

Chapter 8

Remote Sensing Inputs for Flash Flood Forecasting in Urban Areas

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8.1 Introduction

Urban rainfall-runoff models were the first hydrologic simulation models that computed runoff separately for different land cover classes, namely pervious and impervious areas. The two contributions were added and routed together through sewers and surface drainage systems. This method of simulating storm runoff has been successfully applied to a larger number of land use classes, namely impervious, barren or low vegetation, intermediate height vegetation, forests, wetlands and water covered areas.

The problem encountered was the definition of parameter values, the most important being the effective saturated conductivity of the soil and the overland flow resistance. For urban areas, these values are well known for impervious areas. Thus only the values for the pervious areas needed to be optimised. However, for non urban areas, or for urban areas with

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a greater diversity of land cover classes, these parameters (and others) needed to be determined for each land cover class. This can only be accomplished on watersheds where there are at least as many streamflow gauges as there are land cover classes and where there is a diversity of the mix of classes.

Remotely sensed data offers in each gauged area the detailed real-time information on watershed conditions and rainfall amounts necessary to solve this problem. This information is of particular importance in flood forecasting because the hydrologic processes that most directly affect flash floods occur at the land surface and are greatly influenced by the terrain, or land cover characteristics of the watershed. Weather radar now provides detailed real-time rainfall data at frequent intervals. The timing and areal distribution of rainfall also directly affect the flood hydrographs. It thus appears that data management systems and hydrologic models designed to make maximum use of this remotely sensed data would offer improved flash flood forecasting.

This paper describes the application of the WATFLOOD data management system and the SIMPLE rainfall-runoff model to a heavily urbanised watershed that exceeds a size that can be readily modelled by a conventional urban runoff model. The problems associated with parameter optimisation and the estimation of rainfall distributions is discussed.

8.2 Watflood Data Management System

WATFLOOD is an integrated set of computer programs to forecast flood flows for watersheds having response times ranging from one hour to several weeks. A shell program organises all the menus used for data input and correction functions and acts as the manager for the hydrologic model SIMPLE and utility programs. The emphasis of the WATFLOOD system is on making optimal use of remotely sensed data. Radar rainfall data, LANDSAT or SPOT land cover data can thus be directly incorporated in the hydrologic modelling.

WATFLOOD is unique in its ability to preserve the distributed nature of a watershed's hydrologic and meteorologic characteristics without sacrificing computational efficiency. This has been accomplished through the use of **Grouped Response Units** (GRU's), in which process parameters are tied to land cover and land cover mixes vary from basin element to basin element.

The system is completely modular but has a consistent data structure throughout. It has been under continuous development since 1972. Several MSc and PhD research programmes have provided the rationale incorporated in the software.

8.2.1 WATFLOOD components

The WATFLOOD system consists of a user interface program that presents a set of menus that allow the user to carry out a number of tasks that are required to produce a flood forecast. Separate computer programs create basin files, convert radar Constant Altitude Precipitation Index maps (CAPPI's) to rainfall maps, calibrate radar weather data with ground level rain gage data in a real-time environment, perform a simulation of the hydrology of a watershed, and plot flow forecast at various scales. While the WATFLOOD system has been designed to optimally use remotely sensed data, conventional data can just as readily be used to set up and operate the system.

The system's most important component is a hydrologic simulation model that is self-calibrating in terms of watershed parameters and initial conditions. Since 1972, SIMPLE has served as a numerical laboratory to experiment with various rainfall-runoff modelling techniques and data utilisation. The model and data management system are unique in the following ways:

1. It is a geo-referenced system that was designed from the outset to incorporate remotely sensed data such as weather radar, LANDSAT or SPOT land cover data, GOES snow

cover data, or any other hydrologically significant remotely sensed data such as soil moisture or percent of snow covered area.

2. The model was used to develop the "Grouped Response Unit" (GRU) approach to hydrologic modelling. This is a method of weighting the watershed response to land cover distribution instead of the usual parameter weighting schemes. The GRU method allows the transfer of parameters to other watersheds without concern about the relative amounts of the various land cover types. The grouped response unit is an extension of urban storm water modelling where the contributions from pervious and impervious areas are calculated separately and added prior to sewer and streamflow routing.
3. The model has been calibrated and validated in time on one watershed and validated in time and space on several others. This is not often possible with other models, which have weighted parameters instead of weighted responses. SIMPLE incorporates a pattern search optimisation algorithm. The pattern search is said not to be affected by the inter-dependency of a model's parameters.
4. The flood forecasting system is completely self-contained with respect to data input and can be run on a laptop computer, thus making it a stand alone system that can continue during power failures or data interruptions. The entire system is menu-driven with all the complicated activities hidden from the final user, who may not have detailed knowledge of hydrologic modelling, remotely sensed data or computing systems.
5. The flood forecasting system is designed to operate automatically, using real-time weather radar precipitation data as well as conventional rainfall and streamflow data. It can be run as a background task on a computer to activate an alert if a potential for flooding occurs. In addition, it can give

specific, detailed local forecasts for the purpose of evacuation, road closures, emergency vehicle routing and the like.

8.3 Hydrologic Model

SIMPLE is a physically based simulation model of the hydrologic budget of a watershed programmed in FORTRAN 77. Because the model is aimed at flood forecasting, only those processes which dominate flood flows are included. These processes are: interception, infiltration, interflow, baseflow, overland and channel routing. The model is limited to these only because to introduce others serves only to introduce more degrees of freedom, which would make calibration more difficult. At the same time, the exclusion of other processes (such as evaporation, direct interaction of the river with the groundwater reservoir) will necessarily limit the use of the model to those areas where these additional factors are not of concern.

Furthermore, the model has been kept simple to allow its use on micro-computers within a time frame suitable for forecasting. Typically, the program executes in 4 - 6 seconds for a 120 hour simulation on a 486/33 computer. The size of the watershed does not affect running time, since the size of the grid is scaled to provide just enough resolution for the drainage pattern. Normally about 30 to 60 elements will suffice. On the IBM-AT or compatible computer a maximum of approximately 200 elements can be accommodated.

This following sections describe the watershed model in detail. The values of many parameters need to be determined and while some may be assigned standard well known values, others may be subject to great variations and uncertainty. Where possible, standard values are used, but those parameters which cannot be predicted are calibrated using a pattern search optimization technique. In the following sections, those parameters which are optimized are identified.

The modelling process begins with the addition of rainfall to the watershed. The various processes are described below.

8.3.1 Interception

Interception of precipitation by vegetation is calculated in SIMPLE using the equation given by Linsley et al. (1949)

$$V = (S_i + C_p E_a t_R)(1 - e^{-kP}) \quad (8.1)$$

where:

- V is depth of interception from the beginning of the storm,
- S_i is storage capacity per unit of projected area,
- C_p is ratio of vegetal surface area to its projected area,
- E_a is evaporation rate per unit per unit of surface area,
- t_R is the duration of the rainfall,
- k is a constant,
- P is the precipitation since the beginning of the storm.

In SIMPLE, C_p is assumed to be 100 and E_a at 0.00025 mm/hr. The values for S_i are set for each month and each land cover class and t_R is taken as the time from the beginning of rainfall. The product of C_p and E_a is used as a single parameter A7.

8.3.2 Surface Storage

The ASCE Manual of Engineering Practice No. 37 for the design of sanitary and storm sewers (ASCE, 1969) gives typical values of retention for various surface types. Table 8.1 is a listing of depression storage for various conditions and values are seen to vary greatly. Because of the uncertainty associated with depression storage, this is one of the parameters included for optimization, but it is ranked 5th out of 5 in priority.

As with interception, it is assumed that the limiting value of depression storage S_d is reached exponentially (Linsley et al., 1949):

$$D_s = S_d (1 - e^{-kP_e}) \quad (8.2)$$

where D_s is the depression storage, P_e is the accumulated rainfall excess and k is a constant.

Table 8.1. Surface retention values (ASCE, 1968).

Type of Surface:	Retention (mm) S_d
Impervious Urban Areas	1.25
Pervious Urban Areas	3.0
Smooth Cultivated land	1.3 - 3.0
Good pasture	5.0
Forest litter	8.0

8.3.3 Infiltration

Due to the importance of the infiltration process in runoff calculations, but also because infiltration capacity is such a highly variable quantity, this process requires a great deal of attention in any hydrologic model. Many formulae are used (see for instance Viessmann et al., 1977) and any choice is open to criticism.

In keeping with the underlying philosophy of keeping the model based on identifiable physical processes, the Philip formula (Philip, 1954) was chosen as representing the important physical aspects of infiltration process. It also readily incorporates the notion of surface detention. The Philip formula is identical to the Green-Ampt equation (Green & Ampt, 1911) except that it includes the head due to surface ponding as well as the capillary

potential. The Green-Ampt approach assumes the ponding head is insignificant when compared to the potential head. The Philip formula (Philip, 1954) expresses the rate of infiltration as:

$$\frac{dF}{dt} = k \left(1 + \frac{(m - m_o)(P + H)}{F} \right) \quad (8.3)$$

where:

- F is the total depth of infiltrated water in mm, t is time in seconds,
- k is permeability in mm/sec,
- m is the average moisture content of the soil to the depth of the wetting front,
- m_o is initial soil moisture content,
- P is the capillary potential at the wetting front in mm,
- H is detention storage.

Equation 8.3 represents the physical process of infiltration since the pressure gradient acting on the infiltrating water is used to determine the flow using Darcy's Law. Because of the uncertainty of the effective value of k over the basin, it is an optimized parameter.

Initially, the infiltration capacity is very high because of the shallow depth of the wetting front. This causes a very large pressure gradient inducing high infiltration. However, as the wetting front descends, the pressure gradient is quickly reduced, thus reducing the potential infiltration rate. Using the information in Philip (1954) relating permeability to capillary potential, the following relationship provides the capillary potential:

$$CP = 250 \log(k) + 100 \quad (8.4)$$

where:

CP is the capillary potential in mm and
 k is the permeability in nmvs.

Water depth on the soil surface is continually modified to reflect the net precipitation input, infiltration, and overland flow discharge.

8.3.4 Interflow

Infiltrated water initially is what is commonly referred to as the Upper Zone Storage (UZS). Water within this layer percolates downward or is exfiltrated to nearby water courses and called interflow. In the model, percolation downward is ignored because in most cases when dealing with single rainfall events, the path from the UZS to the stream via the groundwater reservoir is too long in duration to contribute appreciably to streamflow during the event. Of course exceptions do occur and must be recognized.

Interflow is represented by a simple storage-discharge relation:

$$QINT = REC * WAC \quad (8.5)$$

where:

QINT is interflow in m³/sec,
 REC is a coefficient (optimized),
 WAC is water accumulation in the UZS region.

REC is a coefficient which cannot be predicted and is therefore determined through optimization.

8.3.5 Overland flow

When the infiltration capacity is exceeded by the water supply,

and the depression storage has been satisfied, water is discharged to the channel drainage system. The relationship employed is based on the Manning formula and takes the form:

$$QI = (D1 - Ds)^{1.67} SI A/R3 \quad (8.6)$$

where:

QI is the channel inflow from each land cover class to the element's major drainage system,

D1 is average depth of water stored on the element,

Ds is depression storage capacity (optimized),

SI is average overland slope, determined by entering the number of contours within a basin element and the contour interval,

A is the area of the basin element,

R3 is a roughness parameter (optimized).

In SIMPLE, Eqs. 8.1 through 8.66 are used separately for each land class in each computational element.

8.3.6 Base flow

The base flow in SIMPLE is determined from a measured hydrograph at the basin outlet. The baseflow contributed by each basin sub-element is found by simply prorating it to the total basin area. A recession constant is used to gradually diminish the pre-rainfall flow over the duration of the event being modelled.

8.3.7 Total runoff

The total inflow to the river system is found by adding the surface runoff, the interflow and the baseflow for the land cover classes. These flows are then added to flows entering the channel from upstream and routed to the downstream basin element.

8.4 Routing Model

The routing of water through the channel system is accomplished using a storage routing technique. This is an adequate approach for upstream routing and is suitable because it is based on river cross-section and profile data. The method involves a straightforward application of the continuity equation

$$\frac{I_1 + I_2}{2} - \frac{O_1 + O_2}{2} = \frac{S_2 - S_1}{\Delta t} \quad (8.7)$$

where:

$I_{1,2}$ is inflow to the reach consisting of overland flow, interflow, baseflow, and channel flow from all contributing upstream basin elements,

$O_{1,2}$ is the outflow from the reach,

$S_{1,2}$ is storage in the reach,

Δt is the time step of the routing.

The subscripts 1 and 2 indicate the quantities at the beginning and the end of the time step. The flow is related to the storage through the Manning formula:

$$O = (1/R2)(AX)^{1.33} S_o^{1/2} \quad (8.8)$$

where:

O is flow in m³/s,

$R2$ is the channel roughness parameter (optimized),

AX is channel cross-section area which is related to storage by dividing the storage by the channel length,

S_o is channel slope.

A change in this relationship occurs when the flow exceeds the channel capacity and the flow spills into the flood plain. One

requirement for running SIMPLE is a relationship which gives the channel capacity at any point in the basin. This is accomplished by measuring the channel cross-section area at various points in the watershed and fitting a relationship such that the channel cross-section area is given as a function of drainage area. This relationship is used to determine if the flow exceeds the channel's capacity at any point at any time.

8.4.1 Data Requirements

The data required for the model can be put into three categories: watershed data, hydrologic parameters, and hydrometric data. The following watershed data is required for each element: the elevation of the streambed at the halfway point; element area; drainage direction to receiving element; surface slope as indicated by contour density; stream density; and percentage of land cover classes. The parameter list includes: depression storage; saturated conductivity; interflow storage-discharge coefficient; overland flow roughness coefficient; and river roughness coefficients. Finally, hourly rainfall amounts and measured hydrographs are required to calibrate the model.

8.4.2 Parameter Optimisation

The model features the Hooke and Jeeves (1961) automatic pattern search optimization algorithm taken from Monro (1971). The program can be run to automatically determine which combination of parameters best fit measured conditions. The optimised parameters are: saturated conductivity; the interflow storage-discharge coefficient; surface roughness; and stream roughness. In this study, the only parameter changed for Black Creek was the stream roughness. Obviously, this parameter is unique for each watershed.

8.5 Study Area

The WATFLOOD system was first calibrated on the Grand River watershed above Cambridge (Galt), Ontario, Canada. Three rainfall - runoff events were used to estimate the model's parameter values. Most parameters were based on accepted values but some, for instance, permeability, surface roughness, and an interflow depletion factor were optimized separately for each of four major land cover class. A fourth parameter was optimized for river roughness, using five regional values to allow for differences in river conveyance characteristics in various parts of the watershed. In total, seventeen parameters were determined using the Hooke and Jeeves (1961) pattern search algorithm.

Since the advent of micro computers, the application of optimisation to models such as SIMPLE has become affordable. During the past eight years, at least 500,000 iterations of the model have been conducted to arrive at an acceptable parameter set. Usually, the parameters have to be recalibrated when the model is changed. This often results in 2000 to 5000 iterations. First, a sensitivity analysis of the model parameters is carried out. The objectives of this part of the exercise is to find the valid range of the parameters. All processes have to contribute properly to the total runoff. Limits are set on the parameters and the automatic pattern search routine is applied to the model. When the error cannot be further reduced, a check is made to ensure that the relative value of the parameters is approximately correct. For instance, the saturated conductivity should be larger for forested land than for pasture or lawns. If discrepancies occur, new values with the proper relationships are assigned as starting values and the optimisation repeated. This process continues until the best fit is obtained for a number of events and the parameter values are physically correct, although not always directly comparable to laboratory values for say permeability or channel roughness. These discrepancies are caused by for instance, pooling of surface runoff, flow concentrations and other effects.

The model was then validated on eight more events on the

Grand River as well as other events on the Saugeen River, the Rouge River, Duffins Creek, Lynde Creek, Oshawa Creek and the Humber River. The results of these calibration studies have been reported elsewhere (Kouwen et al, 1992; Kouwen et al., 1990). These watersheds are primarily rural watersheds and when SIMPLE was being written, its application to urban watersheds was not contemplated, although a provision was made at the beginning to include impervious areas as a separate land cover class. The model was developed for the Grand River basin and the urban area being a relatively small fraction, was not considered in detail. It was treated differently from the pervious areas by setting interception, depression storage and infiltration equal to zero and the surface roughness was set to 0.1 times the surface roughness for lightly vegetated areas.

When the model was applied to the Humber River basin in the Western part of Metropolitan Toronto, it became apparent that the model performed poorly for most of the Humber River basin but very well in the totally urbanized Black Creek subwatershed. This led to a more detailed investigation of the model's performance on the Black Creek watershed.

Figure 8.1 is a map of the Humber River watershed with the Black Creek sub-watershed shown on its East side. Also shown are the streamflow and rainfall gauge locations and the 4 km by 4 km UTM coordinate grid used to subdivide the watershed. The rainfall-runoff process is modelled separately for each watershed element. Black Creek has a drainage area of 58 km² and is modelled with six elements. Table 8.2 shows the characteristics of each of the six contributing elements as determined from a Landsat MSS composite image taken on May 5, 1987.

The Landsat image was classified by using the reflectance in three bands. The pixel size was 79 m by 79 m and as a result, many pixels contain mixed land cover classes. This results in many pixels that cannot be classified as belonging to a specific land use class or it can result in pixels being wrongly classified. While the percentages listed in Table 8.2 seem reasonable, there is room for improvement, especially if remote sensing imagery with a greater resolution is used.

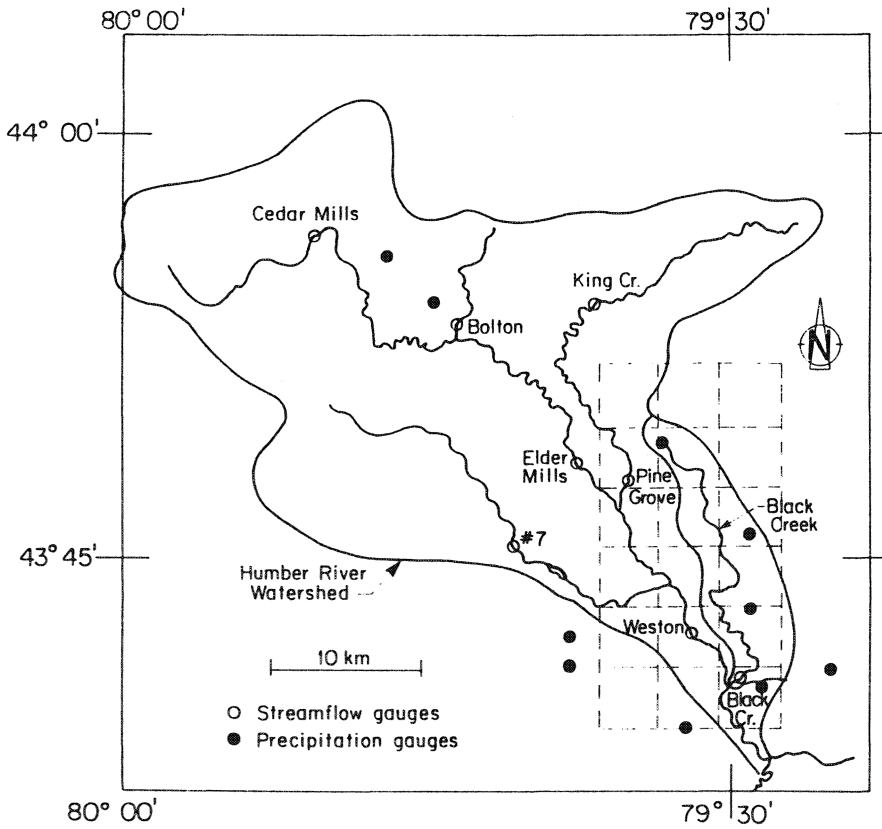


Figure 8.1: Map of the Humber River watershed.

In spite of these difficulties, the application of SIMPLE to the Humber River watershed resulted in much better agreement between the measured and computed hydrographs for Black Creek gauge than for the other locations. Most of the error is probably due to the poor distribution of the raingage locations. However, as shown on Figure 8.1, the Black Creek watershed has very good raingage coverage. In fact, there is almost one gauge in each computational element, which is about ideal for the purpose at hand.

Table 8.2: Basin land cover classifications.

Element		Percent land cover					
No.	Area	Imp.	Grass	Forest	Brush	Wetl.	Water
48	3	32	05	05	56	01	01
56	15	46	08	01	43	00	01
59	2	51	13	01	34	00	00
63	16	55	07	01	36	02	00
65	19	34	02	01	60	06	00
74	16	29	01	02	61	06	00

Figure 8.2 is an example of the output produced by SIMPLE. The figure shows the measured and computed hydrograph for eight locations on the Humber River and its tributaries. The eight one is for Black Creek. The heavier line followed by the dots is the measured hydrograph while the thin line is the computed hydrograph. The vertical line denotes the end of the rainfall and the time at which a flow forecast might be made.

8.6 Modelling results

The computed hydrographs in the upper, rural parts of the

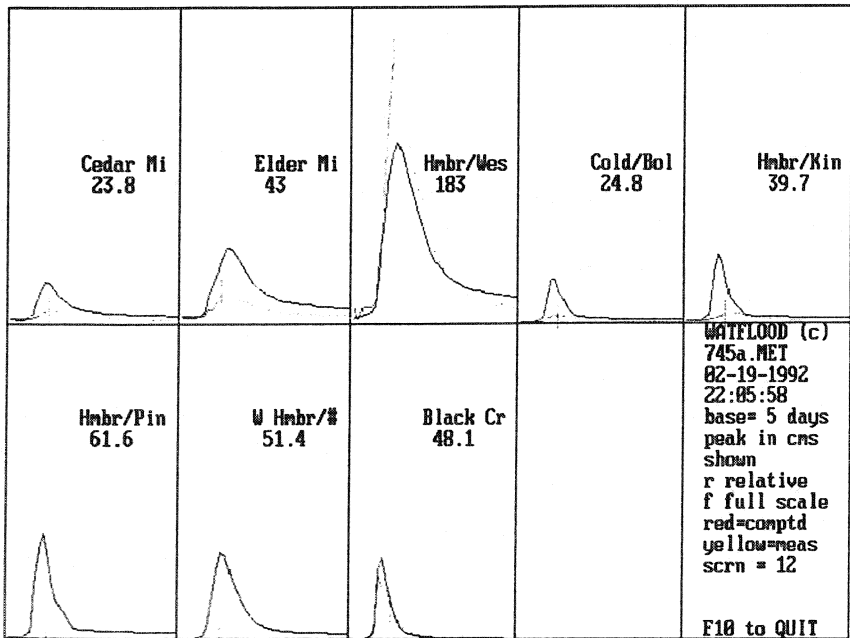


Figure 8.2: Humber River hydrographs.

watershed are all too high while the two hydrographs in the lower Humber show much better agreement, the hydrograph for Black Creek being the better of the two. Figure 8.3 is an enlargement of the Black Creek hydrograph for the May 1974 event. The computed hydrograph shape is in close agreement with the measured hydrograph.

Considering that the model was developed for rural watersheds and calibrated on the Grand River Watershed, this good result on an urban watershed was not expected. Many of the computed hydrographs on the other watersheds (Saugeen River, Eastern Metropolitan Toronto rivers, and the Grand River) are in good also in good agreement with the measured hydrographs. The most probable cause for the poor results on the Humber River is the very poor distribution of the raingages

(Figure 8.1).

The inability to obtain a better fit between the computed and measured hydrographs for the upper reaches of the Humber River points to the obvious need for a denser raingage network if rainfall events that exhibit areal non-uniformity are to be properly modelled. From the foregoing results, it might be concluded that one gauge for each computational elements yields satisfactory results. Obviously, this is not a practical solution for larger watersheds. For Black Creek, there happens to be one raingage for each element.

The good modelling results can be attributed in part to having a dense raingage network. However, the model also appears to be represent the urban rainfall-runoff-routing process very well. This is an important finding because it shows that urban runoff modelling does not have to be carried out at as detailed a scale as might previously have been thought.

While specialised equipment is required to process Landsat imagery, the effort involved in processing the data and setting up the necessary data files for SIMPLE is minimal for an experienced operator. Also, the remaining watershed data required to run SIMPLE can be obtained from a 1:50,000 scale topographic map. In fact, all the data requirements can be

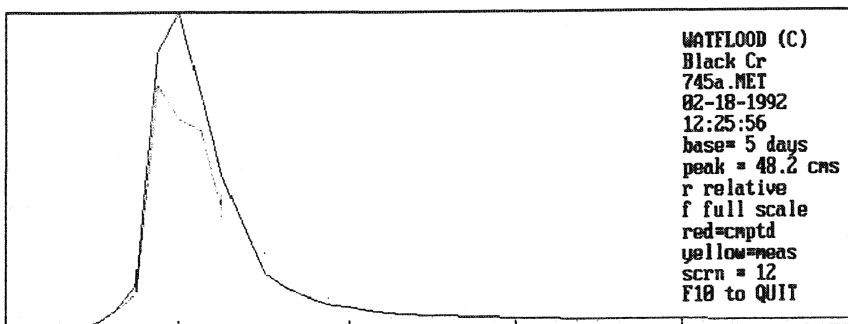


Figure 8.3: Black Creek - May 1974.

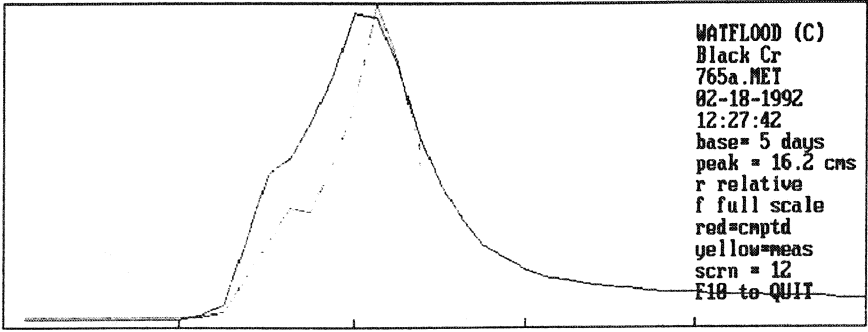


Figure 8.4: May 1976 hydrograph.

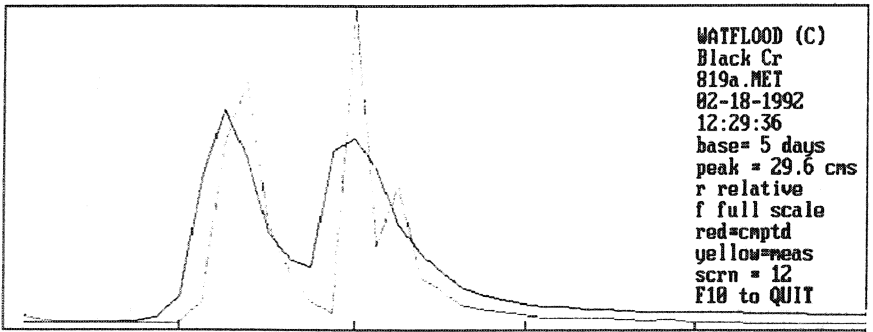


Figure 8.5: September 1981 hydrograph.

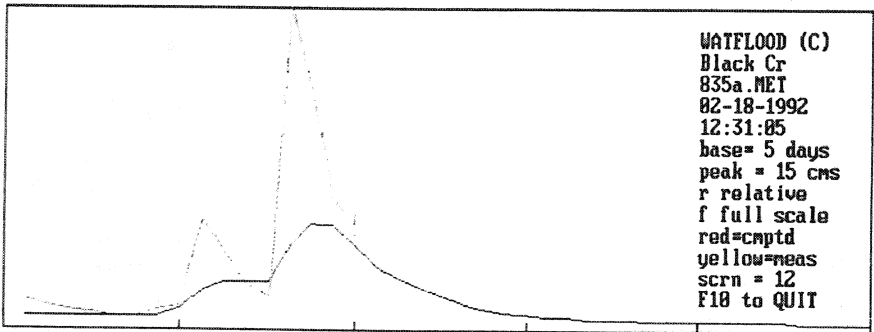


Figure 8.6: May 1983 hydrograph.

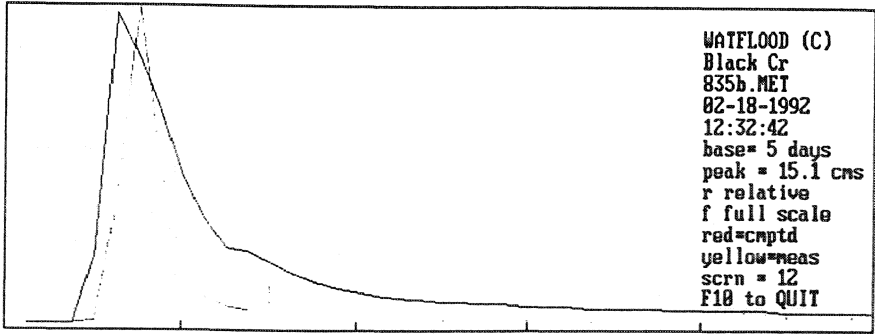


Figure 8.7: May 1983 hydrograph.

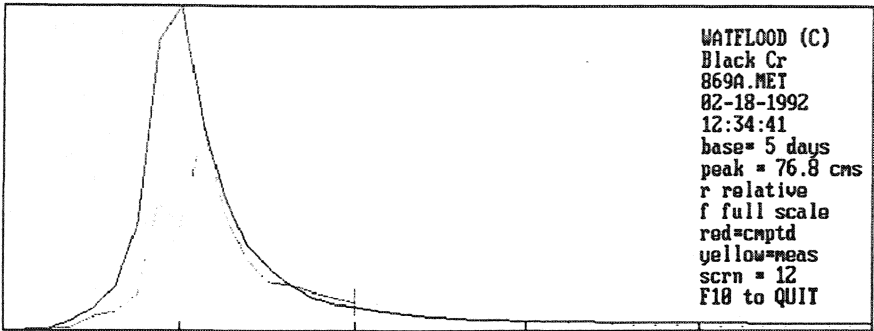


Figure 8.8: September 1986 hydrograph.

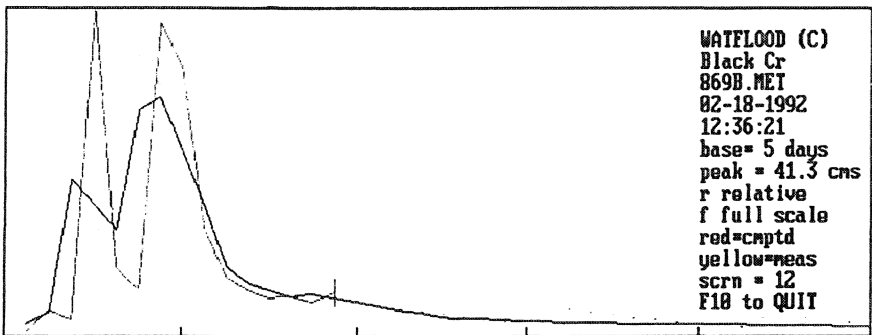


Figure 8.9: September 1986 hydrograph.

obtained from conventional sources but would involve more effort. The only data that requires a visit to the watershed is a table of channel cross-sectional area versus drainage area. In summary, the data that was used to obtain the hydrographs shown in Figures 8.3 through 8.8, would not normally be considered as "detailed data". It is certainly less detailed than the normal data requirements for urban runoff models. It is not intended that SIMPLE be used as a design tool for storm water management facilities. It is intended as an operational model, that is for flood forecasting or reservoir operation. For this purpose, it appears that remotely sensed land cover data adequately delineates the land cover characteristics, and hence the hydrologic characteristics of an urban watershed.

Radar is sometimes quoted as being the ideal rainfall measuring device but many problems with weather radar remain (Wilson, 1976; Browning and Collier, 1989). Still, it is generally agreed that radar improves rainfall estimates when rainfall gauges are spaced at a lower densities than approximately one gauge per 300 to 400 km². Similarly, radar rainfall measurements adjusted with raingage measured rainfall amounts improved flow forecasts when the raingage density was lower than the same range (Cooper, 1988). Based on these figures, it would appear that in general, the flow estimates on the Humber River and its tributaries could be improved with the use of radar rainfall data. However, the raingage density for the Black Creek watershed is approximately one gauge per 15 km. As a result, radar rainfall data is unlikely to improve flow forecasts on Black Creek.

8.7 Summary and Conclusions

The Grouped Response Unit is a familiar concept to urban runoff modellers. The runoff contributions from different land cover or land use classes are computed separately and then added prior to streamflow routing. Instead of using just two land cover classes, pervious and impervious, SIMPLE allows runoff contributions to be calculated for up to six different classes: impervious, barren

ground or light vegetation, forests, crops and low vegetation, wetlands, and water covered areas. The model was designed for rural applications but its application to the Humber River watershed near Metropolitan Toronto revealed it simulated the hydrology for a heavily urbanised watershed very well. Computed hydrographs are compared to measured hydrographs for seven events.

The modelling results shown in Figures 8.3 through 8.8 show that a fairly coarse representation of an urban watershed can still yield good flow predictions provided that the proper percentages of land cover and good rainfall estimates are incorporated in the simulation.

Finally, the use of GRU's is based on the assumption that model parameters are associated with land cover. Each class has its own set of parameters and these should be transferable from one watershed to another without further calibration. The permeability for impervious area is obviously zero, but, other than river roughness, all other parameters used in the simulation were those transferred from the Grand River watershed. These parameters were also successfully applied to the Saugeen and Eastern Metropolitan watersheds (Kouwen et al., 1990)

8.8 Acknowledgements

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