |
| Contoured Good | 55 | 69 | 78 | 83 |
| Contoured & terraced Poor | 63 | 73 | 80 | 83 |
| Contoured & terraced Good | 51 | 67 | 76 | 80 |

| **Pasture or range** |
| **Poor** | 68 | 79 | 86 | 89 |
| Contoured Poor | 47 | 67 | 81 | 88 |
| Contoured Fair | 25 | 59 | 75 | 83 |
| Contoured Good | 6 | 35 | 70 | 79 |

| **Meadow** | 30 | 58 | 71 | 78 |

| **Woods or Forest land** |
| Poor | 45 | 66 | 77 | 83 |
| Contoured Fair | 36 | 60 | 73 | 79 |
| Contoured Good | 25 | 55 | 70 | 77 |

| **Farmsteads** | --- | 59 | 74 | 82 | 86 |

---

**Table 4:** CN values for AMC class II to be used in the curve number method (USDA 1972)
The woods designation in the above table refers to small isolated groves of trees raised for farm or ranch use. Where commercial forest covers a large part of the watershed, (such as in the Agassiz Research Watershed - 87% of the watershed being upland forest) the guidelines for national and commercial forest-range prepared by the U.S. Forest Service (USDA 1972) should be consulted.

In the forest-range regions of the western United States, soil group, cover type, and cover density are the principal factors used in estimating the CN. The nomographs developed for estimating the runoff curve numbers of forest-range complexes in the Western United States (figures 14 and 15) were used for estimating the curve numbers for the forest region in the Agassiz Research Watershed. Two complexes are identified: herbaceous and oak-aspen complexes, and juniper-grass and sage-grass complexes. These covers are defined as follows:

- **herbaceous**: grass-weed-brush mixtures with brush the minor element,
- **oak-aspen**: mountain brush mixtures of oak, aspen, mountain mahogany, bitter brush, maple, and other brush,
- **juniper-grass**: juniper or pinon with an understory of grass
- **sage-grass**: sage with an understory of grass.

The amount of litter is taken into account when estimating the density of cover.
Figure 14: Graph for determining runoff curve numbers of forest-range complexes in western United States: herbaceous and oak-aspen complexes (USDA 1972).

Figure 15: Graph for determining runoff curve numbers of forest-range complexes in western United States: juniper-grass and sage-grass complexes (USDA 1972).
The chosen curve numbers for all regions of the watershed were then adjusted for AMC I or AMC III when required using Table 5 below.

| Curve Numbers for AMC Conditions |
|-------------------------------|---|---|
| II | I | III |
| 100 | 100 | 100 |
| 95 | 87 | 99 |
| 90 | 78 | 98 |
| 85 | 70 | 97 |
| 80 | 63 | 94 |
| 75 | 57 | 91 |
| 70 | 51 | 87 |
| 65 | 45 | 83 |
| 60 | 40 | 79 |
| 55 | 35 | 75 |
| 50 | 31 | 70 |
| 45 | 27 | 65 |
| 40 | 23 | 60 |
| 35 | 19 | 55 |
| 30 | 15 | 50 |
| 25 | 12 | 45 |
| 20 | 9 | 39 |
| 15 | 7 | 33 |
| 10 | 4 | 26 |
| 5 | 2 | 17 |
| 0 | 0 | 0 |

Table 5: Curve numbers as adjusted for AMC

Curve numbers for the watershed were then used to compute runoff using the following relationships:

\[ Q = \frac{(P - 0.2S)^2}{P + 0.8S} \text{ mm} \quad P > 0.2S \quad [64] \]

where:

- \( Q \) = stormflow (mm)
- \( P \) = storm rainfall (mm) and
- \( S \) = a catchment storage factor or potential maximum retention (mm)
\[ S = \left( \frac{1000}{CN} - 10 \right) 25.4 \]  

where:

\[ CN = \text{curve number} \]

For each storm event studied, a check was made to ensure the storm precipitation was greater than the initial abstraction (0.2S). Initial abstraction includes interception, infiltration and surface storage occurring before runoff starts. This relationship may not be correct under all circumstances, however, it remains in use until more comprehensive study is accepted.

The rainfall runoff relationship may also be determined by reference to figure 16.

![Curve number graph](image)

Figure 16: Curve number graph for the conversion of rainfall into runoff (Smedema and Rycroft 1983).

The SCS method estimates direct runoff only. The proportions of surface runoff and subsurface flow are appraised by means of
the runoff curve number (CN): the larger the CN, the more likely that the estimate is of surface runoff, and the smaller the CN the more likely that the estimate is of subsurface runoff (USDA 1972).

The SCS curves were developed to predict direct runoff based on one or more storms occurring in a calendar day (since 24 hr rainfall totals are the most readily available type of data). For a storm which lasts more than one day, the storm can be treated as a separate day analysis or a single event analysis. The separate day analysis considers the storm as a series of separate daily storms, each having its own antecedent moisture conditions based on what happened in the preceding five days. The runoff for each of the daily storms is added to give the total direct runoff. The storm may also be treated as a single event, although it may last for several days. The antecedent moisture condition at the beginning of the storm is used to determine the curve number to be used throughout the storm.

For this research, data was collected using a recording raingauge, therefore runoff was calculated on an event basis. Each storm producing a distinct response in the stream hydrograph was analysed separately. If several events occurred in a row, a new antecedent moisture condition was calculated for each storm. This allowed direct comparison with runoff as calculated from the stream hydrographs for each event.
F.2.e. model calibration

F.2.e.i. sprinkling infiltrometer design

A sprinkling infiltrometer was built for this research patterned after a model used by Lowrey (1980) at Oregon State University (as adapted from Meeuwig (1971) and Froehlich and Hess (1976)).

The water chamber is constructed of plexiglass 1.27 cm (1/2 inch) thickness on the bottom, and 0.635 cm (1/4 inch) thickness for the top and sides with inside dimensions of 60.96 by 60.96 by 25.4 cm (24 by 24 by 10 inches). A hose attachment on the box allows for rapid draining of the water, accompanied by a screw drain plug in the centre of the chamber. Levelling bubbles are located on the top surface at opposite corners of the chamber. A ruler on the inside front of the chamber allows regulation of the head controlling the infiltration rate. A large lid on the top also provides access to the box (figure 17).
Figure 17: Diagram of Infiltrometer Chamber

Simulated rainfall is produced from 517 evenly spaced 21-gauge hypodermic needles (inside bore diameter; 0.495 mm, outside needle diameter; 0.813 mm). The plastic cup on the needles has been cut off, to prevent formation of air bubbles. The needles are 25.4 mm (1 inch) long, and project 12.7 mm (1/2 inch) below the infiltrometer tank bottom. The sidewalls of the infiltrometer extend 3.8 cm (1 1/2 inches) below the base to protect the needles from being damaged, as well as preventing the operator from injuring himself on the needles (figure 18).
Figure 18: Base of infiltrometer chamber

Figure 19: Infiltrometer stand

The chamber is supported by a stand constructed from angle
iron and pipe. The stand is supported by four adjustable legs, and sits on wood supports to maintain a level chamber (figure 19).

The base piece, miniplot, is constructed of 0.635 cm (1/4 inch) sheet metal with three sides 20.32 cm (8 inches) high, and one side 10.16 cm (4 inches) high with a lip welded on (figure 20). The miniplot is pounded into the ground 10.16 cm (4 inches) with a sledge hammer, until the lip is at the ground surface. A trough constructed of alluminum is placed under the lip on a slope leading to a collection bucket.

![Diagram of miniplot for infiltrometer](image)

Figure 20: Miniplot (base) for infiltrometer

The water supply is contained in two 30 gallon steel drums transported in the back of a pick-up truck. Garden hose is used to siphon the water to the infiltrometer, and a flow control valve allows the input rate to be controlled. Figure 21 below shows the field setup.
Figure 21: Field set up of the sprinkling infiltrometer apparatus.

F.2.e.ii. sprinkling infiltrometer calibration procedures

The infiltrometer was calibrated using a range of 2 cm head to 20 cm head. This produced a simulated rainfall rate of 60 mm/hr to 425 mm/hour. The calibration curve is illustrated in figure 22. Data for this graph was generated by covering the bottom of the infiltrometer with plastic, thereby collecting the total precipitation while operating at different heads.
SPRINKLING INFILTROMETER CALIBRATION

Figure 22: Calibration Curve for sprinkling infiltrometer

- Calibration line
- Linear regression

$R = 0.9995$

$y = 2.075x + 2.5$
The simulated rainfall rates produced are, once again, higher than the observed rainfall rates in the Lower Fraser Valley. Maximum intensities from the Agassiz IDF curve occur for a 5 minute duration giving a range of 30 to 70 mm/hr for the 2 - 100 year return periods.

Originally, smaller diameter needles (23 gauge needles - inside diameter, 0.318 mm; outside diameter 0.635 mm) were used in the infiltrometer chamber. The calibration produced a range of rainfall intensity ranging from 4 mm/hr to 88 mm/hr. This provided a very realistic rainfall intensity range, but problems with air-bubbles and dust from the field blocking some needles caused uneven rainfall intensity over the plot area. Calibrated rainfall intensities could no longer be applied. Replacing the needles gave repeatable intensities at specified heads, and the air bubble problem was eliminated.

The infiltrometer used at the University of Oregon produced a precipitation rate ranging from 27 to 185 mm/hr, although all infiltration measurements were conducted using a precipitation rate of 71.8 mm/hr.

Therefore, although a realistic rainfall intensity can be obtained using smaller diameter needles, operating problems such as air-bubbles and sediments clogging the needles necessitate going to a larger diameter needle, thereby increasing the rainfall intensities.
F.3. Peak flow estimation

F.3.a. time of concentration determination

Time of concentration values were derived using the time observations from the stream hydrographs \( t_c = 1.429 t_p \). The hydraulic length of the watershed was determined using the DEM and profiling program. The following time of concentration estimation procedures were tested to determine which gave the most reasonable estimates as compared to the \( t_c \) obtained from the hydrograph analysis:

F.3.a.i. Nomograph

Figure 23 below provides an estimate of the time of concentration, assuming that the values of Manning's \( n \) and hydraulic radius prevail. The nomograph is modified from Kirpich's equation:

\[
t_c = \frac{L^{1.15}}{7700 H^{0.38}} \quad [66]
\]

where: \( t_c = \) hours

\( L = \) length of the watershed along the main stream from the watershed outlet to the most distant ridge in ft (hydraulic length)

\( H = \) difference in elevation between the watershed outlet and the most distant ridge in ft.
Figure 23: Nomograph for estimating time of concentration (Chow 1964)

F.3.a.ii. Kerby formula

The Kerby formula was originally used in conjunction with the rational formula.

\[ t_{c}^{2.14} = \frac{2}{3} \frac{\ln}{\text{S}^{0.5}} \]  \[ \text{[67]} \]

where:  
\( L \) = length of flow in ft.
\( S \) = slope of the surface
\( n \) = Manning's roughness coefficient.  (Chow 1964)

F.3.a.iii. Flow Velocity Method (also called the upland method)

The Velocity method incorporates slope and land use in an intermediate step to estimate velocity in a given reach along the hydraulic flow length. The time of concentration equals the ratio of the hydraulic flow length to the velocity:
\[ t_c = \frac{l}{v} \]  \hspace{1cm} [68]

where: \( l \) = travelling distance (ft or m)

\( v \) = velocity of overland flow (fps or m\(^3\)/s)

When velocity varies along the flow path, \( t_c \) may be calculated as:

\[ t = \sum \frac{l_i}{v_i} \]  \hspace{1cm} [69]

where \( l_i \) and \( v_i \) respectively represent the travelling distance and the velocity of flow in individual reaches.

Nomographs such as in figure 24 below are available for estimating velocities for the upland method.
Figure 24: Velocities for upland method of estimating $T_c$ (McCuen 1982)

F.3.a.iv. Kirpich formula

The most accepted formula for small ($A < 50$ ha) agricultural basins relating $t_c$ to the relevant basin characteristics such as
basin area, basin shape, slope, and soil conditions is the Kirpich formula (Smedema and Rycroft 1983; Raudkivi 1979). Once again, this empirical formula deals with estimating the time of overland flow:

\[ t_c = \frac{L^{1.15}}{3080 \cdot H^{0.38}} \]  

where \( t_c \) = hours
\( L \) = maximum travelling distance in the basin (m)
\( H \) = the difference in elevation over the above distance (m).

**F.3.a.v. Lag method**

The lag method relates the time lag \( L \) which is defined as the time in hours from the center of mass of rainfall excess to the peak discharge, to the slope \( Y \) in percent, the hydraulic length \( l \) in feet, and the maximum retention \( S \) (as calculated using the SCS CN procedures):

\[ L = \frac{1^{0.8} (S+1)^{0.7}}{1900 \cdot Y^{0.5}} \]  

\[ S = \frac{1000}{CN} - 10 \]  

where: \( CN \) = Curve Number

Empirical evidence used in developing the SCS methods resulted in the following relationship between the time of concentration and the lag:

\[ t_c = \frac{5 \cdot L}{2} \]  

where \( t_c \) is measured in hours.

By incorporating the curve number in the lag method, the antecedent moisture condition, soil hydrologic condition, and
land use and treatment classes are all included. Because the curve number varies with dormant and growing seasons, and the AMC condition, the time of concentration must be calculated for each storm.

Initial comparison of the various $t_c$ estimation procedures led to the selection of the lag method for use in peak flow calculations.

**F.3.b. SCS unit hydrograph procedure**

The constant in equation 73 may be adjusted to reflect the increased area under the rising limb of the hydrograph in a mountainous region (McCuen 1982).

$$q_p = \frac{726 \cdot AQ}{t_c} \quad [73]$$

This assumes an increase in overland flow response reaching the stream in a shorter period of time (as is often the case for Horton overland flow in grassland catchments). The Agassiz Research Watershed did not reflect this increase in overland flow response time, therefore, all peak flow estimates used the formula as illustrated above.

There are two potential sources of error in the above equation; namely resulting from incorrect estimates of either runoff ($Q$), or $t_c$. In order to isolate these terms, peak flow estimates were performed using the following combinations of values:

1) $t_c$ using the lag method
   
   $Q$ as estimated using the SCS CN method

2) $t_c$ using estimate based on the observed $t_p$
Q as determined by measuring the area under the stream hydrographs.

**F.3.c. Rational formula method**

The Rational formula method is based on the following relationship:

\[ q_p = \frac{CIA}{360} \]  \[74\]

where:

- \( q_p \) = peak discharge (m³/sec) (design peak runoff)
- \( I \) = rainfall intensity in mm per hour (for the design recurrence interval and for the duration equal to the time of concentration of the watershed)
- \( A \) = watershed area (ha)
- \( C \) = runoff (discharge) coefficient (proportion of rainfall discharging rapidly as shallow flow)

Peak flow determination involved the following steps:

1) Determination of soil type(s) for the basin (by reference to published soil maps), and their effect on infiltration.
2) Determination of the watershed area (using the DEM).
3) Delineation of the watershed into different land use types (by area).
4) Evaluation of the effect of land use on interception.
5) Estimation of the time of concentration for the basin.
6) Estimation of the intensity or rainfall index (I) (the rainfall intensity for the time of concentration for each particular storm).
7) Estimation of the runoff (discharge) coefficient. The
following table was used to determine the discharge coefficient:

<table>
<thead>
<tr>
<th>Infiltrability of the soil</th>
<th>High</th>
<th>Medium</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arable land</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>slope &lt; 5%</td>
<td>C = 0.30</td>
<td>C = 0.50</td>
<td>C = 0.60</td>
</tr>
<tr>
<td>5 - 10%</td>
<td>0.40</td>
<td>0.60</td>
<td>0.70</td>
</tr>
<tr>
<td>10 - 30%</td>
<td>0.50</td>
<td>0.70</td>
<td>0.80</td>
</tr>
<tr>
<td>Pasture</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>slope &lt; 5%</td>
<td>C = 0.10</td>
<td>C = 0.30</td>
<td>C = 0.40</td>
</tr>
<tr>
<td>5 - 10%</td>
<td>0.15</td>
<td>0.35</td>
<td>0.55</td>
</tr>
<tr>
<td>10 - 30%</td>
<td>0.20</td>
<td>0.40</td>
<td>0.60</td>
</tr>
<tr>
<td>Forest</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>slope &lt; 5%</td>
<td>C = 0.10</td>
<td>C = 0.30</td>
<td>C = 0.40</td>
</tr>
<tr>
<td>5 - 10%</td>
<td>0.25</td>
<td>0.35</td>
<td>0.50</td>
</tr>
<tr>
<td>10 - 30%</td>
<td>0.30</td>
<td>0.50</td>
<td>0.60</td>
</tr>
</tbody>
</table>

Table 6: Guidelines for the determination of the discharge coefficient C in the rational formula (USDA 1972)

F.3.d. weir calibration

The rectangular weir installed on site has dimensions 1.524 meters (5 feet) wide across the crest, and 0.762 meters (2.5 feet) high above the crest. Field calibration resulted in the following formula for translating recorded water table heights to discharge:

\[ Q = 1.77 \cdot L \cdot H^{1.5} \]

where:
\[ Q = \frac{m^3}{s} \]

\[ L = \text{crest width (m)} \]

\[ H = \text{head above the crest (m)} \]
G. RESULTS AND DISCUSSION

G.1. Digital Elevation Model performance

G.1.a. data collection techniques

The original stereo-pair used to stereoplot the 1:5 000 base map was taken with a 12 inch focal length at a flying height of 20 000 feet (1:20 000 scale). The stereoplotted map has a scale of 1:5 000, with a 10 meter interval +/- 50 % (standard variance in contour accuracy for a 1:5 000 map produced from 1:20 000 air photos). Within the forested region of the watershed, the stereoplotter operator must be able to find openings to the ground in order to accurately keep the floating point at surface level. This was not a serious problem in the Research watershed since adequate openings were available at rock outcrops or between coniferous trees with low cover density. One region of cloud shadow in the northwest corner of the watershed caused some difficulty in viewing the ground.

The digitizing of the 1:5 000 stereoplotted map using the contour method proved to be an efficient procedure for manual entry of the elevation data. The procedure was far more operator friendly than the grid system originally tested, resulting in fewer errors due to operator fatigue. Setting an interval of 2mm along the X-axis and following transects in the Y-direction (as was the case in the grid system) can cause considerable eyestrain, and easy loss of proper horizontal location.

G.1.b. DEM creation

The DEM was created on the VAX by using the triangulation
procedure, then converting the TIN to a grid (binary file). The grid file was converted to an image file, representing the elevation range of 790 m by 255 grey shades. This gave a resolution of 3 m elevation per grey level. The photograph below is the raw image of the Agassiz Research watershed as seen on the rastertec image display at the lab for computational vision at UBC. The dark grey shades represent lower elevations, and the lighter shades the higher elevations. One can easily distinguish between the lowland and upland components of the watershed.

![Raw image](image_url)

Figure 25: Raw image
Creating a synthetic image from the raw image serves to refine the screen output. The following photograph is a black and white synthetic image of the watershed as would be viewed on February 7 at 12:00 noon.

Figure 26: Synthetic image of Research Watershed on February 7 at noon (azimuth 174°, elevation 25°).

The relief can now be seen in the image along with runoff channels in the northeast uplands. The triangular lines at the SE edge of the lowland are artifacts created by the lack of
digitized points in that region (that region is beyond the study area - the southernmost cut off being the creek leading from drained and undrained fields).

To illustrate the ability of studying an image at specified times of day, the sun movement for May 1 can be charted as described in the following table:

<table>
<thead>
<tr>
<th>DATE</th>
<th>SUN AZIMUTH</th>
<th>SUN ELEVATION</th>
<th>TIME</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 1</td>
<td>79°</td>
<td>11°</td>
<td>7:00</td>
</tr>
<tr>
<td></td>
<td>102°</td>
<td>30°</td>
<td>9:00</td>
</tr>
<tr>
<td></td>
<td>133°</td>
<td>48°</td>
<td>11:00</td>
</tr>
<tr>
<td></td>
<td>178°</td>
<td>56°</td>
<td>13:00</td>
</tr>
<tr>
<td></td>
<td>225°</td>
<td>49°</td>
<td>15:00</td>
</tr>
<tr>
<td></td>
<td>256°</td>
<td>32°</td>
<td>17:00</td>
</tr>
<tr>
<td></td>
<td>279°</td>
<td>12°</td>
<td>19:00</td>
</tr>
<tr>
<td></td>
<td>302°</td>
<td>3°</td>
<td>20:00</td>
</tr>
</tbody>
</table>

Table 7: Sun angles for the Agassiz Research Watershed

The following photographs show the synthetic images produced for the above sun angles on May 1 (note: the viewer angle is 45° azimuth, and 30° elevation):
Figure 27: May 1 9:00 am

Figure 28: May 1 1:00 pm
Figure 29: May 1 5:00 pm

Figure 30: May 1 7:00 pm
Contours can also be derived from the original raw image file and either displayed on their own or overlaid on the synthetic image. The following photograph shows the top half of the research watershed in various contour intervals: from the top right 10 m, 20 m, 40 m, and from the top left 60 m, 80 m, and 100 m.

Figure 31: Contour maps for the top half of the research watershed illustrating various contour intervals.
The 40 and 100 meter contours have been overlaid on the synthetic images for February 7 at 12:00 noon as illustrated in the following two photographs. This aids the interpretation of the synthetic image.

Figure 32: Synthetic image from Feb. 7
40 meter contour interval
Figure 33: Synthetic image from Feb. 7
100 m contour interval.

The next photograph is a combination of the raw image (blue), synthetic image (red) and contour overlay for February 7 at noon. Addition of the raw image (grey shades) helps to highlight ridges in the upland.
Figure 34: Synthetic image for Feb. 7 at noon combined with the raw image and a 100 m contour overlay.

The following two photographs illustrate the pixel composition in an image. The top half of each photograph is the northern section of the watershed. The bottom half is a four and eight times enlargement respectively of the top section.
Figure 35: Pixels in an image four times enlargement.

Figure 36: Pixels in an image eight times enlargement.
The map output created using DISSPLA was a good representation of the original map with only minor discrepancies. DISSPLA proved to be difficult to run with such a large database, and would only provide a minimum contour interval of 20 m. Contour maps created on the VAX were unable to be transferred to a plotter. The feasibility of using the latest edition of AUTOCAD was explored, but Autocad does not provide the software required for creating the contours. There are companies filling this void by marketing contouring software for micro-computers, (not accessible for this research.)

G.1.c. area comparisons

The areas obtained using the conventional approaches of planimetering from the 1:50 000 NTS map sheet, plus planimetering from the 1:5 000 stereoplotted map were compared to those obtained by digitizing the respective boundaries of the sub-areas then using the area programs provided with the DEM. The results are presented in the following table:
Table 8: Area comparisons

The area program gives the area in square pixels. The scale of the original map is 1:5 000, the map represented by 300 rows and 168 columns of pixels. Each pixel represents a ground resolution of 10 X 10 meters (2 mm X 2 mm on the map), 100 m². Therefore, the total map area was represented as 47412.613716 sq. pixels, which translates to 4741261.3716 m², or 474 ha.

As illustrated in the above table, the areas measured in the lowland do not show significant differences in their amount. This is due to the fact that for most regions in the lowland there is no significant slope.

The areas obtained for the upland region, which exhibits extreme slopes especially on the eastern slopes of the upland, show a significant difference between methods used. This emphasizes the potential underestimation of areas measured from a planimetric map for regions of extreme terrain. Watershed area
is a key component of many runoff and peak flow estimation techniques, thereby a gross underestimation of error may yield misleading results.

The watershed boundaries drawn onto the NTS map sheet may cause gross error in area measurement if they are incorrectly placed. Due to the small scale of the map, a change of location of the boundary of only a few millimeters can cause dramatic overestimation or underestimation of area. It appears that the boundaries were chosen well, as the computed area does not significantly differ from that obtained using the large scale map.

G.1.d. profiling performance

In the determination of the hydraulic length of the watershed (as indicated on the map in appendix B), the profiling program was used in order to include the slope in the length calculation. A comparison of the length measured from the profile, to the planar distance is illustrated below:

<table>
<thead>
<tr>
<th>GROUND DISTANCE</th>
<th>PLANAR DISTANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>meters</td>
<td>meters</td>
</tr>
<tr>
<td>UPLAND</td>
<td>1291</td>
</tr>
<tr>
<td>PANTH</td>
<td>422</td>
</tr>
<tr>
<td>LOWLAND</td>
<td>770</td>
</tr>
</tbody>
</table>

Table 9: Comparison of distances along the hydraulic length

Once again, in the lowland region where there is very little
slope, there is no difference in resultant distances. The fan section has a slope of 17.6%, and the profile program takes this into account resulting in a slightly increased distance over the planar distance. The most dramatic difference between the two measurement procedures occurs in the upland segment with a slope of 54.2%. There is an increase of 280 m in the hydraulic length as calculated using the profile program when incorporating slope.
G.2. Runoff comparisons

G.2.a. watershed curve numbers

Curve numbers for all regions of the watershed were determined according to recommended procedures from the SCS and U.S. Forest Service (USDA 1972). The upland forest is composed of approximately 50% deciduous trees; thereby the cover density is highly effected by season. The following table illustrates the curve numbers derived for the upland region B, taking season into account.

<table>
<thead>
<tr>
<th>FOREST TYPE</th>
<th>COVER</th>
<th>CN</th>
<th>AVE. CN</th>
</tr>
</thead>
<tbody>
<tr>
<td>GROWING</td>
<td>oak/aspen</td>
<td>80%</td>
<td>32</td>
</tr>
<tr>
<td>SEASON</td>
<td>coniferous(pine)</td>
<td>50%</td>
<td>57</td>
</tr>
<tr>
<td>DORMANT</td>
<td>oak/aspen</td>
<td>10%</td>
<td>82</td>
</tr>
<tr>
<td>SEASON</td>
<td>coniferous(pine)</td>
<td>50%</td>
<td>57</td>
</tr>
</tbody>
</table>

Table 10: Curve Numbers for the upland region of the Agassiz Research Watershed.

The graphs provided by the US Forest Service for the estimation of CNs (figures 14 and 15) do not provide estimates for Soil hydrologic condition A. Therefore interpolating from the graphs, the following curve numbers for the forested fan A region were obtained.
FAN A (70/30 DECIDUOUS/CONIFEROUS)

<table>
<thead>
<tr>
<th>FOREST TYPE</th>
<th>COVER</th>
<th>CN</th>
<th>AVE. CN</th>
</tr>
</thead>
<tbody>
<tr>
<td>GROWING</td>
<td>oak/aspen</td>
<td>80%</td>
<td>25</td>
</tr>
<tr>
<td>SEASON</td>
<td>coniferous (pine)</td>
<td>50%</td>
<td>50 33</td>
</tr>
<tr>
<td>DORMANT</td>
<td>oak/aspen</td>
<td>10%</td>
<td>75</td>
</tr>
<tr>
<td>SEASON</td>
<td>coniferous</td>
<td>50%</td>
<td>50 68</td>
</tr>
</tbody>
</table>

Table 11: Curve Numbers for the Fan region of the Agassiz Research Watershed.

It is important to note that the forest types signified in the tables for the western United States are not the same species composition as found in the Research Watershed (these were the only forest types for the western region of the United States presented by the U.S. Forest Service for CN determination) (USDA 1972). The oak-aspen and juniper-grass complexes were used for choosing curve numbers. The species identified in these complexes include mountain brush mixtures of oak, aspen, mountain mahogany, bitter brush, and maple, plus juniper or pinyon. Of the above species, only some maples (vine maple, and bigleaf maple), and black cottonwood (poplar) are found in the Agassiz Research watershed. The other species listed by the U.S. Forest Service are found in the dryer oak woodlands and chaparral regions covering the foothills and lower mountain slopes in areas such as California, southern Arizona, and New Mexico. In areas
where the winters are cold, such as the Great Basin and the Colorado Plateau, woodlands are dominated by pinyons or junipers rather than oaks. Chaparral coexists with all of these woodlands throughout much of their range (Whitney 1985).

The Agassiz Research watershed is part of the Pacific Coastal Region, supporting mainly small hemlock, douglas fir, cedar, along with hardwoods and shrubs such as giant bigleaf maples, red alders, cottonwoods, and vine maple.

Nonetheless, use of the U.S. Forest Service guidelines seemed more appropriate than using the woods classification in table 2 (cover density for the different seasons could be taken into account when determining curve numbers).

The remaining land use categories were also evaluated to derive curve numbers, and the following table shows the appropriate curve numbers for the complete watershed:
<table>
<thead>
<tr>
<th>LAND USE</th>
<th>HYDROLOGIC SOIL GROUP</th>
<th>AREA</th>
<th>CN</th>
<th>DORMANT</th>
<th>GROWING</th>
</tr>
</thead>
<tbody>
<tr>
<td>forested U/L</td>
<td>B</td>
<td>83%</td>
<td>70</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>forested fan</td>
<td>A</td>
<td>4%</td>
<td>68</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td>L/L scrub/marsh</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(pasture or range) D</td>
<td></td>
<td>12.335%</td>
<td>89</td>
<td>89</td>
<td></td>
</tr>
<tr>
<td>undrained fallow</td>
<td>D</td>
<td>0.29%</td>
<td>94</td>
<td>94</td>
<td></td>
</tr>
<tr>
<td>drained fallow</td>
<td>C</td>
<td>0.375%</td>
<td>91</td>
<td>91</td>
<td></td>
</tr>
</tbody>
</table>

Table 12: Curve Numbers for the Agassiz Research Watershed.

G.2.b. runoff estimates

The curve numbers outlined in table 12 were used to estimate runoff for each of the storms outlined in table 13 below.

For computing the runoff from complex hydrographs, a composite storm recession curve for the watershed was derived from analysing six single event storm hydrographs (Appendix D). This was used for extending the recession curves in complex hydrographs for base flow separation. Hydrograph separation for all storms can be found in Appendix E.

Table 13 below is a summary of the runoff estimates as calculated using the SCS Curve Number approach, and as measured from the stream hydrographs.
<table>
<thead>
<tr>
<th>DATE/STORM NO.</th>
<th>SEASON</th>
<th>AMC</th>
<th>SCS CN (mm)</th>
<th>HYDROGRAPH (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sept 4 - 8 1984</td>
<td>G</td>
<td>I</td>
<td>2.87</td>
<td>15.2</td>
</tr>
<tr>
<td>Sept 4 - 8 1985</td>
<td>G</td>
<td>I</td>
<td>1.59</td>
<td>9.7</td>
</tr>
<tr>
<td>Sept 20 - 2 3 1984</td>
<td>G</td>
<td>I</td>
<td>0.34</td>
<td>2.2</td>
</tr>
<tr>
<td>Oct 7 - 14 1984</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>G</td>
<td>I</td>
<td>0.00</td>
<td>0.7</td>
</tr>
<tr>
<td>2</td>
<td>G</td>
<td>I</td>
<td>0.00</td>
<td>1.7</td>
</tr>
<tr>
<td>3</td>
<td>G</td>
<td>I</td>
<td>1.24</td>
<td>14.6</td>
</tr>
<tr>
<td>4</td>
<td>G</td>
<td>III</td>
<td>0.85</td>
<td>-</td>
</tr>
<tr>
<td>Oct 23 - 26 1984</td>
<td>G</td>
<td>I</td>
<td>0.44</td>
<td>5.9</td>
</tr>
<tr>
<td>Oct 27 - 31 1984</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>G</td>
<td>II</td>
<td>2.20</td>
<td>4.8</td>
</tr>
<tr>
<td>2</td>
<td>G</td>
<td>II</td>
<td>0.07</td>
<td>1.3</td>
</tr>
<tr>
<td>Nov 18 - 22 1984</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>D</td>
<td>I</td>
<td>0.00</td>
<td>2.2</td>
</tr>
<tr>
<td>2</td>
<td>D</td>
<td>I</td>
<td>0.00</td>
<td>3.3</td>
</tr>
<tr>
<td>3</td>
<td>D</td>
<td>II</td>
<td>0.20</td>
<td>3.5</td>
</tr>
<tr>
<td>Dec 6 - 8 1984</td>
<td>D</td>
<td>I</td>
<td>1.87</td>
<td>14.6</td>
</tr>
<tr>
<td>Dec 8 - 17 1984</td>
<td>D</td>
<td>II</td>
<td>15.00</td>
<td>23.98</td>
</tr>
<tr>
<td>Mar 19 - 22 1985</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>G</td>
<td>I</td>
<td>0.00</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>G</td>
<td>I</td>
<td>0.00</td>
<td>1.6</td>
</tr>
<tr>
<td>Mar 22 - 25 1985</td>
<td>G</td>
<td>I</td>
<td>0.11</td>
<td>3.0</td>
</tr>
<tr>
<td>Mar 28 - Apr 4 1985</td>
<td>G</td>
<td>I</td>
<td>0.01</td>
<td>2.1</td>
</tr>
<tr>
<td>1</td>
<td>G</td>
<td>I</td>
<td>0.13</td>
<td>4.0</td>
</tr>
<tr>
<td>4</td>
<td>G</td>
<td>III</td>
<td>7.90</td>
<td>12.4</td>
</tr>
<tr>
<td>Apr 10 - 21 1985</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>G</td>
<td>I</td>
<td>0.04</td>
<td>5.2</td>
</tr>
<tr>
<td>2</td>
<td>G</td>
<td>I</td>
<td>0.00</td>
<td>2.0</td>
</tr>
<tr>
<td>3</td>
<td>G</td>
<td>II</td>
<td>0.01</td>
<td>1.5</td>
</tr>
<tr>
<td>4</td>
<td>G</td>
<td>I</td>
<td>0.00</td>
<td>1.1</td>
</tr>
<tr>
<td>5</td>
<td>G</td>
<td>I</td>
<td>0.00</td>
<td>2.6</td>
</tr>
<tr>
<td>Apr 22 - 26 1985</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>G</td>
<td>I</td>
<td>0.00</td>
<td>2.4</td>
</tr>
<tr>
<td>2</td>
<td>G</td>
<td>I</td>
<td>0.00</td>
<td>1.5</td>
</tr>
<tr>
<td>Apr 26 - May 1 1985</td>
<td>G</td>
<td>I</td>
<td>4.10</td>
<td>18.9</td>
</tr>
<tr>
<td>May 4 - 7 1985</td>
<td>G</td>
<td>I</td>
<td>0.00</td>
<td>2.0</td>
</tr>
<tr>
<td>2</td>
<td>G</td>
<td>I</td>
<td>0.00</td>
<td>0.8</td>
</tr>
<tr>
<td>May 10 - 16 1985</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>G</td>
<td>I</td>
<td>0.00</td>
<td>5.2</td>
</tr>
<tr>
<td>2</td>
<td>G</td>
<td>I</td>
<td>0.01</td>
<td>4.0</td>
</tr>
</tbody>
</table>
Table 13: Runoff estimates based on the SCS Curve Number method and hydrograph analysis

The above results show that the SCS CN runoff estimates for each of the storms studied are less than the runoff measured from the stream hydrographs. In some storms, the SCS procedure predicted no runoff at all.

These results may be explained in various ways. Firstly, the majority of the watershed (87%) is forested. The curve numbers for the forested regions are very low, thereby reflecting high storage potential in the soil. In order for runoff to occur, the rainfall must be greater than 0.2S (S being the potential maximum storage capacity). There were only two storms, Dec 8 - 17, 1985, and March 28 - April 4, 1985, where the precipitation was great enough to fill the potential storage capacity (0.2S) in the forested regions, and cause runoff. For the majority of the storms, runoff was generated from the lowland scrub/marsh region, drained, and undrained fields only. The curve numbers for these regions were much higher than for the forested region, thereby indicating a smaller potential storage capacity in the soil. On May 10 - 16, 1985, runoff occurred from the drained and undrained fields only. Some storms only
generated runoff from the undrained field since all other regions provided more potential storage than the total precipitation (Oct 7-14 1984 (2nd storm), April 10-21, 1985 (2nd storm), April 22-26, 1985 (1st storm), May 4-7, 1985, (1st storm)). The storms with no predicted runoff reflect adequate storage in the entire watershed to accommodate all precipitation.

Review of runoff results from the stream hydrographs indicates that all storms studied did indeed produce runoff as recorded at the basin outlet. This indicates that the SCS CN procedure is not adequately reflecting runoff processes occurring in the watershed. The SCS procedure considers each characteristic region of the watershed independently. A curve number is assigned to each region then a weighted runoff estimate is made based on the relative area of each characteristic region. This does not allow for one region to influence runoff production in adjacent regions (i.e. subsurface flow from the forested upland filling the storage capacity of the lowland soils causing the saturated region to spread upslope - the variable contributing area concept).

Runoff as predicted using the SCS CN procedure is almost exclusively from the lowland regions (thereby assuming the only type of runoff generated in the Research Watershed is overland flow and that the upland region does not contribute to runoff production). This is contrary to research findings from other forested upland regions where subsurface runoff is observed (Hewlett and Hibbert 1967).
The USDA (1972) point out that errors in runoff estimates are due to one or more of the following: empiricisms in the antecedent moisture classification (table 2), Curve Number guidelines (table 4 and figures 14 and 15), the relation between the AMC and Curve Numbers, the equation for initial abstraction; and errors in determinations of average watershed rainfall, soil groups, land use and treatment, and related computations. Consequently, it is impossible to state a standard error of estimate for the runoff equation [64]; comparisons of computed and actual runoffs indicate only the algebraic sum of errors from various sources (USDA 1972).

The Curve Number approach was for the most part developed in mid-western watersheds of the United States, where storms are high intensity, short duration events as compared to the low intensity, long duration storms in the Lower Fraser Valley Region. The climatic differences between mid-western USA and the western coastal region may also introduce difficulties in assigning Curve Numbers to catchments (not only due to different rainfall patterns, but also different topography, and vegetation). A study in the Palouse area of Washington and Idaho, a region also experiencing a maritime climate and low rainfall rates, indicated difficulty in estimating the appropriate Curve Number (Molnau et al. 1983).

The SCS model was originally intended for drainage areas of 2000 acres (8094 ha) or less, with slopes limited to less than 30 percent (Dickey et al. 1979). The Research Watershed exhibits
slopes over 50 percent in the upland which composes 87 percent of the watershed area. The SCS procedures do not include slope as a parameter in runoff estimation, it is only introduced in the time of concentration determination and applied in peak flow estimation. Therefore, the effects of upland regions in runoff production is not adequately addressed in the SCS CN procedures.

Another potential source of error may be the adjustments that are made to the CN according to the three classes of antecedent moisture condition (AMC). Problems with the approach followed by the SCS have been criticised by Hope et al. (1982) on the basis of the following three points:

1) The relationships between AMC and rainfall are shown as discrete classes, rather than being a continuum, thus implying sudden shifts in curve numbers and corresponding quantum jumps possible in calculated stormflow (Hawkins 1978).

2) The use of five antecedent days' rainfall is not based on physical reality but is, according to Miller in Hope et al. (1982), based on subjective judgement.

3) No consideration is given to the depletion of catchment storages due to evapotranspiration and drainage which may vary from region to region and within a season.

Therefore, it appears that the SCS CN method does not adequately represent the runoff processes occurring in an upland forested watershed in a humid climate such as the Agassiz Research Watershed. Runoff estimates are consistently underestimated.
G.3. **TOPMODEL evaluation**

In the development of TOPMODEL, the need for a simple, physically-based hydrological forecasting model with parameters that are directly measurable was emphasized. Review of various studies by Beven and his associates over the past ten years indicated promising results giving incentive to model application. However, when planning the field work and model calibration, it became apparent that practical problems in the model application still existed. Therefore, the model procedures were evaluated, but not applied in this research.

TOPMODEL has always been very much a research tool and existed in many forms. The essentials underlying the use of \( a/tan^\theta \) distributions are very simple and the coding of the calculations for one time step are very compact (Beven 1985). The model should not be used with very short time steps (less than 1 hour) or very flat hillslopes because of the steady state assumptions that underly the development of the theory. The model was also intended for use in unforested watersheds in humid-temperate climates (due to the problems of accounting for evapotranspiration).

The least satisfactory part of TOPMODEL is the "unsaturated zone" routing. In the original applications the \( S_d, S_c, i_o, OFV, \) and FC parameters were all constant within each subcatchment, and were not measured in all subcatchments but rather were determined on the basis of vegetation/soil type combinations. The \( i_o \) was always so high that it had little effect on any unsaturated zone
delays, therefore three hour time steps were used. This illustrated that essentially the "unsaturated zone" had little or no control over the form of the hydrograph. This may not be considered as realistic, the answer probably depending on the depth of the watertable (Beven 1985).

To allow more flexibility, Beven presented the

\[ q_v = \frac{S_u z}{t_d S_i} \]  

[25]

approach (Beven and Wood 1983), but this has never been applied with measured parameters. The \( t_d \) parameter is not readily obtained from field measurements (a constant parameter which could be different for different sub-catchments).

Inherent in the determination of infiltration characteristics of a watershed is the problem of using single point measurements. Beven recommends that at least one infiltration test be performed per characteristic sub-area of the catchment. These tests are then assumed to be representative of the entire sub-area. Providing that the assumptions of soil properties changing exponentially with depth and of unsaturated flow being predominatly in the vertical plane are true, the theoretical basis for extrapolating from plot to catchment scale would appear to be capable of further development (Beven 1977).

In practice, after subdividing the watershed into characteristic regions according to landuse, soil type, and slope, it is a very subjective decision as to where the infiltrometer measurements should be made. The decision becomes increasingly more difficult in the upland where there can be
extreme differences in relief and cover. In order to be able to collect runoff from the plot and calculate OFV, the plot must have some slope towards the trough, and should not have large depressions which will prevent the runoff from reaching the collection bucket. In order to achieve this, one could consider that the results are biased by choosing plots with a relatively smooth soil surface, and representative ground cover, but the mechanics of the procedure dictates this. Ground cover can remain undisturbed, except for any trimming necessary to allow the infiltrometer to stand above the plot (the maximum extended height of the infiltrometer in the stand is approximately 0.9 meters).

Taking more than one test per sub-region does not guarantee more confidence in the results. Two plots only a few meters apart can give very different results dependent upon the soil profile and microtopography of the plot. The hydrologist must make a decision as to how he wishes to approach this problem. In order to make the tests statistically significant, a statistical design adequately representing the variation per sub-unit must be adapted giving a final error sum of squares with 30 degrees of freedom. In a watershed with 5 characteristic regions such as the Agassiz Research Watershed (drained field, undrained field, lowland scrub, forested fan region (including logging site), and forested uplands) a high number of tests would be required. The additional time and effort spent on these tests may still not give more confidence to the results again due to the change in
microtopography, cover, slope, and soils for each sub-plot. Since TOPMODEL is a deterministic model, a stochastic approach to infiltration determination may not be required. A single point estimate per sub-region may be adequate and consistent with the model design.

In the calculation of \( q_0 \) (the subsurface flow when \( S_z = 0 \)) the moisture content of various soil samples taken from different parts of the profile is involved. The soil moisture sampling is a problem since it is a highly variable quantity. This was addressed by Beven in the methodology by recommending profiles be sampled down to the watertable or impermeable layer at at least 10 sites in a subcatchment. These should ideally have the same probability of occurrence in space as the \( a/tan\beta \) values so that an approximately weighted average could be taken. Once again, as with the infiltrometer tests, the hydrologist must decide how he wishes to approach this point sampling problem.

Evaluation of TOPMODEL as applied in Crimple Beck catchment in England, and White Oak Run in Virginia predicted contributing areas for individual storms in accordance with observed saturated areas in the field (Beven and Wood 1984). This was based on initial storage deficits, along with the prediction of combined surface and subsurface responses. Simple regressions were carried out for comparison with the model, but the coefficient of determination \( (R^2) \) was below that obtained by TOPMODEL (Beven and Wood 1983).

Beven et al. (1984) report results for three grassland
catchments in Britain and Wales. These illustrate that most of the storm flow is derived from quick response runoff, and that the lack of infiltration delay is not very significant. The model appeared to work best under wet conditions. There is concern that the potential evaporation estimates used in the model do not adequately represent the actual evapotranspiration rates during the summer months. A comparison of model efficiencies however showed there was no seasonal variation for these catchments (Beven et al. 1984). This may not be the case for catchments with large areas of woodland or crops such as the Agassiz Research Watershed, and a more scientific approach for estimating evapotranspiration may be required.

TOPMODEL in its present stage of development is not ready to be used operationally for estimating runoff and peak flow for subsurface drainage design. Specific problems associated with attaining required parameters, evapotranspiration, and the effect of the infiltration storage on runoff processes in forested catchments must be addressed. However, it still presents an interesting approach utilizing physically based characteristics of the catchment, and warrents further research effort.
G.4. Peak flow comparisons

G.4.a. time of concentration – hydraulic length

Figure 37 below illustrates a profile created along the hydraulic length of the watershed as outlined on the map in Appendix B. The profile is divided into three sections: upland, fan, and lowland, each having a characteristic slope.

**Figure 37:** Profile for hydraulic length of Agassiz Research Watershed.
The lengths and slope of each segment are measured as follows:

<table>
<thead>
<tr>
<th></th>
<th>LENGTH</th>
<th>SLOPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>upland</td>
<td>1291 m</td>
<td>0.532</td>
</tr>
<tr>
<td>fan</td>
<td>422 m</td>
<td>0.176</td>
</tr>
<tr>
<td>lowland</td>
<td>770 m</td>
<td>0.0026</td>
</tr>
</tbody>
</table>

(note: the above lengths were calculated using PROFILE.C and the DEM, thereby incorporating slope in the calculations).

G.4.b. time of concentration

The calculation of $t_c$ using the first four methods outlined was straightforward. The hydraulic length was divided into the three sections: upland, fan, and lowland, and the individual $t_c$ estimates for each section were totaled to give the final $t_c$.

Estimation of $t_c$ using the lag method was somewhat more involved as the SCS CN is one of the required parameters. The hydraulic length traverses four of the five hydrologic complexes identified in the SCS Runoff estimation procedures: the forested upland segment, hydrologic soil condition B; the forested fan segment, hydrologic soil condition A; the shrub/wet lowland section, hydrologic soil condition D; and a portion of the drained field, hydrologic soil condition C.

Since the CN selected for a runoff event depends upon the season, and the moisture condition (AMC), table 14 provides a summary of the CNs, and $t_c$, for the possible combinations of available moisture class and season for the three segments of the hydraulic length:
Table 14: Curve Numbers and \( t_c \) estimates using the Lag method

A summary of the five time of concentration estimation procedures studied is presented below:

<table>
<thead>
<tr>
<th>Method</th>
<th>( t_c )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Nomograph</td>
<td>46 min.</td>
</tr>
<tr>
<td>2) Kerby</td>
<td>53 min.</td>
</tr>
<tr>
<td>3) Flow velocity</td>
<td>228 min. (3.8 hr)</td>
</tr>
<tr>
<td>4) Kirpich</td>
<td>41 min.</td>
</tr>
<tr>
<td>5) Lag method</td>
<td>(as indicated in table 14)</td>
</tr>
</tbody>
</table>

Table 15: Time of concentration estimates
From the above testing of the various $t_c$ estimation procedures, the wide range of results easily illustrates the large degree of error which can be introduced into a runoff model using $t_c$. The lag method appeared to produce the most reasonable $t_c$ estimates, therefore was chosen to use in the peak flow calculations. One must note though, that the $t_c$ estimates from the lag method still underestimate the observed $t_c$ estimates from the stream hydrographs (table 16). This problem may be explained by the slower response time of subsurface flow as dominant in forested watersheds compared to overland flow response. The procedures for estimating $t_c$ assume direct overland flow to be the runoff generating process in operation. This is a major problem for forested watersheds located in humid climates such as in the Lower Fraser Valley.

The following table outlines the $t_p$ observations as obtained from the review of storm hydrographs in appendix F, and the corresponding $t_c$ (as calculated by $1.43 \, t_p$).
<table>
<thead>
<tr>
<th>DATE/STORM NO.</th>
<th>STREAM</th>
<th>UNDRAINED FIELD</th>
<th>DRAINED FIELD</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tₚ(h)</td>
<td>Tₜ(h)</td>
<td>Tₚ(h)</td>
<td>Tₜ(h)</td>
</tr>
<tr>
<td>Sept4-8/84</td>
<td>12.0</td>
<td>17.1</td>
<td>**</td>
<td>19.0</td>
</tr>
<tr>
<td>Sept4-8/85</td>
<td>8.0</td>
<td>11.4</td>
<td>6.0</td>
<td>8.6</td>
</tr>
<tr>
<td>Sept20-23/84</td>
<td>7.0</td>
<td>10.0</td>
<td>0.1</td>
<td>0.14</td>
</tr>
<tr>
<td>Oct7-14/84</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>18.0</td>
<td>25.7</td>
<td>6.0</td>
<td>8.6</td>
</tr>
<tr>
<td>2</td>
<td>18.0</td>
<td>25.7</td>
<td>12.0</td>
<td>17.1</td>
</tr>
<tr>
<td>3</td>
<td>17.0</td>
<td>24.3</td>
<td>2.0</td>
<td>2.9</td>
</tr>
<tr>
<td>4</td>
<td>8.0</td>
<td>11.4</td>
<td>5.0</td>
<td>7.1</td>
</tr>
<tr>
<td>Oct23-26/84</td>
<td>12.0</td>
<td>17.1</td>
<td>7.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Oct27-31/84</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>18.0</td>
<td>25.7</td>
<td>17.0</td>
<td>24.3</td>
</tr>
<tr>
<td>2</td>
<td>8.0</td>
<td>11.4</td>
<td>1.0</td>
<td>1.4</td>
</tr>
<tr>
<td>Nov18-22/84</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>6.0</td>
<td>8.6</td>
<td>flooded</td>
<td>4.0</td>
</tr>
<tr>
<td>2</td>
<td>5.0</td>
<td>7.1</td>
<td>flooded</td>
<td>9.0</td>
</tr>
<tr>
<td>3</td>
<td>10.0</td>
<td>14.3</td>
<td>flooded</td>
<td>4.5</td>
</tr>
<tr>
<td>Dec6-8/84</td>
<td>31.0</td>
<td>44.3</td>
<td>17.0</td>
<td>24.3</td>
</tr>
<tr>
<td>Dec8-17/84</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>6.0</td>
<td>8.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>17.0</td>
<td>24.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>11.0</td>
<td>15.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>17.0</td>
<td>24.3</td>
<td>19.0</td>
<td>27.1</td>
</tr>
<tr>
<td>Mar19-22/85</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>17.0</td>
<td>24.3</td>
<td>12.0</td>
<td>17.1</td>
</tr>
<tr>
<td>2</td>
<td>7.0</td>
<td>10.0</td>
<td>4.0</td>
<td>5.7</td>
</tr>
<tr>
<td>Mar22-25/85</td>
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<td>26.0</td>
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</tr>
<tr>
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<td>11.0</td>
<td>15.7</td>
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</tr>
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<td></td>
<td></td>
</tr>
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<td>25.7</td>
<td>6.0</td>
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</tr>
<tr>
<td>Apr26-May1/85</td>
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<td>21.4</td>
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<td>2.9</td>
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<td>9.0</td>
<td>12.9</td>
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<td></td>
<td></td>
<td></td>
</tr>
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<td>18.6</td>
</tr>
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<td>27.0</td>
<td>38.48</td>
<td>18.0</td>
<td>25.7</td>
</tr>
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</table>
Review and comparison of the time to peak for the stream, drained and undrained fields gave the following observations:

1) For the majority of storms the undrained field response was faster than the stream response, therefore precipitation on the undrained field contributes to stream discharge.

2) For the majority of storms, the groundwater response to precipitation in the undrained field was faster than that in the drained field.

3) For approximately 60% of the storms studied, the response of the drained field to precipitation was slower than the stream response.

4) For almost all storm events the groundwater level was near the surface at the beginning of the storm in the undrained field, indicating very poor natural drainage conditions.

G.4.c. peakflow estimates

Peak discharge estimates using the rational formula required an estimate of C (discharge coefficient). A weighted value of C
was calculated as outlined in table 17:

<table>
<thead>
<tr>
<th>Area</th>
<th>Slope</th>
<th>Infiltration</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>FOREST</td>
<td>0.87</td>
<td>&gt;30%</td>
<td>0.30</td>
</tr>
<tr>
<td>PASTURE</td>
<td>0.12335</td>
<td>10 - 30%</td>
<td>0.60</td>
</tr>
<tr>
<td>LOWLAND</td>
<td>0.00665</td>
<td>&lt;5%</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Table 17: Estimation of the runoff coefficient C for the Agassiz Research Watershed.

Therefore, the weighted value of C equals 0.31.

The following table provides a summary of peak flow estimates as determined using the weir calibration, SCS Unit Hydrograph method, and the Rational formula. The following combinations of $t_c$ and runoff (Q) estimates were used to obtain these results:

1) SCS Unit Hydrograph Method
   1 - $t_c$ as estimated by the lag method, and Q (runoff) as estimated using SCS CN method.
   2 - $t_c$ as estimated from hydrograph observation of $t_p$, and Q as measured from the stream hydrograph.

2) Rational Formula
   1 - rainfall intensity (I) determined for $t_c$ as estimated by the lag method.
   2 - rainfall intensity (I) determined for $t_c$ as estimated from hydrograph observation of $t_p$.

3) Rainfall Intensity values
1 - I determined for $t_c$ as estimated by the lag method
2 - I determined for $t_c$ as estimated from hydrograph observation of $t_pe$. 
### PEAK FLOW $q_p$ (m$^3$/s)

<table>
<thead>
<tr>
<th>DATE/STORM NO.</th>
<th>WEIR 1</th>
<th>SCS 2</th>
<th>RATIONAL 1</th>
<th>RATIONAL 2</th>
<th>INTENSITY 1</th>
<th>INTENSITY 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sept4-8/84</td>
<td>1.25</td>
<td>0.95</td>
<td>1.32</td>
<td>1.54</td>
<td>1.55</td>
<td>3.45</td>
</tr>
<tr>
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<td>0.52</td>
<td>1.26</td>
<td>2.20</td>
<td>1.74</td>
<td>4.91</td>
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<td>0.11</td>
<td>0.33</td>
<td>0.64</td>
<td>1.31</td>
<td>1.43</td>
</tr>
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<td>0.05</td>
<td>0.00</td>
<td>0.04</td>
<td>0.55</td>
<td>0.12</td>
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<td></td>
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<td>0.00</td>
<td>0.10</td>
<td>0.10</td>
<td>0.18</td>
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<tr>
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<td>3</td>
<td>1.07</td>
<td>0.41</td>
<td>0.89</td>
<td>0.68</td>
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<tr>
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<td>4</td>
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<td>0.73</td>
<td>-</td>
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<td>Dec8-17/84</td>
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</tr>
<tr>
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<td>0.30</td>
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<td>0.76</td>
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<td>1.31</td>
<td>0.99</td>
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<td>0.23</td>
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<td>0.00</td>
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<td>0.51</td>
<td>0.00</td>
<td>0.15</td>
<td>0.29</td>
<td>0.20</td>
</tr>
</tbody>
</table>
Table 18: Peak flow estimates

All peak flow estimates were compared to the peak discharge as recorded at the weir.

Peak flow results using the runoff (Q) and time of concentration ($t_c$) as estimated using the SCS CN procedures present various problems. For many of the storm events, the SCS CN procedure predicted no runoff from the watershed. This translated into a zero value for peak flow. When runoff was estimated from all regions of the watershed, an unreasonably high peak flow was generated (Dec 3-17 1984, and Mar 28-Apr 4 1985, storm 4). For the remaining storms with runoff contributions only from the lowland, the majority of peak flow estimates were underestimated.

The SCS unit hydrograph approach using $t_c$, and Q as observed from the stream hydrographs, produces estimates of peak flow that are reasonable but underestimated for the majority of storms. The watershed appears to respond slower than the SCS procedures are designed for, perhaps indicating that the unit hydrograph approach is more applicable in watersheds generating overland flow. According to the average SCS dimensionless unit hydrograph developed, 3/8 of the total volume of flow occurs before the time to peak. In a watershed experiencing subsurface flow, the time
to peak may be delayed due to the slower response time of subsurface flow from the forested region as compared to the expected response time from an equivalent area generating overland flow, and a greater proportion of the total flow may reach the outlet before peak flow is attained.

The results for the peak flow estimates using the Rational Formula provide good estimates of peak flow, both using the $t_c$ as estimated from the SCS lag method, and observed from the stream hydrograph. The $t_c$ from the hydrograph was always longer than the $t_c$ from the lag method, therefore causing a change in rainfall intensity input ($I$). The rainfall intensity depends on the distribution of rainfall in the storm. For some events, the time of concentration observed from the hydrograph was longer than the rainfall event, therefore a reduced rainfall intensity value ($I$) was used in the rational formula calculations.

The objective of using either the SCS unit hydrograph approach, or the Rational Formula was to be able to apply the methods to ungauged catchments. Therefore, excluding the calculations using runoff and time of concentration from the hydrograph records, the Rational Formula provides the best estimates of peak flow.
H. CONCLUSIONS

One of the objectives of this research was to evaluate the operational potential of using a digital elevation model based on an IBM-PC for obtaining watershed information as required by a drainage engineer, or hydrologist. Since most people in the position of preparing drainage designs have access to a microcomputer, this could become a realistic component of the design procedures. This research indicated that the use of digital elevation models (DEMs) in the field of agricultural hydrology has definite potential benefits. The DEM provides a much more accurate representation of the terrain than do standard NTS 1:50 000 topographic maps. Not only can areas and profiles be computed retaining ground truth, but the watershed can be displayed as an image on an image analysis system or plotted as a contour map for further analysis. The process of creating a DEM for a specific watershed by stereoplotting then digitizing the resultant map works well. A less labour intensive approach would be to obtain direct digital output from the stereoplotting process. Recent trends within the mapping agencies of the Federal government, as well as the Provincial governments of British Columbia and Alberta, suggest that digital data will become available through data banks. This will eliminate the data collection process for most users (unless larger scale coverage is required than that provided), and allow an operational system to be based around an IBM-PC and the software capable of extracting the specific resource information.
At the present time, the use of a digital elevation model for on-farm drainage design procedures is still a feasible approach. Stereoplotter operators are locally trained at the British Columbia Institute of Technology (BCIT), and small contractors provide good work at a reasonable cost. Digitizing procedures are straightforward, and provide an alternative approach if large scale maps already exist for the drainage site. The creation of the grid data base in this research was done on a VAX minicomputer system, but there are microcomputer-based image analysis systems available at reasonable costs. The computation of area and profiles anywhere within the DEM are easily performed on the micro-computer.

The potential for the application and further development of digital elevation modelling, especially in conjunction with complete geographic information systems, is certainly a feasible approach only limited by budget restrictions and user imagination.

The SCS CN approach for estimating runoff does not adequately represent the potential subsurface runoff from forested regions. Due to the low rainfall intensities common in the Agassiz Research Watershed (and consequent low precipitation totals), many storms were predicted to produce no runoff at all (assuming that once the initial demands of interception, infiltration, and surface storage have been satisfied (initial abstraction), there is no rainfall available for runoff). For the storms satisfying the initial abstraction, runoff was generally only produced from
the lowland regions (overland flow).

When extending conclusions into the region, it should be noted that this research is based on 1.5 years of stream discharge data. Since the statistical approach to runoff estimation, i.e. regression analysis, was not evaluated, this relatively short data collection period should not cast doubt on the results. Approximately forty storm events were evaluated during the study period. Ideally, a longer study period allowing for larger event storms to occur, plus allowing a period of local calibration then subsequent model testing would be ideal.

The Rational Formula appears to be the preferred approach for calculating peak flows in this research. The SCS unit hydrograph approach runs into problems when using the underestimated runoff values from the SCS CN approach. Using runoff and time of concentration calculated from the stream hydrographs, the SCS unit hydrograph estimates are still underestimated for the majority of storms. This may be due to the procedure being tailored to overland flow generation, rather than subsurface flow as occurs in forested upland regions.

A common problem in peak flow estimation is the time of concentration variable. All estimation procedures evaluated underestimated the time of concentration as compared to the results from the stream hydrograph analysis. Ultimately, a stochastic approach using regression relationships with similar watersheds in the region, or a modelling approach which accounts for the physical watershed characteristics may provide a more
feasible approach to both runoff and peak flow estimation.

Review of a physically-based deterministic hydrologic model, TOPMODEL, developed by Beven indicated that in its present stage, it is not yet in an operational state for use in drainage design. Problems in the treatment of the infiltration store, plus confusion in parameter determination must first be addressed. Physically based models, such as TOPMODEL, do however present an attractive alternative to conventional methods of runoff and peak flow estimation in theory since topographic features of the watershed are a key component. Variable source areas can be modelled, an important feature in a forested catchment. Nonetheless, complex, expensive models do not always provide better results. As a recent study by Loague and Freeze (1985) indicates, simpler and less data intensive models provide as good or better predictions than a physically based model. If physically based models become less data intensive and more straightforward to use, they may have a future place in drainage design procedures.

The question of dealing with runoff from the upland, or seepage in subsurface drainage design must still be addressed. An underestimate of runoff used in subsurface drainage design may result in an underdesigned system. In subsurface drainage design, it is advisable to deal with any upland runoff input before it reaches the main drainage system. This could be accomplished through interception of the runoff by either a surface ditch, or an interceptor drain when surface ditching would cause an
inconvenience in farming operations.

An important consideration in making decisions regarding subsurface drainage design in the Lower Fraser Valley, is the regional drainage infrastructure one must work within. Ultimately, most regional drainage systems handle upland runoff, especially during the spring freshet. But, as agriculture spreads into the fringes of the lowland, and into parts of the upland, many farms are not protected by the regional drainage system, and are subject to the local effects of the adjacent uplands. Such subsurface projects must ensure that adequate outlets exist, either via the natural drainage system or municipal ditches nearby.

Accurate upland runoff estimates are crucial for successful subsurface drainage design for lowland agriculture adjacent to upland regions.
I. REFERENCES


APPENDICIES
APPENDIX A
APPENDIX B
PROGRAMS FOR CALCULATING AREA
#include <stdio.h>

#define MAXROW 300
#define MAXCOL 200
#define ROW 0
#define COL 1

char grid[MAXROW][MAXCOL];

main(argc, argv)
int argc;
char *argv[];
{
    int rlast, clast, r, c, rl, cl, rint, cint;

    /* initialize the grid */
    for (r = 0; r < MAXROW; r++)
        for (c = 0; c < MAXCOL; c++)
            grid[r][c] = 0;

    /* read the interior point */
    scanf("%d %d", &rint, &cint);

    /* read the first point */
    scanf("%d %d", &rl, &cl);
    rlast = rl;
    clast = cl;

    /* read new (r c) points and draw the edges */
    while(1){
        scanf("%d %d", &r);
        if(r == -1)
            break;
        scanf("%d %d", &c);
        line(rlast, clast, r, c, 2);
        rlast = r;
        clast = c;
    }

    fprintf(stderr, "Working ... relax\n");

    /* join the last point to the first point */
    line(rlast, clast, rl, cl, 2);

    /* fill the interior with ones */
    fill(rint, cint, 2);

    /* write the grid */
    for (r = 0; r < MAXROW; r++)
        for (c = 0; c < MAXCOL; c++)
           putc(grid[r][c], stdout);

    exit(0);
}

line(r1, c1, r2, c2, colour)
int r1, c1, r2, c2, colour;
{
    double rinc, cinc, length, tlen, r, c;
    int i;

    /* Based on the simple DDA from Newmann and Sproull */

    length = r2 - r1;
    if (length < 0.0) length *= -1.0;

    tlen = c2 - c1;
    if (tlen < 0.0) tlen *= -1.0;
if (tlen > length) length = tlen;

if (length != 0.0) {
    rinc = (r2 - r1)/length;
    cine = (c2 - c1)/length;
    r = r1; c = c1;

    for (i = 0; i < length; i++) {
        grid((int)r][(int)c] = colour;
        r += rinc;
        c += cine;
    }
}

fill(rseed, cseed, colour)
int rseed, cseed, colour{
    static int newgyro[7] = {3, 0, 1, 2, 3, 0, 1};
    static int inc[4][4][2] =
        /* LEFT FRONT RIGHT BACK */
        ( { { 0, -1, }, (-1, 0), (0, 1), (1, 0) }, /* NORTH */
          { { -1, 0, }, (0, 1), (1, 0), (0, -1) }, /* EAST */
          { { 0, 1, }, (1, 0), (0, -1), (-1, 0) }, /* SOUTH */
          { { 1, 0, }, (0, -1), (-1, 0), (0, 1) } }; /* WEST */

    int gyro, idx, turn;
    struct coord (int r, c;) current, new;

    while(!grid[rseed][cseed]) /* move left to perimeter */
        cseed++;
    gyro = NORTH; /* start pointing NORTH */
    current.r = rseed;
    current.c = cseed;

    while(1){
        if(grid[current.r][current.c])
            for(idx = current.c; idx < MAXCOL; idx++) /* lit line */
                if(grid[current.r][idx])
                    break;
            else
                grid[current.r][idx] = 1;
        for(turn = 0; turn++;
            new.r = current.r + inc[gyro][turn][ROW];
            new.c = current.c + inc[gyro][turn][COL];
            if(grid[new.r][new.c] != colour)
                break;
        }
        current.r = new.r;
        current.c = new.c;
        if(current.r == rseed & current.c == cseed)
            break;
    gyro = newgyro[gyro + turn];
}
area - November 1985
Original by Mark Majka
Additions and adaptation to DeSmet C by Francois Dumoulin

Purpose: To compute the area within a polygon.

Usage: area -m mask -c cosi [-help] [-nr rows] [-nc cols]

Options:
- -m mask  name of mask file
- -c cosi  name of cosi file
- -help  help message
- -nr rows  number of rows
- -nc cols  number of columns

#ifndef GETARGS
#define GETARGS(X) getarg(X,argc,argv)
#define MAXROW 300
#define MAXCOL 168

static char PROGNAME[] = "area",
USAGE[] = "Usage: area -m mask -c cosi [-help] [-nr rows] [-nc cols]\n";

main(argc,argv)
int argc;
char *argv[];
{  
FILE *cfp, *mfp, *fopen();
int row, col, argn, maxrow = MAXROW, maxcol = MAXCOL;
double area, cosi, i, mask;

        /* parsing the command line */
if (GETARGS("help"))
   messout("Xs\n", USAGE);
if (argn = GETARGS("nr")) maxrow = atoi(argv[++argn]);
if (argn = GETARGS("nc")) maxcol = atoi(argv[++argn]);
if (argn = GETARGS("m"))
   mfp = fopen(argv[++argn], "r");
   else
   messout("no mask file specified!\nXs\n", USAGE);
if (mfp == NULL)
   messout("can't open mask file!\n");
if (argn = GETARGS("c"))
   cfp = fopen(argv[++argn], "r");
   else
   cfp = stdin;
if (cfp == NULL)
   messout("can't open cosi file!\n");

        /* the job */
for (row = 0, area = 0.0 ; row < oaxrow ; row++)
    for (col = 0 ; col < uaxcol ; col++) {
        mask = (unsigned) fgetc(mfp);
        cosi = (unsigned) fgetc(cfp);
        if (mask) area += 255.0 / (cosi * mask);
    }
printf("area = %lf\n", area);
exit(0);
/
function getarg: get arguments on command line
/
getarg(desig, argc, argv)
int argc;
char *desig, *argv1[];
{
    int argn;
    char minus[2], lookfor[12];
    strcpy(minus, "-"),
    strcpy(lookfor, minus);
    strcat(lookfor, desig);
    for (argn = 1; argn < argc; argn++)
        if (!strcmp(argv[argn], lookfor)) return(argn);
    return (0);
/
function messout: error messages
/
messout (msg, par1, par2, par3, par4)
char *msg, *par1, *par2, *par3, *par4;
{
    fprintf(stderr, "%s: ", PROGNAME);
    fprintf(stderr, msg, par1, par2, par3, par4);
    fprintf(stderr, "\n");
    exit(1);
} /* end of function messout */
PROGRAM FOR CALCULATING PROFILES
/**
 * Copyright (c) 1985 Marc S. Najka - UBC Laboratory for Computational Vision
 * Permission is hereby granted to copy all or any part of this program for non-commercial use. The author's name and this copyright notice must be included in any copy.
 */

/* profile - construct an intensity profile of an image */

/* synopsis: profile */
/* options: -i iff (Xs) (input image file, default = stdin) */
/* -r n (Xd) (number of rows) */
/* -c n (Xd) (number of columns) */
/* -p r1 c1 r2 c2 (Xd Xd Xd Xd) (start and end points) */
/* -s n (Xd) (number of steps) */
/* -d f (XIf) (step size. Ignored if -s given) */
/* -help (print options summary and exit) */

/* compile: cc -o profile profile.c -la */

#include <stdio.h>
#include <math.h>
#define MAXIM 1024
#define GETARG(x) getarg(x,argc,argv)

main(argc,argv)
int argc;
char #argv[argc];
{
 FILE *ifp, *ofp;
 int i, j, argn, r1, c1, r2, c2, reverse, step, nstep, a, b;
 int rowx1, rowx2, nrows, ncols;
 long iline[2][MAXIM], pix, v00, v01, v10, v11;
 double rc, cc, dist, val, theta, dr, dc, scale, ssize;
 double sqrt(), sin(), cos(), acos();
 unsigned getpix();

 if (GETARG("help")) {
  fprintf(stderr,"usage: profile [-i iff] [-r n] [-c n] [-p r1 c1 r2 c2] [-s n] [-d f]\n*);
  fprintf(stderr,"-i iff = input image file\n*);
  fprintf(stderr,"-r n = number of rows in image [300]\n*);
  fprintf(stderr,"-c n = number of columns in image [200]\n*);
  fprintf(stderr,"-p r1 c1 = start point\n*);
  fprintf(stderr,"-s n = number of steps\n*);
  fprintf(stderr,"-d f = step size (float)\n*);
  exit(0);
}

 if (argc = GETARG("i")) ifp = fopen(argv[++argn],"r");
 else ifp = stdin;

 if (ifp == NULL) {
  fprintf(stderr,"profile: can't open input image\n*");
  exit(1);
}

 if (argc = GETARG("r")) nrows = atoi(argv[++argn]);
 else nrows = 300;
if (argn = GETARG("c")) ncols = atoi(argv[++argn]);
else ncols = 200;

if (argn = GETARG("p")) {
    r1 = atoi(argv[++argn]); c1 = atoi(argv[++argn]);
    r2 = atoi(argv[++argn]); c2 = atoi(argv[++argn]);
}
else {
    fprintf(stderr,"starting row and column: ");
    scanf("%d %d",&r1,&c1);
    fprintf(stderr," ending row and column: ");
    scanf("%d %d",&r2,&c2);
}

if (argn = GETARG("s")) nstep = atoi(argv[++argn]);
else if (argn = GETARG("d")) {
    sscanf(argv[++argn],"%lf",&ssize);
    dist = sqrt(sqr((double)(r2 - r1)) + sqr((double)(c2 - c1)));
    nstep = 0.5 + dist / ssize;
} else {
    fprintf(stderr,"number of steps: ");
    scanf("%d",&nstep);
}

/* sort the points so that r1 is less than r2 */
reverse = 0;
if (r1 > r2) {
    fprintf(stderr,"profile: can't scan from (%d %d) to (%d %d)\n",r1,c1,r2,c2);
    fprintf(stderr," profile will be (%d %d) to (%d %d)\n",r2,c2,r1,c1);
    reverse = 1;
    i = r1; r1 = r2; r2 = i;
    i = c1; c1 = c2; c2 = i;
}

/* move down to starting row */
for (i = 0; i < rl; i++)
    for (j = 0; j < ncols; j++) pix = getpix(ifp);

/* initialize */
rc = r1; cc = c1;
for (i = 0; i < ncols; i++) iline[i] = getpix(ifp);
for (i = 0; i < ncols; i++) iline2[i] = getpix(ifp);

/* calculate distance and angle between the two points */
dist = sqrt(sqr((double)(r2 - r1)) + sqr((double)(c2 - c1)));
theta = acos((double)(r2 - r1)/dist);

/* find delta_r and delta_c steps */
dr = cos(theta) * dist / (double)(nstep - 1);
dc = sin(theta) * dist / (double)(nstep - 1);
if (c1 > c2) dc *= -1.0;

/* first point (easy) */
ival = iline2[c1];
printf("%8.2f %8.2f %8.2f\n",rc,cc,ival);
rc += dr; cc += dc;

/* now step by delta_r and delta_c along the profile */
for (step = 1; step < nstep; step++) {
    /* decide if more rows must be read */
    while (rc > (double)rowx2) {
        rowx1++; rowx2++;
        a = !a; b = !b;
        for (i = 0; i < ncols; i++) iline2[i] = getpix(ifp);


```c

double interp(r, c, v00, v01, v10, v11)
double r, c;
long v00, v01, v10, v11;
{
    double a, b, v;
    a = (v10 - v00) * r + v00;
    b = (v11 - v01) * r + v01;
    v = (b - a) * c + a;
    return(v);
}

double sqr(x)
double x;
{
    return(x*x);
}

unsigned getpix(fp)
FILE *fp;
{
    /* reads 8 bits (1 pixel) from a file */
    return((unsigned)getc(fp));
}

getarg(desig, argc, argv)
int argc;
char *desig, argv[];
{
    int argn;
    char minus[2], lookfor[12];
    strcpy(minus, "-");
    strcpy(lookfor, minus);
    strcat(lookfor, desig);

    for (argn = 1; argn < argc; argn++)
    {
        if (!strcmp(argv[argn], lookfor)) return(argn);
    }

    return(0);
}
```
APPENDIX D
COMPOSITE TOTAL STORM RECESSION CURVE

DISCHARGE (m$^3$/s)

TIME (hours)
SEPT 4 - 8 1984 HYDROGRAPH

RECESSION ANALYSIS

LOG OF DISCHARGE (m³/s)

TIME (hours)
SEPT 4 – 8 1985 HYDROGRAPH

RECESSION ANALYSIS

LOG OF DISCHARGE (m³/s)

TIME (hours)
SEPT 16 – 19 1985 HYDROGRAPH

RECESSION ANALYSIS

LOG OF DISCHARGE (m^3/s)

TIME (hours)

Sept 16 7 13 19 1 7 13 19 1 7 13 19 1 7 13 19
OCTOBER 27 – 31 1984 HYDROGRAPH

RECESSION ANALYSIS

LOG OF DISCHARGE (m³/s)

TIME (hours)
SEPT 4 - 8 1985 HYDROGRAPH

DISCHARGE (m$^3$/s)

TIME (hours)
NOVEMBER 18-22 1984 HYDROGRAPH

DISCHARGE (m$^3$/s)

TIME (hours)
MARCH 28 - APRIL 5 1985 HYDROGRAPH
APRIL 10 - 21 1985 HYDROGRAPH

DISCHARGE (m³/s)

TIME (hours)
MAY 10 - 16 1985 HYDROGRAPH

TIME (hours)

DISCHARGE (m$^3$/s)
SEPT 4 – 8 1985 HYDROGRAPH ANALYSIS

HYETOGRAPH

0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

0
1
2
3
4
5
6
7
8
9
10
11
12
13
14

PREDICTION (mm)

0
1
2
3
4
5
6
7
8
9
10
11
12
13
14

TIME (hours)

WATERTABLE FLUCTUATIONS

DRAINED AND UNDRAINED FIELDS

-140
-130
-120
-110
-100
-90
-80
-70
-60
-50
-40
-30

GROUNDWATER LEVEL (cm)

0
1
2
3
4
5
6
7
8
9
10
11
12
13
14

TIME (hours)
OCTOBER 23 - 26 1984 HYDROGRAPH ANALYSIS

OCTOBER 23 - 26 1984 HYDROGRAPH

WATER TABLE FLUCTUATIONS
DRAINED AND UNDRAINED FIELDS
April 22 — 26 1985 HYDROGRAPH ANALYSIS

HYETOGRAPH

April 22 — 26 1985 HYDROGRAPH

WATERTABLE FLUCTUATIONS
DRAINED AND UNDRAINED FIELDS
MAY 4 - 7 1985 HYDROGRAPH ANALYSIS

HYETOGRAPH

MAY 4 - 7 1985 HYDROGRAPH

WATERTABLE FLUCTUATIONS
DRAINED AND UNDRAINED FIELDS
MAY 10 — 16 1985 HYDROGRAPH ANALYSIS

HYETOGRAPH

PRECESSION (mm)

TIME (hours)

WATERTABLE FLUCTUATIONS
DRAINED AND UNDRAINED FIELDS

GROUNDWATER LEVELS (cm)

TIME (hours)
JUNE 6 – 17 1985 HYDROGRAPH ANALYSIS

HYETOGRAPH

JUNE 6 – 17 1985 HYDROGRAPH

WATERTABLE FLUCTUATIONS
DRAINED AND UNDRAINED FIELDS