SPATIAL SCALE
AND HYDROLOGICAL MODEL RESPONSE

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by

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ABSTRACT

This thesis focuses on the effects of varying spatial scale on the numerical simulation of hydrological processes. Specifically, it examines the impact of changing the number and sizes of sub-basins on the performance of the SLURP hydrological model. Automated watershed segmentation and parameterization was essential for this scaling analysis. The TOPAZ digital landscape analysis model was used to process a raster digital elevation model (DEM) to derive a wide range of topographic and topologic variables that are physically meaningful to watershed runoff processes. TOPAZ automatically subdivides a main watershed into a variable number of sub-basin units at specified levels of detail or scale. The SLURPAZ interface was used to manipulate relevant output data from TOPAZ along with land cover, routing and climate station data to provide all the necessary inputs for the SLURP hydrological model. Results of an application using these techniques is presented for a northern alpine basin (i.e. Wolf Creek, Yukon, Canada).

A comparative analysis is presented from an earlier hydrological simulation, for which the physiographic parameters were derived manually using a geographical information system (GIS), with a hydrological simulation of the same scale, where the physiographic parameters were derived automatically using the digital landscape analysis model, TOPAZ, and the SLURPAZ interface. Generally, simulations from the hydrological model, SLURP, are very similar when comparing the automated and manual runs. The major benefits of using the automated segmentation parameterization techniques versus the manual ones are the cost and time factors, and that the automated methods offer rapid parameterization at several scales or levels of detail.

Several model runs, varying in scale from 1 to approximately 1600 sub-basins, are discussed. Varying sub-basin scale showed interesting trends at two levels of detail. First, as the number of Aggregated Simulation Areas (ASAs) increases, it is necessary to
have a sufficient number of ASAs to allow variations in water balance components to be adequately represented. Secondly, results suggest that with an increasing number of sub-basins, accuracy of the hydrological model outputs tend to increase up to a certain threshold. Thereafter, any further subdivision does not enhance model performance significantly. Another comparison ensued where a short channel versus a long channel, both for the whole basin as one ASA, in order to evaluate SLURP’s ‘within-ASA’ routing sensitivity. Additionally, the ‘between-ASA’ storage routing method was evaluated by assessing the sensitivity of the Alpha and Beta routing parameters. Optimal scales found in previous research from varying the size and number of sub-basins are also compared to those found in this research.

Automated parameterization allows for scaling studies to take place in a more rapid and cost effective manner. SLURPAZ acts as a useful link between the SLURP hydrological model and the TOPAZ digital landscape analysis model. Such tools offer the benefits of speed, precision and reproducibility in drainage basin analyses.
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LIST OF ACRONYMS

AGNPS ........ AGricultural Non-Point Source pollution model (p.3)
ASCII .......... American Standard Code for Information Interchange (p.41)
ASA ............. Aggregated Simulation Area (p.31)
CSA ............. Critical Source Area (p.40)
CSS ............. Continuous Streamflow Simulation (p.17)
DEDNM ........ Digital Elevation Drainage Network Model (p.39)
DEM ............. Digital Elevation Model (p.21)
DIAND .......... Department of Indian Affairs and Northern Development (p.50)
EBSS ............. Event Based Streamflow Simulation (p.16)
EMAN............ Ecological Monitoring and Assessment Network (p.44)
GCM ............. Global Circulation Model (p.18)
GEWEX ........ Global Energy and Water Cycle Experiment (p.44)
GIS .............. Geographical Information System (p.1)
INAC ............. Indian and Northern Affairs Canada (p.44)
IWMI............ International Water Management Institute (p.106)
MSCL ............ Minimum Source Channel Length (p.40)
NAD27.......... North American Datum 1927 (p.45)
NAD83 ......... North American Datum 1983 (p.61)
NHRI ............ National Hydrology Research Institute (p.105)
NHRC .......... National Hydrology Research Centre (p.44)
RASBIN........ RASter to BINary network (p.41)
RASFOR ...... RASter FORmatting (p.41)
RASPRO ...... RAster PROperties (P.41)
REA ............. Representative Elementary Area (p.30)
SCE-UA ....... Shuffled Complex Evolution, University of Arizona (p.37)
SLURP......... Simple LUmped Reservoir Parametric (old name, p.31)
SLURPAZ .... Interface between SLURP and TOPAZ (p.2)
TOPAZ ....... TOpographic ParameteriZation (p.38)
TM .............. Thematic Mapper (p.54)
USDA ............ United States Department of Agriculture (p.103)
UTM ............. Universal Transverse Mercator (p.45)
CHAPTER 1
INTRODUCTION

1.1 Statement of Problem

The primary purpose of this study is to integrate automated digital landscape analysis and hydrological modelling in order to evaluate scaling effects. In other words, a digital terrain analysis model will be linked with a hydrological model to study the impact of varying the number and size of sub-basins on a hydrological model.

The idea of an interface between two such models is based on the notion that a digital terrain analysis model could provide the physiographic parameters needed for the hydrological model more quickly and more accurately than manual methods. This would enable a user to produce a prompt and accurate analysis of a particular drainage basin. In the past, physiographic parameters (e.g. sub-basin areas, mean latitudes, mean elevations, etc.) were derived manually or from laborious geographical information system (GIS) manipulations. These manipulations were both costly and time consuming and, in practice, they allowed for only one representation (i.e. at only one scale) of the main drainage area being studied due to budgetary and time constraints. Therefore, an interface between a digital terrain analysis model and a hydrological model would be beneficial in that it would allow for prompt and accurate analysis at several sub-basin scales allowing to determine the optimal sub-basin resolution for the most fitting hydrological simulation.
1.2 Objectives

The objectives of this study are both applied and theoretical in nature. First, the applied objective is the development and use of an interface, SLURPAZ (Lacroix and Martz, 1997; [1]), between an automated digital landscape analysis tool, TOPAZ (Garbrecht and Martz, 1997a; [2]) and a hydrological model, SLURP (Kite, 1997). Secondly, the theoretical, or scientific objective of the study, is to evaluate sub-basin scale effects on the accuracy of hydrological modelling. This will result in an assessment of the automated segmentation versus the manual; and in evaluating a range of scales or segmentation in order to determine optimal hydrological model performance.

The objectives will allow comparison between SLURP outputs using physiographic parameters derived from TOPAZ against those derived manually using a GIS. Also, due to the ease of generating various segmentation using the TOPAZ model, this will assist in determining the optimal level of segmentation required in a basin for the SLURP hydrological model to perform adequately. This modelling and analysis using various numbers of sub-basins will provide information on the effects of scaling on the accuracy of hydrological modelling and will add to the existing knowledge of scaling effects of input data (Kite, 1995). Thus, it will enable the user to further compare and contrast the model outputs and their level of accuracy. The results of this research will hopefully improve the level of accuracy associated with this hydrological model by clarifying the degree to which a basin must be sub-divided before the significant hydrological processes can be modelled with acceptable accuracy.

1.3 Scope of Research

This research involves the development of a computer interface (i.e. SLURPAZ) that links both SLURP and TOPAZ. SLURPAZ processes physiographic outputs from TOPAZ along with land cover data into usable inputs for SLURP. Adjusting parameter
inputs to TOPAZ that control the topology, subcatchment and network properties, will allow for the parameterization at various scales or levels of detail. This research parallels similar studies by other scientists who have developed an interface between TOPAZ and the AGricultural Non-Point Source pollution model (AGNPS) model (Bingner et al., 1997) and are developing an interface with the WATFLOOD hydrological model (Seglenieks et al., 1998).

The use of TOPAZ and the SLURPAZ interface to provide physiographic parameters for the SLURP hydrological model has the attraction of reducing the cost and time required for parameterization of a drainage basin. SLURPAZ forges the flexible sub-basin definition capabilities of TOPAZ available to parameterize SLURP in order to simulate the response of a drainage area. This operational method for the automated physiographic parameterization of the SLURP hydrological model will facilitate the examination of the spatial scale or level of detail with which sub-basins must be represented for significant hydrological processes to be adequately simulated.
CHAPTER 2
LITERATURE REVIEW

2.1 General Background

Physiographic parameters (e.g. sub-basin areas, overland flow distances, surface gradients, mean elevations) for hydrologic models are usually derived manually or using geographical information system (GIS) techniques. These techniques for deriving physiographic parameters in watershed analyses, including those based on GIS, can be tedious, costly, and time consuming. These methods are often constrained by the availability of relevant landscape data and the fact that a number of hydrologically-significant physiographic variables are not readily derived using general purpose GIS tools. Also, watersheds are normally sub-divided into a fixed number of sub-basin units according to an a priori scheme imposed by the hydrologist. In most cases, budgetary and time constraints limit these methods of deriving parameters at only one level of detail or scale (i.e. at only one set of sub-basins) and limit interpretation and modelling to only one scale.

The study of spatial scale effects requires the ability to parameterize watersheds over a range of scales. This can only be done rapidly and systematically using automated methods. The automated physiographic parameter extraction techniques discussed in this thesis are able to derive necessary information rapidly and accurately, and allow varying levels of detail to easily be generated.
The remainder of this chapter will examine the following topics: hydrological modelling, structure of hydrological models, historical development of hydrological models, future development in hydrological modelling, scaling in hydrological modelling, the SLURP hydrological model and digital terrain analysis modelling (i.e. TOPAZ).

2.2 Hydrological Modelling

Models are the purposeful simplification of reality (Hammond, 1989: 288) and the formal presentation of a theory (Harvey, 1967). Models imply some kind of explanation, prediction, or prescription (Hammond, 1989: 288). They have long been implemented in the field of hydrology. For example, the 'rational method' (Q=CIA; where C is the runoff coefficient, I the rainfall intensity and A the watershed area) was one of the earliest approaches expressing flood magnitudes in terms of rainfall, catchment area and runoff characteristics (Mulvaney, 1851); and the concept of the ‘unit hydrograph’ (Sherman, 1932) is still widely used to this day (Fleming, 1979; Anderson and Burt, 1985). The main aim of these models is to conceptualize the 'real-life' hydrological cycle, or some of its components.

This ‘real life’ representation is most often obtained via the use of mathematical models (Figure 2.1). With the advent of computer technology and the advancement of mathematical models, the realm of hydrological modelling has expanded. Such mathematical models have been defined as:

i) A mathematical model is a simplified representation of a complex system in which the behavior of the system is represented by a set of equations, perhaps together with logical statements, expressing relations between variables and parameters (Clarke, 1973).
ii) A mathematical model may be defined as a numerical system inter-relating in a given time reference a sample of input, cause or stimulus of matter, energy or information and a sample of output, effect or response of information, energy or matter (Fleming, 1975).

Although a model is a representation of reality, it is just that - a representation. It can never be a full and complete description of the real world (Blackie and Eeles, 1985: 311). The use of mathematical models in hydrology is, in essence, a reasonably accurate simulation of what is, in reality, the response of a drainage area to certain inputs. One must bear in mind that the inherently complex nature of watersheds and the incomplete knowledge we have of such areas is difficult to replicate in a complete and accurate fashion. Therefore, the best we have is a generalization of processes, built from theory, which can be used to represent a system as accurately as possible (Blackie and Eeles, 1985: 311).

![Figure 2.1: The mathematical model concept. Source: Fleming, 1979:2.](image)
It has to allow for the refinement of the simulation (i.e. the model), until it resembles the real life system within the constraints of time, processing capabilities, current knowledge and the modeller's own competence (Blackie and Eeles, 1985: 312). The rational behind these types of simulations was well described by Rosenblueth and Wiener (1945):

No substantial part of the universe is so simple that it can be grasped and controlled without abstraction. Abstraction consists in replacing the parts of the universe under consideration by a model of similar but simpler structure. Models, formal or intellectual on the one hand, of material on the other, are thus a central necessity of scientific procedure.

Traditionally, model development has followed a set pattern (Mackay and Riley, 1991; O'Connell, 1991) that include the following steps:

(1) collection and analysis of data;
(2) development of a conceptual model that describes the important hydrological characteristics of a catchment;
(3) converting the conceptual model into a mathematical model;
(4) adjusting various coefficients and parameters via 'calibration' of the model to fit to a part of the historical data; and
(5) ‘validating’ the model against the remaining historical data set (Blöschl and Sivapalan, 1995: 251-252).

The objective of the next section (Section 2.3) will be to describe the structure of hydrological models. The literature on this topic is exhaustive, embracing a variety of disciplines. Additionally, terms are used interchangeably due to the many different academic classifications of mathematical models (Fleming, 1979: 2). Thus, the following sections attempt to organize the literature in a meaningful way.
2.3 Structure of Hydrological Models

2.3.1 General Overview of Model Structures

This first section will briefly discuss the various structures of models and will be followed by sections in which each topic will be considered in more detail.

A main aspect of hydrological modelling is the attempt to explain the natural processes that change precipitation into runoff (Kite, 1994). Not only is hydrologic response modelled, but also some models incorporate components such as erosional response, sediment yields and water quality. Many models are in existence. They can be categorized as lumped conceptual models to distributed physically-based models (Kite, 1994). The categorization process involves the spatial components of the hydrological models, i.e. a lumped model is simple and grouped; while a distributed model tends to be more complex and includes greater spatial variability. Requirements for the latter type of models include parameters such as those derived from field measurements (e.g. temperature, precipitation, discharge). Models can also be further defined as stochastic to deterministic by their level of randomness or precision, and inclusion of processes (Figure 2.2). In other words, stochastic models will have 'probable outcomes' while deterministic models tend to be, in theory, more 'precise' in nature.

Several models will often fall somewhere in the middle using varying levels of spatial complexity, i.e. being 'semi-distributed'; and using a varying number of parameters and thus increasing their level of precision, i.e. referred to as parametric or mixed. Bear in mind that there is much overlap between spatial structures and processes (i.e. categories), and that any one form of model can easily encompass one or more categories (Figure 2.2). The model complexity will vary according to the requirements of the user and the availability of data (Kite and Pietroniro, 1996: 564).
In recent years, the use of remotely sensed data and geographical information systems (GIS) has increased dramatically due to the increasing complexity of hydrological models in attempting to describe more processes within larger watersheds (Kite, 1994). A differentiation between conceptual and functional (or operational) is also necessary. Most models are conceptual in nature (i.e. in this case an idea or abstract notion of hydrological processes is modelled), but the level of functionality will vary from one model to the next depending on whether they were designed for site specific applications or for more general applications.

The universality of a model is also important. Where some models are easily applicable or adaptable to a variety of watersheds, models tend to be site specific (i.e. simplifications and assumptions are made with respect to a specific site) (Renard et al., 1982: 507). As Wood and O'Connell (1985: 556) exemplify:

...it is important to stress that there is no ‘best’ model for hydrological forecasting. Different types of models are required to fulfill different roles and objectives.

Usually the more spatially complex the model (i.e. distributed), the more precise or deterministic the model becomes; but at times, one might obtain precise results using a lumped model avoiding the impractical, complex and time-consuming calculations required with physically-based distributed models. Therefore, semi-distributed models are most often the models of choice, producing good results and avoiding the complex operations and massive data requirements of fully distributed models (Kite et al., 1996: 239).

Models not only vary in the three space dimensions, but they often include time variations. Although models encompassing the dimension of time are most often distinguished as daily, monthly, yearly or smaller time frames depending on the intended use of the model; most often models are formulated for event-based streamflow
simulations (EBSS) or continuous streamflow simulations (CSS) (Singh, 1988; 1989; 1995).

Figure 2.2: A classification system for hydrological models (modified from Kite, 1994: 192).

Chow *et al.* (1988) categorize models based on whether they consider randomness, spatial and time variations. Thus, for a model to include all five sources of variations (three space dimensions, randomness and time) is a formidable task. Albeit, nowadays most models being *distributed* and hence more *deterministic* are achieving this chore.
But, in the past and for most practical instances, models tended to consider only one or two sources of variation (Chow et al., 1988: 12).

*Deterministic* models tend not to include randomness, i.e. a certain input will always produce the same output. On the other hand, *stochastic* models will have some partially random outputs. These model types have been differentiated by saying that a *deterministic* model makes ‘forecasts’, whereas a *stochastic* model makes ‘predictions’ (Chow et al., 1988). Dingman (1994: 361) distinguishes between these two terms as follows:

**Forecasts** are estimates of the streamflow response to an actual event that is occurring or is *forecast* to occur; for example, the peak flow rate that will result from the rain that is *forecast* to occur in the next 24 h on a given watershed. *Forecasts* are used to guide the operation of reservoir systems and to provide flood warnings to floodplain occupants.

and

**Predictions** are estimates of the magnitude of some feature of streamflow response (e.g. the peak flow) that is either (1) associated with a particular exceedence probability (i.e., is a quantile of the streamflow feature), or (2) produced by a hypothetical rainfall or snowmelt event with a particular exceedence frequency (i.e., by a quantile of the input event; e.g., the 10-yr, 1-h rainfall on a given watershed). *Predictions* are the basis for the design of civil engineering works and the formulation of land-use plans.

### 2.3.2 Lumped Models

For a watershed to be modelled ‘accurately’, it would necessitate that "all" the physical, biological and chemical processes and their interactions that control water movement be included in the model (Blackie and Eeles, 1985: 313). In a practical sense, absolute
knowledge is not attainable, thus a compromise or simplification is needed. It should be noted that a model may be developed to accurately simulate one particular aspect of catchment response while ignoring other aspects. Thus, a model needs to encompass only those aspects of a catchment which are relevant to its purpose. For example, to predict the timing of a hydrograph peak it is not necessary to include the biochemical processes taking place in the catchment.

The most common simplification that can be made in watershed modelling is via **lumping** or **spatial averaging** (Blackie and Eeles, 1985: 313; Fleming, 1979: 8-9). This method essentially groups together the individual processes as a single unit. In other words, it uses an average of each process for the entire basin to simulate streamflow (Kite, 1994: 191). The basin, its inputs and outputs, are thus represented mathematically using only the dimensions of depth and time (Blackie and Eeles, 1985: 313). Put another way, this type of model treats the whole watershed, or the majority of it, as being homogeneous as it is affected by all processes and subject to uniform rainfall (Linsley et al., 1986: 340). For example, soil moisture will vary over a whole basin depending on land cover, soil types, aspect, antecedent soil moisture content, amount of precipitation received and so on; but in a **lumped** model, only the average soil moisture over the entire basin is used (Fleming, 1979: 8-9). Therefore, this method does not account for any variations in precipitation, soil types, geology, topology and so forth within a system.

**Lumped** models are best applied to small watersheds having relatively homogeneous spatial characteristics, although their use has proven to be applicable to larger and more heterogeneous watersheds (Blackie and Eeles, 1985: 313). The important factors for the success of this type of model is: i) stability of the drainage system; and ii) stable distributions of precipitation, land cover and soil distributions (Blackie and Eeles, 1985: 313).
2.3.3 Distributed Models

Distributed models are physically-based models, that is, they are based on the physical characteristics or physics of the hydrological processes associated with streamflow within a drainage area (Beven, 1985: 405). This type of model takes into account values of each process included in the model for each grid point or cell value (e.g. 30m x 30m, or 20m x 20m grid cells). Using soil moisture as an example, each cell could have its own soil moisture value. Thus, the response of the whole system would be dependent upon the integration of each cell for the area concerned (i.e. whether it is a sub-area or the area of the whole basin) (Fleming, 1979: 9).

A distributed model subdivides a watershed into sub-basins; simulates each separately; and then amalgamates the simulated results to obtain the response for the whole drainage basin. In principle, it would seem logical that the distributed models simulate more accurately the catchment response than lumped models. But, if inadequate knowledge of the physical processes and spatial parameters occurs, the results produced by distributed models are no more a reflection of reality than lumped models (Linsley et al., 1986: 340).

Computational processing of the distributed models can be time consuming. However, with the advancement of computer technology, this has become less of an issue. Thus, the major advantage of the distributed model is its ability to encompass heterogeneity within watersheds (Linsley et al., 1986: 340).

It has also been suggested that hydrology, or physically-based models, do not operate on grid squares, but rather such meshes are used as a computational convenience. It may be that any model that proposes to simulate hydrology realistically, should use topographic subdivisions rather than grid squares (Kite, 1998a).
2.3.4 Stochastic Models

Stochastic, empirical or black box models tend to be associated with lumped models. They are simple models with little or no attempt to explain or include natural processes, and thus have 'probable' outcomes. Stochastic models tend to include some level of randomness in the inputs or process operation which can lead to one or several possible outcomes (Hardisty et al., 1993: 21; Kirkby et al., 1993: 3). These types of models tend to lack theoretical support and are usually defined experimentally (Fleming, 1979: 8; Kirkby et al., 1993: 14). This functional type of model is suitable for initial research, since it allows for the initial identification of the processes involved within a drainage area and for establishing associations amongst the variables (Kirkby et al., 1993: 14). In these types of models, the modeller tends to have a poor idea of how the system (i.e. drainage area) functions. However, these types of models allow for numerous simulations to be executed in a rapid manner (i.e. less computational time), thus enhancing the modeller's knowledge with respect to a watershed's operation and limitations (Kirkby et al., 1993: 36).

2.3.5 Deterministic Models

Deterministic or white box models are closely linked with distributed models. They are more complex, physically-based with generally more 'precise' outcomes. Most models tend to be deterministic, in the sense that there is a specific output from a given set of inputs (Kirkby et al., 1993: 3). In these types of models, knowledge of the variables involved and their relationships within a system is known (Kirkby et al., 1993: 14). A truly deterministic model would theoretically be very difficult to achieve, since a system can be infinitely subdivided into smaller and more precise spatial grids encompassing all the processes involved.
It is important to point out the differences between *deterministic* and *distributed* models. *Deterministic* models are based on the physics (i.e. physically-based) of the problem, e.g. a *deterministic* model of runoff generation could incorporate the Richards equation of unsaturated water flow (i.e. the theoretical equation for vertical unsaturated flow in a homogeneous porous medium). A *distributed* model would account for the spatial variability of the parameters and variables in the Richards equation. Also, you can have a *deterministic* model which is lumped if you assume, for instance, that the soil water characteristics are the same everywhere in the catchment. Similarly, you could have a *stochastic* model which is *distributed*.

### 2.3.6 Parametric Models

*Parametric, mixed or grey box* models (i.e. falling anywhere between *stochastic* and *deterministic*) can be associated with *semi-distributed* models (i.e. that fall anywhere between *lumped* and *distributed* models). These are models in which physical parameters are included over spatial areas of certain scales. As Kirkby *et al.* (1993: 14) state:

> Of course, it must be stressed that this classification is somewhat arbitrary: all models are really a shade of 'grey' since even the most realistic models involve some simplification of the real world.

These types of models include both time and space components in all the processes used to determine the response of the drainage area, and the relevant inclusion of the physical parameters within the mathematical functions (Fleming, 1979: 8). An example of such a conceptual model, for flood forecasting purposes, would include land cover types and soil types to determine infiltration rates and deficit soil moisture storage to account for lag times. Therefore, *parametric* models include a higher degree of physical
representation with mathematical functions in relating the hydrological processes of a catchment (Fleming, 1979: 9).

2.3.7 EBSS Models

The event based streamflow simulation (EBSS) models, since their inception in the early 1960s, are useful for several water resources problems. These include, as indicated by Singh (1989:237):

(1) the design of hydraulic structures (e.g. dams, culverts, bridges, spillways);
(2) urban and highway drainage;
(3) planning of flood control works;
(4) urban planning and development;
(5) assessment of non-point source pollution;
(6) disposal of waste material;
(7) evaluation of environmental impacts of land use and management practices; and
(8) planning of soil conservation works.

These types of models are used to simulate rainfall-runoff processes. Important components needed in streamflow simulations are a good representation of a watershed, determination of effective rainfall (ER) amount or volume of direct runoff (DR), determination of an effective rainfall hyetograph (ERH), computation of direct runoff hydrograph (DRH), flow routing (e.g. using the Muskingum method), and parameter estimation (e.g. optimization, calibration and verification). Other needed data for such event-based simulations include watershed characteristics (e.g. areas, elevations, channel slopes, channel lengths), rainfall characteristics, infiltration, interception, depression storage, antecedent soil moisture characteristics, and streamflow characteristics (Singh, 1989).
2.3.8 CSS Models

Continuous streamflow simulation (CSS) models, as the name suggests, are simulations over longer periods of time. They attempt to replicate the complete land phase of the hydrological cycle, whereas the EBSS only attempt to represent the DRH from specific events (i.e. storms). Therefore CSS models mimic the hydrologic cycle, and the EBSS models represent the rainfall-runoff processes (Singh, 1989). Applications of CSS models include, as indicated by Singh (1989: 246):

(1) extending streamflow records;
(2) flow forecasting;
(3) watershed experimentation;
(4) supplementing of stream gauging program;
(5) evaluating the effect of land-use practices on watershed response;
(6) designing urban drainage, highway culverts, reservoirs, and the like;
(7) planning urban development, river training works;
(8) water quality modelling;
(9) developing water supplies;
(10) flood mitigation;
(11) drought management; and
(12) irrigation planning and management.

The land phase and the channel phase are the phases being simulated in these types of models. As in EBSS models, certain components are needed to allow for these simulations. These include: watershed representation, mean areal rainfall, interception, depression storage, soil moisture storage, infiltration, evapotranspiration, interflow, baseflow, surface runoff, channel flow routing, and reservoir flow routing. Three important data types needed for these models are: (1) watershed characteristics (e.g. soil, land-use, topography); (2) climatic characteristics (e.g. rainfall, temperature, humidity); and (3) hydrological characteristics (e.g. streamflow). CSS models also require parameter optimization. It should be noted that CSS models, while encompassing components of the hydrologic cycle, will undoubtedly include components of EBSS models.
2.4 Future Developments in Hydrological Modelling

Due to the rapid development in computer technologies, hydrological modelling has been able to achieve new limits at an unprecedented pace. New technologies being incorporated into this type of modelling includes those of remote sensing, Geographical Information Systems (GISs), artificial intelligence and radar data. These tools are able to provide physiographic information of watersheds, allow for easy manipulation and queries of data and allow for real-time forecasting.

More ‘general’ models will have to become key in the future, i.e. those including a variety of applications (e.g. watershed response; water quality; non-point source pollution; sediment yield; etc.). Having these models integrated with other management tools, as in social, economic and management models, would produce, to a greater extent, well-rounded modelling endeavours (Singh, 1995: 5).

A key to this will also be to make such models readily available and easy to use for people that do not necessarily have the appropriate background, but will be using these models as decision-making tools (e.g. environmental consultants). In other words, these models have to be developed for a wide range of applications within watersheds, and be easily adaptable to a wide range of users, while eliminating the limited usage to the model developers and their immediate associates.

One goal is to increase their applicability from a hillslope scale and a watershed scale, to a more global scale (Kite, 1994). For example, it is hoped that integrating a versatile distributed type hydrological model within a global circulation model (GCM) would prove to be a tactful technique. This would be due to the fact that GCMs take minimal account in surface and hydrological characteristics while calculating land surface to atmospheric fluxes (Beven et al., 1995: 655).
Another new technique as of more recently, is to incorporate digital terrain analysis models with hydrological models (Grayson et al., 1995). This type of integration is based on the notion that a digital terrain model is able to provide the physiographic parameters needed for the hydrological models more quickly and more accurately than previous manual methods. This enables a user to produce prompt and accurate analyses for particular drainage basins, since in the past, physiographic parameters (e.g. sub-basin areas, mean latitudes, mean elevations, etc.) were derived manually, and more recently, from laborious GIS manipulations. These manipulations were both costly and time consuming. More importantly, they allowed for only one representation (i.e. at only one scale) of the main drainage area being studied. Thus, integrating two such models is beneficial in that it would allow for prompt and accurate analyses at several sub-basin scales.

Since heterogeneity is linked to scale, one will have to be cautious when applying these types of models at larger scales (Singh, 1995: 11). In other words, since the numerical equations developed within a model were derived at a certain scale or under laboratory conditions, is it safe to presume that these calculations will be applicable at larger scales while including ‘all’ the parameters and their spatial variabilities?

In the past, availability of data and computer capabilities were insufficient. Thus, lumped models sufficed; but with increasing accessibility to data and advancement of complex technology, distributed modelling has gained in popularity (Singh, 1995: vii). Although their spatially distributed nature of input data and predictions, and their measurable physically-based parameters have proven advantageous, distributed models are also subject to improvements (Beven, 1985; 1989; 1992). Associated with this gain in popularity and usage, a variety of ‘newer’ dilemmas are introduced and have to be addressed in the future.
Reducing uncertainty and increasing reliability are the key to continued successful usage of such models. Beven (1989: 170) points out some of the improvements needed for the future:

1. physically-based modelling must take into account of the need for a theory of the lumping of subgrid scale processes;
2. for closer correspondence in scale between model predictions and measurements;
3. for closer correspondence between model equations and field processes; and
4. for the rigorous assessment of uncertainty in model predictions.

This would necessitate an improved knowledge of the physical processes, an understanding of the variable parameter values and thus more suited measurement techniques. For an elaborate discussion on this matter, please refer to Beven (1985; 1989; 1992), Jensen and Mantoglou (1992), Bathurst and O'Connell (1992), Beven and Binley (1992), Drayton et al. (1992), and Grayson et al. (1992).

2.4.1 Summary

A complete representation of reality is achieved in the ideal 'fully-distributed' and 'fully-deterministic' model. Such a model is practically impossible to achieve since the inclusion of all existing processes under every type of condition known, and at all scales, is perhaps beyond the realistic scope of human's to fully understand. But, the reliance remains on replicating the 'real' life scenario to a certain level of precision, enabling us to make sound judgements of the processes taking place, and to predict them with a certain level of confidence. This is the best we can do for the moment, due to the infinite amount of processes occurring variably over such complex distributed areas.

Figure 2.2 illustrates that the best or most realistic representation that can be achieved is one that is the lightest shade of grey, since a 'white box' representation is unattainable and unrealistic under the current knowledge and theories. The important aspect to be illustrated from a hydrological model, is that the structure of the model and the value of
its parameters should represent the hydrologic reality of watersheds and their natural conditions. In doing so, the status in scientific modelling is heightened while stimulating scientific hydrology (Zhao and Liu, 1995). This point was well illustrated by the following comment from Phillip (1980: 447):

> We should not abandon the task of seeking to understand as much about these systems as we possibly can. We can have no hope of understanding determinate heterogeneous systems unless we first understand homogeneous ones, and to take this further, we shall have no hope of understanding stochastic heterogeneous systems without first understanding determinate ones.

It should be obvious that no predictive model will be able to incorporate all the parameters replicating the 'real life' situation. Theory determines the important factors that become incorporated into a model (Hammond, 1989: 289). Therefore, no model can ever completely be 'fully distributed' and 'fully deterministic' (i.e. absolute white box) since the spatial structure of a basin can ultimately be 'infinitely distributed'. What is important is that we are aware of the assumptions upon which a model is based, and within that context, we can draw conclusions.

### 2.5 Scaling in Hydrological Modelling

This topic has been debated extensively in the past, and continues to do so today. The most relevant reviews of scale issues in hydrology are Dooge (1982; 1986), Klemeš (1983), Wood *et al.* (1988; 1990), Wood (1995), Beven (1991), Mackay and Riley (1991), Rodriguez-Iturbe and Gupta (1983), Gupta *et al.* (1986a; 1986b), Dozier (1992), Blöschl and Sivapalan (1995) and Song and James (1992). Scaling issues in hydrology can take many forms, some of which include:

1. varying the grid cell size of input digital elevation models (DEMs) to hydrological models (e.g. 1 cm, 10 cm, 1 m, 10 m, 1 km, 10 km, etc.),
(2) varying drainage areas (i.e. microscale (100 km$^2$ or less), mesoscale (100-1000 km$^2$) and macroscale (greater than 1000 km$^2$)), and

(3) varying the number and size of sub-basins for a particular drainage area.

The latter is of interest to this research. Background notions of scale and some definitions will be discussed.

### 2.5.1 Background Notions of Scale and Definitions

For an in-depth description on these topics, the reader is urged to refer to Blöschl and Sivapalan (1995). Hydrological processes can occur over a wide range of temporal and spatial scales (Figure 2.3). Blöschl and Sivapalan (1995: 255) suggest that time scales of a hydrological process be grouped into three distinct categories: (1) the lifetime (or duration; e.g. for an intermittent process such as a flood); (2) the period (or cycle, e.g. for a periodic process such as snowmelt); and (3) the correlation length (or integral scale, e.g. for a stochastic process exhibiting some sort of correlation (Figure 2.4)) (Haltiner and Williams, 1980; Dooge, 1982; 1986; Klemes, 1983; Dagan, 1986; Stull, 1988).

Spatial scales can also be described in the same manner, whereby defined as spatial extent, period or integral scale, depending on the nature of the process (Blöschl and Sivapalan, 1995: 255).

Hydrological processes often display 'preferred' time scales of one day and one year separated by a 'spectral gap'. Preferred scales are scales of a certain length or time, that are more likely to occur than other scales, and are also sometimes referred to as 'natural scales’. A spectral gap refers to scales that are less likely to occur than other scales (Blöschl and Sivapalan, 1995: 255). Processes such as precipitation in spatial scales, do not seem to demonstrate signs of preferred scales and/or spectral gaps (Gupta and Waymire, 1993). Usually in hydrology, spatial resolutions tend to be poorer than time contributions (Blöschl and Sivapalan, 1995: 256).
Additional scales in modelling are observation scales and working scales. Observation scales require a finite number of samples. Observation scales in space and time, fall into three categories (Blöschl and Sivapalan, 1995: 256): (1) the spatial (temporal) extent (i.e. coverage) of a data set, (2) the spacing (i.e. resolution between samples), or (3) the integration volume (time constant) of a sample (e.g. spatially: 1 dm$^3$ for a soil sample to several km$^2$ for discharge measurements; temporally: usually a function of a particular instrument) (Figure 2.5).
The working scales tend to be related to both processes (Figure 2.3) and applications of the hydrological models (Figure 2.6) (Blöschl and Sivapalan, 1995: 257). Dooge (1982; 1986) refers to working scales, in space, as:

- the local scale (1 m);
- the hillslope (i.e. reach) scale (100 m);
- the catchment scale (10 km); and
- the regional scale (1000 km);

and, in time, they are:

- the event scale (1 day);
- the seasonal scale (1 year);
- the long-term scale (100 years).

Also, these scales tend to be larger or smaller than the observation scales; and hence, 'scaling' is required to bridge the gap (Blöschl and Sivapalan, 1995: 257).

Other common terminology used in scaling research is upscaling, distributing and aggregating; and opposite are downscaling, disaggregating and singling out (Figure 2.7) (Blöschl and Sivapalan, 1995). Upscaling is defined as relating information of a certain scale to a larger scale; and downscaling translates information to a smaller scale (Gupta et al., 1986a). For example, estimating rainfall over a drainage area involves upscaling when data is collected from one, or very few, precipitation gauges; then distributing that precipitation over the drainage area (while considering topographical influences); and then aggregating the spatially distributed rainfall into one single value (Blöschl and
Sivapalan, 1995: 260). The opposite is downscaling, which involves disaggregating and singling out. Regionalization occurs when information from a particular drainage area is taken and used in another location for a basin similar in size and characteristics.

![Image](image.png)

**Figure 2.5:** Three alternative definitions of measurement scale in space $l$ (and time $t$): (a) Spatial (temporal) extent; (b) spacing (=resolution); and (c) integration volume (time constant). *Source:* Blöschl and Sivapalan, 1995: 256.

![Image](image.png)

**Figure 2.6:** Problem solutions required at a range of time-scales. *Source:* Blöschl and Sivapalan, 1995: 252.

In their natural state, drainage areas tend to display a great degree of heterogeneity and variability in both space and time (Blöschl and Sivapalan, 1995: 257). Also, heterogeneity and variability reveal themselves for a wide range of scales (Figure 2.8). The heterogeneity of a drainage area will vary spatially at the local, hillslope, catchment and regional scales. Similarly, variability will vary temporally at the event, seasonal and long term scales. Typically, heterogeneity varies over space and is used for media
properties (e.g. hydraulic conductivity); and variability varies over both space and time and is used for fluxes (e.g. runoff) (Blöschl and Sivapalan, 1995).

![Figure 2.7: Linkages across scales as a two-step procedure. Source: Blöschl and Sivapalan, 1995: 260.](image)

Hydrological processes often display aspects of discontinuity, periodicity and randomness. Discontinuities can occur over discrete zones of varying differences (e.g. zones of varying geology); or within zones of relative uniformity and being somewhat predictable. Periodicity, on the other hand, is more predictable (e.g. diurnal or annual cycles of runoff). Randomness is not completely predictable, but is more so in terms of statistical properties (Blöschl and Sivapalan, 1995:258). Terms related to heterogeneity and variability are disorder, order, structure and organization. Disorder occurs when there is variation over space and time as with randomness, but it is not probabilistic in nature. This is opposite of order, which displays regularity or undeniable constraints (Allen and Starr, 1982). Structure in a general sense has the same meaning as order; but on the other hand, it is used in a more stochastic form to display instances of a distribution like mean and variance. Organization also parallels order in meaning, but also, usually refers to a more complex sense or regularity (Blöschl and Sivapalan, 1995: 258-259).
2.5.2 Previous Studies Varying Sub-Basin Scales

The study that most closely resembles this research is that of Song and James (1992). It reflects the difficulties in modelling continuous simulations of runoff from ungaged sub-catchments by estimating model parameters from catchments as a whole (Song and James, 1992). This is based on the notion that catchment heterogeneity, introduces errors at larger scales (i.e. coarse subdivisions), and thus by subdividing a catchment into finer areas (i.e. smaller scales), parameters will be better represented.

In previous research, continuous hydrologic simulations revealed how catchments would respond over time to various climatic conditions and how some of the processes interacted with these variations. Also, these types of simulations proved beneficial in estimating basin responses to hypothetical instances of climate (Song and James, 1992: 833). To strengthen this type of research, ensuing studies linking model parameters to catchment characteristics were essential. But, the natural spatial heterogeneity of catchment areas posed difficulties in representing model parameters adequately. In other words, runoff generations become less sensitive to spatial variations at larger scales.
Differences in physical, vegetative and topographic features do however limit this spatial extent. Therefore, hydrological models have to incorporate these complexities in order to represent catchments adequately.

An optimal scale (i.e. adequate number of subdivisions) for suitable model parameter representation has to be determined. Song and James (1992: 833) define this optimum as:

...the size of a unit or subcatchment, within which the hydrologic response to rainfall can be treated as homogeneous and still have runoff simulation reproduce the hydrologic response of the catchment. This scale must not be so small as to be dominated by local physical features, nor so large as to ignore significant hydrologic heterogeneity caused by spatial variabilities of catchment characteristics.

Song and James (1992), using the Stanford Watershed Model (SWM), aimed at finding this optimal scale. They assume that scale effects are directly linked to heterogeneity; and that with greater heterogeneity, smaller optimal scales are needed (Song and James, 1992: 834). Their evaluation took place on three different basins of varying size and topography by comparing values of objective functions (Song and James, 1992: 839-841). The first basin, Bodfish Creek is a moderately steep catchment with an area of 19.2 km². The second basin, Georges Creek is in a gently rolling area covering 23.9 km²; and the third basin, San Dimas Creek is a very steep mountainous basin with an area of 42 km². Optimal scales were found to range between 0.78 and 5.98 km² (Song and James, 1992). Their observations indicated a trend toward smaller optimal scales for basins with greater relief. Song and James (1992) also indicate that with continued segmentation of a basin, results improve up to a certain optimum, but then begin to worsen beyond this optimal scale. At smaller scales, simulated flows began to fluctuate between simulations, thus destabilizing the objective functions (Song and James, 1992: 841). Similar relationships have also been observed by Wood et al. (1988; 1990) at smaller scales.
Wood et al. (1988; 1990) also studied the behavior of mean areal response with increasing catchment scale. They introduced the concept of the `representative elementary area" (REA). Wood et al. (1995: 334) define the concept as follows:

The REA is the critical scale at which implicit continuum assumptions can be used without explicit knowledge of the actual patterns of topographic, soil, or rainfall fields. It is sufficient to represent these fields by their statistical characterization.

This research used a modified and spatially distributed version of TOPMODEL (Beven and Kirkby, 1979; Beven, 1986) on the Coweeta River experimental watershed in North Carolina (area = 17 km$^2$) (Wood et al., 1988), and for the Kings Creek catchment (area = 11.7 km$^2$), Konza Prairie Nature Reserve, Kansas (Wood et al., 1990). The research focus of their studies was to enhance the knowledge of the relationship between small scale variability of topography, soil and rainfalls with that of storm response at the catchment scale (Wood et al., 1990). Their aim is to relate the small scale complexities, apparent in both observations and experimental studies of flow processes, to the relative ease (i.e. loss function and time transformation) needed for useful forecasts at the catchment scale (Wood et al., 1990: 3-4). Wood et al. (1990) concur with Dooge (1982) that it is important to hydrology to enhance knowledge on the effects of spatial variability in parameterizing hydrological processes at a range of scales. As Gupta et al. (1986a: vii) mention:

The scale problems in hydrology stem from the recognition that the mathematical relationships describing the physical relationships are manifested at different space-time scales. The broad scientific problem then is to identify and formulate suitable relationships at the scales of practical interest, test them experimentally and seek consistent analytical connections between these relationships and those known at other scales.

Wood et al. (1988; 1990) have determined that when sub-dividing a catchment area, variability over different scales can be investigated. It is assumed that with increased scales (i.e. from finer to coarser sub-divisions), higher sampling of a hillslope will occur.
and thus lead to a decrease in the variations between subcatchment response (Wood et al, 1990: 8). Once the optimum scale is reached, variability of storm response will be a minimum for basins of the same area. In other words, a “smoothing” or “averaging” of the parameters takes place, reducing the amount of variability of storm responses in catchment areas of similar size. This optimal or threshold scale is the representative elementary area (REA).

2.5.2.1 Summary

Song and James (1992) found that the optimal number of subdivisions ranged from 0.78 km$^2$ to 5.98 km$^2$ for small catchments located in California and Virginia. Smaller optimal scales were found in catchments having greater variability in topography, soils, precipitation and evapotranspiration.

Wood et al. (1988; 1990) found that the size of the REA, using 30m pixels in the areas studied, to be approximately 1 km$^2$ (~1000-1200 pixels, each of which are 900 m$^2$) for all the parameters studied (i.e. infiltration, rainfall, runoff). They conclude that for areas at scales smaller than the REA, the spatial variability of the input parameters must be considered in order to predict surface runoff accurately; and, at scales larger than the REA, only the statistical (e.g. mean and standard deviation) values of the parameters need to be taken into account (Wood et al., 1990: 16).

The optima found by Song and James (1992) and Wood et al. (1988; 1990), will be compared and contrasted in this research in Chapter 5 (Section 5.4).
2.6 The Hydrologic Model: SLURP

In the past, a streamflow hydrograph was usually predicted using a simple lumped basin model (Kite, 1997). However, scientific research often requires the use of a more detailed, physically-based, fully-distributed model such as the Système Hydrologique Européan (SHE) model (Abbott et al., 1986). The SLURP hydrologic model (Figure 2.9) falls somewhere between the lumped basin models and the fully-distributed physically-based models (Kite, 1997).

This intermediate type of semi-distributed model avoids the data and computation demands of fully-distributed models while retaining much of the simplicity in operation of lumped models. It aims to incorporate the necessary physics while maintaining simplicity of operation. The initial version of SLURP stood for Simple LUmped Reservoir Parametric (Kite, 1975) but the model has since evolved and the acronym no longer has meaning. The model has recently been redefined as the Semi-distributed Land-Use Runoff Process model (Kite, 1998b). This model was created to provide an alternative to the use of larger and more complex models in Canadian meso-scale basins (Kite, 1975; 1978).

SLURP is a daily time step hydrological model dividing a watershed into a number of spatial units known as Aggregated Simulation Areas (ASAs) for which the land cover classes are known. SLURP input data consists of physiographic parameters, time series data and a set of physical parameters and coefficients (Table 2.1).

The physiographic parameters are derived using a geographical information system (GIS) or a digital terrain analysis model such as TOPAZ (Garbrecht and Martz, 1997a; [2]) in conjunction with the SLURPAZ interface (Lacroix and Martz, 1997; [1]); the time series data are measured and the remaining parameters and coefficients are either estimated, calibrated or measured (Table 2.2). SLURP simulates the behavior of a
drainage area by carrying out a vertical water balance for each element of a matrix of land covers and sub-basin areas and then routing the resulting runoff between the subareas.

Figure 2.9: Concept of SLURP hydrological model. Source: Kite, 1997: 2.

A canopy, snowpack, rapid response (combined surface storage and top soil layer storage), and slow response (groundwater) comprise the four non-linear reservoirs or tanks (Figure 2.10) for which the vertical structure of the model operates at a daily time step (Kite et al., 1996). The model is able to simulate snowpack accumulation and depletion, groundwater response of watersheds, and rainfall and snowmelt generated
streamflow. The basic requirements of an ASA are that the distributions of land covers and elevations within the ASA are known, and that the ASA's contribute runoff to a definable stream channel. Each ASA is essentially a sub-basin having one main outlet. In calculating the vertical water balance for a 'water' land cover in order to meet the evaporative demand, SLURP automatically uses the Morton lake model (Morton et al., 1985; Kite, 1997). Also, for larger reservoirs, an external routing program can be written to simulate the effect of the lake or reservoir (Kite, 1997).

Table 2.1: Example input data for SLURP.

<table>
<thead>
<tr>
<th>PHYSIOGRAPHIC DATA</th>
<th>TIME SERIES DATA</th>
<th>PARAMETERS &amp; COEFFICIENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Area</td>
<td>- Precipitation</td>
<td>- Manning's roughness coefficient</td>
</tr>
<tr>
<td>- Distances to streams/outlets</td>
<td>- Air temperature</td>
<td>- Interception coefficient</td>
</tr>
<tr>
<td>- change in elevation to streams/outlets</td>
<td>- Dewpoint Temperature</td>
<td>- Between ASA routing coefficient</td>
</tr>
<tr>
<td>- channel lengths</td>
<td>- Net radiation</td>
<td>- Initial contents of slow store</td>
</tr>
<tr>
<td>- mean elevation.</td>
<td>- Discharge</td>
<td>- Precipitation factor</td>
</tr>
</tbody>
</table>

In order to calibrate the model, at least one ASA should have streamflow data (Kite et al., 1996). Land cover roughness, infiltration rates and hydraulic conductivities are parameters used in a time/contributing area relationship for each element of the ASA and land cover matrix allowing the combined runoff to be converted to streamflow (Kite, 1995). Precipitation is routed by the model through the appropriate processes whereby outputs (evaporation, transpiration, and runoff) and changes in storage (canopy interception, snowpack and soil moisture) are calculated. Rapid and slow runoff are generated from each land cover and combined into a streamflow for each ASA which is then routed downstream to the next ASA and so forth, until the watershed outlet is reached. Calibration of the model is necessary since it is a semi-distributed model with land class parameters being applied over large areas. Once the model has been calibrated for a basin of particular land classes, it can then be applied to other drainage areas of similar land classification without further calibration (Kite et al., 1996).
Table 2.2: Parameters for the SLURP model. Source: Kite, 1997: 29.

<table>
<thead>
<tr>
<th>No.</th>
<th>Parameter name</th>
<th>How derived</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Initial contents of snow store*</td>
<td>Measured/ Estimated</td>
<td>Medium</td>
</tr>
<tr>
<td>2</td>
<td>Initial contents of slow store*</td>
<td>Estimated</td>
<td>Low</td>
</tr>
<tr>
<td>3</td>
<td>Maximum infiltration rate*</td>
<td>Estimated</td>
<td>Low</td>
</tr>
<tr>
<td>4</td>
<td>Manning roughness surface*</td>
<td>Estimated</td>
<td>Low</td>
</tr>
<tr>
<td>5</td>
<td>Retention constant fast store*</td>
<td>Estimated</td>
<td>High</td>
</tr>
<tr>
<td>6</td>
<td>Max. capacity fast store*</td>
<td>Measured/ Estimated</td>
<td>High</td>
</tr>
<tr>
<td>7</td>
<td>Retention constant slow store*</td>
<td>Estimated</td>
<td>High</td>
</tr>
<tr>
<td>8</td>
<td>Max. capacity slow store*</td>
<td>Measured/ Estimated</td>
<td>Medium</td>
</tr>
<tr>
<td>9</td>
<td>Precipitation factor*</td>
<td>Estimated</td>
<td>High</td>
</tr>
<tr>
<td>10</td>
<td>Snow melt temperature*</td>
<td>Estimated</td>
<td>Medium</td>
</tr>
<tr>
<td>11</td>
<td>Temperature lapse rate</td>
<td>Measured/ Estimated</td>
<td>Medium</td>
</tr>
<tr>
<td>12</td>
<td>Precipitation lapse rate</td>
<td>Measured/ Estimated</td>
<td>Low</td>
</tr>
<tr>
<td>13</td>
<td>Initial contents of canopy store</td>
<td>Null</td>
<td>Low</td>
</tr>
<tr>
<td>14</td>
<td>Initial contents of fast store</td>
<td>Null</td>
<td>Low</td>
</tr>
<tr>
<td>15</td>
<td>Max. capacity of canopy store</td>
<td>Estimated</td>
<td>Medium</td>
</tr>
<tr>
<td>16</td>
<td>Albedos (surface, snow)</td>
<td>Measured/ Estimated</td>
<td>Medium</td>
</tr>
<tr>
<td>17</td>
<td>Leaf area index</td>
<td>Estimated</td>
<td>Medium</td>
</tr>
<tr>
<td>18</td>
<td>Interception coefficients a, b</td>
<td>Estimated</td>
<td>Medium</td>
</tr>
<tr>
<td>19</td>
<td>Soil heat flux</td>
<td>Estimated</td>
<td>Low</td>
</tr>
<tr>
<td>20</td>
<td>Areas of the land covers</td>
<td>Measured (GIS)</td>
<td>Medium</td>
</tr>
<tr>
<td>21</td>
<td>Elevations of the land covers</td>
<td>Measured (GIS)</td>
<td>Medium</td>
</tr>
<tr>
<td>22</td>
<td>Distances to stream</td>
<td>Measured (GIS)</td>
<td>Medium</td>
</tr>
<tr>
<td>23</td>
<td>Distances downstream</td>
<td>Measured (GIS)</td>
<td>Medium</td>
</tr>
<tr>
<td>24</td>
<td>Changes in elevation to stream</td>
<td>Measured (GIS)</td>
<td>Medium</td>
</tr>
<tr>
<td>25</td>
<td>Changes in elevation downstream</td>
<td>Measured (GIS)</td>
<td>Medium</td>
</tr>
<tr>
<td>26</td>
<td>Snow melt rates and radiation coeff.</td>
<td>Estimated</td>
<td>High</td>
</tr>
<tr>
<td>27</td>
<td>Between ASA routing coeff. a, b</td>
<td>Estimated</td>
<td>Low</td>
</tr>
<tr>
<td>28</td>
<td>River geometry</td>
<td>Measured/Estimated</td>
<td>Low</td>
</tr>
<tr>
<td>29</td>
<td>Priestley-Taylor Coefficients*</td>
<td>Estimated</td>
<td>Medium</td>
</tr>
<tr>
<td>30</td>
<td>Windspeed function*</td>
<td>Estimated</td>
<td>Low</td>
</tr>
<tr>
<td>31</td>
<td>Field capacity and wilting point*</td>
<td>Measured/Estimated</td>
<td>Medium</td>
</tr>
</tbody>
</table>

*1 Parameter can be included in calibration procedure
*2 Parameter optional

Routing takes place both 'within-ASAs' and 'between-ASAs'. Initially, runoff is routed from each land cover to the nearest stream and then down the stream channel to the ASA outlet (Kite, 1997). The necessary information needed are mean and standard deviation for distances to the nearest stream and for distances along the stream to the ASA outlet by land cover; and the mean changes in elevation to both the nearest stream and down the stream by land cover (Kite, 1997).

Figure 2.11 displays the within-ASA routing concept. Travel times of each land cover for to-stream and down-stream are estimated by calculating velocities using the Manning’s equation. Sums of the to-stream and down-stream travel times make up the
total travel times (Kite, 1997). Total flow is comprised of the weighted average from each land cover within each ASA.

Once the flow has been derived for each ASA, this flow now has to be routed from upstream ASAs to downstream ASAs until flow reaches the main outlet of the drainage area. The SLURP model uses two methods. The first method, referred to as storage routing, is the simplest but least accurate (Kite, 1997). This method uses a non-linear reservoir inflow storage and storage-outflow relationship to calculate routing from ASA to ASA (Klemes, 1979; 1981).

Routing water between ASAs requires two equations to be solved simultaneously: (1) conservation of mass; and, (2) conservation of momentum (McCuen, 1989). The Alpha

Figure 2.10: Simplified flow chart of the vertical water balance applied to each land class within each ASA. Source: Kite, 1997: 8.
(α) and Beta (β) parameters have an effect on both of these equations. As described in
the manual and the model's code, varying Alpha and Beta will affect both lag time and
attenuation while maintaining the correct volume (Kite, 1997).

The second method is the more popular Muskingum-Cunge channel routing method. In
this method, a single-valued depth-discharge relationship is assumed, and the classical
kinematic wave equation is used (Fread, 1985).
Due to the high variability and heterogeneity of hydrological conditions in drainage areas, calibration of parameters is often necessary. The SLURP model uses the Shuffled Complex Evolution (SCE-UA) method that was developed at the University of Arizona (Duan et al., 1992; 1994) to calibrate its parameters. This optimization technique has proven to be both effective and efficient while calibrating hydrological models (Duan et al., 1992; 1994). For an in-depth description of this technique the reader is urged to refer to Appendix 5 in Kite (1997), Duan et al. (1992; 1994), Gan and Biftu (1996) and Freedman et al. (1998).

SLURP's goodness of fit is shown graphically and established using statistical criteria. Also, computed and observed flow may be compared by visually looking at the output hydrographs (Kite, 1997). Statistical indicators include standard error, mean error and largest daily error. Some of the measures of efficiency used are the Nash/Sutcliffe efficiency (Nash and Sutcliffe, 1970); the Previous-Day criterion (Kite, 1991) and deviation of runoff volumes (WMO, 1986). Kite (1997:30-32) describes these measures of efficiency:

(a) Nash/Sutcliffe:

\[
F^2 = \frac{F^2_m - F^2_d}{F^2_m} \tag{2.1}
\]

where

\[
F^2_m = \frac{1}{n} \sum_{i=1}^{n} (q_i - \bar{q})^2 \tag{2.2}
\]

and

\[
F^2_d = \frac{1}{n} \sum_{i=1}^{n} (q_i - c_i)^2 \tag{2.3}
\]

\(q_i\) is the observed flow on day \(i\), \(c_i\) is the simulated flow on day \(i\) and \(\bar{q}\) is the average measured flow.
(b) *The Previous-Day criterion:* Estimates flow on day $i$ from flow on the previous day, $i-1$, taking advantage of the persistence component of river and lake time series.

\[ F_m^2 = \frac{1}{n-1} \sum_{i=2}^{n} (q_i - q_{i-1})^2 \]  

(2.4)

(c) *Deviation of runoff volumes:*

\[ D_v (\%) = 100 \frac{V_m - V_c}{V_m} \]  

(2.5)

where $V_m$ is the measured volume of runoff and $V_c$ is the computed volume of runoff over the period of interest. This criterion is simply a transformation of the mean computed and observed flows for the simulation period. A negative value of $D_v$ means that the mean computed flow is too high. This is somewhat counterintuitive and it might have made more sense for WMO to reverse $D_v$ so that a positive criterion would indicate an excess of simulated water.

### 2.7 The Digital Terrain Analysis Model: TOPAZ

Automated digital terrain analysis using computer models, such as TOPAZ, has greatly enhanced our analytical capabilities and our understanding of drainage areas. Some of the topographic parameters needed for inputs to hydrological models not only come from satellite imagery, but can often be derived from digital landscape analysis. Digital landscape information can often be derived from DEMs that enable linkages with hydrological models.

TOPAZ, which stands for **T**Opographic **P**arameteri**Z**ation (Garbrecht and Martz, 1997a; [2]), processes a raster DEM to derive a wide range of topographic and geometric variables that are physically meaningful to watershed runoff processes. It is comprised of a series of modules that perform the numerical processing of grid DEMs to identify topographic features; measure topographic parameters; define surface drainage; subdivide watersheds along drainage divides; quantify the drainage network; and parameterize subcatchments (Garbrecht and Campbell, 1997).
Initially, module DEDNM (Digital Elevation Drainage Network Model), the core module of the TOPAZ model, is applied for pre-processing of the DEM to correct for depressions and flat areas in order to eliminate indefinite downslope drainages (Martz and Garbrecht, 1993a; Garbrecht and Martz, 1997a). DEDNM is based on the concept of overland flow simulation (O’Callaghan and Mark, 1984; Jenson and Domingue, 1988; Martz and deJong, 1988; Morris and Heerdegen, 1988) for automated watershed segmentation and parameterization. This component of TOPAZ uses the D8 method (Fairchild and Leymarie, 1991) to determine the direction of overland flow for each cell of a DEM. The D8 method allows for elevation comparison of each grid cell against the elevations of its eight adjacent neighbours (i.e. each cell within one row and one column). Flow directions are then derived from high elevation to low elevation cells (i.e. where the steepest down-slope path exists). The surface drainage pattern defined from these overland flow directions is also used to derive the upstream drainage area for each cell. Upslope catchment area is derived for each cell as the number of upslope cells that flow into a cell is determined using the method of Martz and deJong (1988). The watershed boundary is then determined by the user manually selecting the row and column coordinates of the outlet cell. Once the outlet is selected, the watershed boundary is determined and the drainage network for the basin under study can be derived (Martz and Garbrecht, 1992).

There are three steps in fully defining the drainage network. Initially, a continuous drainage network is delineated from the selection of cells with a drainage area that exceeds a user specified critical source area (CSA) (Montgomery and Dietrich, 1992; Tarboton et al., 1991). Secondly, additional pruning of the network is performed to eliminate extraneous links that are shorter than a user specified threshold; the minimum source channel length (MSCL) (Garbrecht and Martz, 1997a) (Figure 2.12). Thirdly, the channel links are ordered using the Strahler (Strahler, 1957) stream-ordering system (Martz and Garbrecht, 1992).
The next algorithms within DEDNM identify the contributing areas for the source nodes of exterior links, and the contributing areas for both left and right banks of all channel links. Relevant topologic identification codes are also assigned to the channel links and to all the contributing areas (Martz and Garbrecht, 1998a; 1998b). TOPAZ uses a method of assigning identification codes to drainage features that is based on a network node numbering system and can be used to determine flow sequencing (Figure 2.13) (Martz and Garbrecht, 1998a; 1998b).

The RASPRO module (RAster PROperties) produces additional spatial landscape information and parameters (e.g. slope; aspect; etc.) (Garbrecht and Campbell, 1997). The RASFOR (RAster FORmatting) module is a raster reformatting utility that reformats the raster outputs from both DEDNM and RASPRO into a usable geographic information system (GIS) format (e.g. ASCII) for display purposes (Garbrecht and Campbell, 1997).
The RASBIN (RAster to BINary network) module generates tables of channel and subcatchment properties for the binary (i.e. 2 inflows per junction) network (Garbrecht and Campbell, 1997). This module essentially eliminates complex junctions (i.e. cells having more than two contributing inflows) by decomposing such junctions (see Figure 4.5) into having a maximum of two inflows per node (Garbrecht and Campbell, 1997). This module provides useful information for cascade-type flow routing by determining the next downstream subcatchment along a channel.

Figure 2.13: Network node numbering and identification codes in TOPAZ. Source: [2].

The final module of TOPAZ, NSSTAT (Network and Subcatchment STATistics), calculates statistics for the channel link and subcatchment properties for both the raster and binary channel network. This module also provides such information as drainage density and network composition parameters (e.g. sinuosity; bifurcation ratio; etc.) (Garbrecht and Campbell, 1997).

TOPAZ generates raster files (.out) of the drainage network, subwatershed areas and a variety of drainage-related topographic variables (Figure 2.14). TOPAZ also generates a
series of tabular output files (.tab) that provide the properties of individual channel links and subcatchments, as well as information about the overall channel network structure.

\[ \text{subwatersheds} \quad \text{distance to sub-basin outlets} \]

\[ \Delta z \text{ to channels} \quad \text{aspect} \]

**Figure 2.14:** Example of TOPAZ raster outputs.

TOPAZ can effectively handle depressions and flat areas in the input DEM using an innovative combination of depression outlet breaching, depression-filling, and relief imposition (Figure 2.15). Martz and Garbrecht (1998a; 1998b) introduce a new algorithm that recognizes instances where inflow sinks could have been introduced not only by elevation underestimates, but also by elevation overestimates. This algorithm offers satisfactory alternatives to conventional methods relying solely on depression filling (Martz and Garbrecht, 1998a; 1998b).

A key advantage of TOPAZ is its capability to delineate the channel network and segment the landscape into sub-basins at varying levels of detail. This is accomplished by manipulating the user-controlled parameters of critical source area (CSA) and minimum source channel length (MSCL).
Figure 2.15: Impact of depression breaching within TOPAZ. *Source:* [2].
CHAPTER 3
STUDY AREA

3.1 Study Basin Location

The study area chosen was the Wolf Creek research basin [3], which is located in the Yukon Territory, Canada (Figure 3.1). Research in this basin began in 1992, and this particular site was selected by government agencies and universities as an applied research area representative of the Yukon’s subarctic. This site, a national research basin falling under the Canadian component of the Global Energy and Water Cycle Experiment (GEWEX) and now the Ecological Monitoring and Assessment Network (EMAN), was chosen for its intermediate size, reasonable complexity, and availability of data due to other ongoing research within the watershed. Also, since 1992, a wide range of cooperating agencies across the nation (i.e. both government and university) have initiated a variety of research endeavours in this basin (Indian and Northern Affairs Canada (INAC), 1993; 1995; 1998). Research in this area has been funded by Indian and Northern Affairs Canada’s Arctic Environmental Strategy program and Environment Canada’s National Hydrology Research Centre (NHRC) (INAC, 1993).

Hydrologically, this site will provide information on northern watersheds that will benefit modelling endeavours at larger (i.e. global) scales. Wolf Creek was also selected due to its accessibility, location, lack of human disturbance and its representativeness of the area. It is located within thirty minutes of Whitehorse, Yukon, and is easily accessible (i.e. a 4x4 road is in place from a previous coal mine) by truck in the summer
months, and by snowmobile in the winter (INAC, 1993). This basin is located at approximately 61° North latitude and 135° West longitude.

![Location of Wolf Creek basin](image)

**Figure 3.1:** Location of Wolf Creek basin (coordinates for UTM Zone 8, NAD27).

### 3.2 Basin Characteristics

The basin displays a dendritic type drainage pattern, and regionally, it flows into the Yukon River which then flows into the Bering Sea. Elevations range from approximately 700 to 2100 metres with a median elevation at 1325 metres (Figure 3.2(a)). It is characterized by a northeasterly aspect (Figure 3.2(b)) and occupies 183.3 km² area in the southern Yukon headwater region of the Yukon River. The main stream has a length (i.e. from the headwaters to the selected outlet) of approximately 41 kilometres and a channel slope of 0.015. Coal Lake, at an elevation of 1300 metres, is the major storage unit. Small headwater cirque lakes and small upland wetlands comprise the remainder of the basin.
The physiographic or morphogeological belt in which the basin is situated is known as the ‘intermontane belt’ [5]. Long, straight slopes and rounded or flat-topped mountains characterize this subdued relief which is primarily composed of sedimentary rocks. This belt falls into a larger group known as the ‘intermontane superterrane’, which is a form of an ‘accreted terrane’ (i.e. terranes: individual rock packages or crustal fragments; accreted: increase in size by gradual external addition) [5]. The primary rock composition comprises sandstones, siltstones, conglomerates and limestones [5]. There is also evidence of volcanic materials consisting of andesite and basalt with some granitic intrusions (INAC, 1998).

Glacial, glaciofluvial and glaciolacustrine deposits comprise the basin ranging in depth from one to two metres. The valley bottoms are made up primarily of a fine textured
alluvium, while at higher elevations shallow colluvial deposits with frequent bedrock outcrops are present (Mougout and Smith, 1994).

The basin is subdivided into three primary ecosystems (Francis, 1997): the boreal forest (22%), the subalpine taiga (58%) and the alpine tundra (20%). In the lower elevations of the boreal forest region, soils are poorly to well drained, and comprised mainly of orthic regosols varying in texture from gravel to clay. At higher elevations, in the subalpine taiga and alpine tundra, primarily orthic eutric brunisols occur which are fairly well drained and range in texture from a sandy loam to a gravelly sandy loam (INAC, 1998). A 2 cm volcanic ash layer is also present at a 10 cm depth below the surface (Rostad et al., 1977). The basin is situated within the discontinuous/scattered permafrost zone (Brown, 1977; [4]).

Table 3.1: Dfc climate classification according to the Köppen-Geiger system. Source: Christopherson, 1994: 278-302.

<table>
<thead>
<tr>
<th>D</th>
<th>- Warmest month above 10 °C; coldest month below 0 °C; - Cool temperate-to-cold conditions; snow climates</th>
</tr>
</thead>
<tbody>
<tr>
<td>f</td>
<td>- Year-round precipitation where all months receive in excess of 6cm.</td>
</tr>
<tr>
<td>c</td>
<td>- 1 to 4 months above 10 °C; - Cool, short summers.</td>
</tr>
</tbody>
</table>

According to the Köppen-Geiger world classification system, this area would be classified as a Dfc type climate, i.e. Mirothermal (Subarctic, cool summers) (Table 3.1). Low relative humidity and relatively low precipitation characterize the subarctic continental climate of the basin. Summer temperatures range from 5° to 20° Celsius and the winter range is from -5° to -20° Celsius (INAC, 1993). The mean annual temperature is -3° Celsius. Extremes of 25° Celsius and -40° Celsius, for the summer and winter months, respectively, are common. An arctic inversion occurs frequently during the winter, causing air temperature to increase with elevation (INAC, 1993). Mean annual precipitation is around 350 mm, with approximately 60% falling as rain (Wahl et al., 1987). Temperatures and precipitation values for the basin are slightly
cooler and slightly greater, respectively, that those of the nearby Whitehorse Airport (Figure 3.3).

![Climograph for Whitehorse Airport](image)

**Figure 3.3:** Climograph for Whitehorse Airport. *Source:* Environment Canada, 1993.

Streamflow response during snowmelt (late May to early June) is characterized by peak flows ranging from 10 to 20 m$^3$/s (Figure 3.4). Minimum flows occurring in March, measuring relatively high around 0.4 m$^3$/s, are due to lake storage and the proximity of the basin to the Gulf of Alaska (Janowicz, 1991). In the summer, the basin is subject to intense rainstorms which produce secondary peaks (Janowicz, 1986). With a main stream length of approximately 41 km and a mean stream velocity ranging from 0.3-0.5 m/s (Janowicz, 1999), water can travel anywhere from 26 km to 43 km in a day. Thus, the travel time along the main channel is anywhere around 1 day to 1.5 days.

### 3.3 Instrumentation

The study area is instrumented with three hydrometric stations and three meteorological stations. One hydrometric station (i.e. main outlet used in this study) is located at km 1486.6 of the Alaska Highway (i.e. approximately 15 km south of Whitehorse) and its basin covers an area of approximately 183.3 km$^2$. Another hydrometric station is located at the outlet of Coal Lake with its basin covering an area of approximately 70.5 km$^2$. 
The final station, located in the headwaters of the creek, has the highest elevation and covers a drainage area of approximately 14.5 km². More data is available from the Alaska Highway site as opposed to the other two sites, as research on it commenced in 1993 (i.e. one year before the other two); thus, the Highway site is used as the main outlet for this research.

![Figure 3.4: Stream Hydrograph for Wolf Creek: September 1994 to August 1996. Source: Li et al., 1997.](image)

The research basin also includes three very sophisticated meteorological stations situated in representative ecosystem zones: the Black Spruce Forest station; the Alpine Tundra station and the Buckbrush Taiga station. The Black Spruce Forest station, with an elevation of 750 m, is a mature black spruce forest site and is situated on a flat valley bottom near the Wolf Creek basin outlet into the Yukon River (INAC, 1993). The Alpine Tundra station, with an elevation of 1615 m, is situated within a wind-swept, high alpine tundra plateau along a drainage divide at the northern edge of the basin. Vegetation is sparse and consists of mosses and lichens with occasional patches of shrub willows and birch which are less than 20 cm tall. There are also boulders up to 1 metre tall scattered on the plateau (INAC, 1993). The Buckbrush Taiga station, at an elevation of 1250 m, is situated on a gentle slope near the valley bottom between Mount Granger
and the ridge west of the Coal Lake hydrometric station. The vegetation consists of tall willows and alders (i.e. 1-2 metres) with very scattered spruce. For several kilometres, a sloping fetch extends NE and SW. To the NW, the valley slopes up and to the SE the valley drops before rising to Coal Ridge (INAC, 1993). A wide variety of measurements are made at all of these sites, but the ones of interest to this research are: stream discharge measurements from the main outlet hydrometric station; temperature, precipitation, relative humidity and net radiation from the three meteorological stations.

### 3.4 Study Site Selection Consideration

Understanding and modelling hydrological processes in northern watersheds is a vital step towards the larger-scale modelling of the global water and energy cycles. In order to comprehend more fully larger scale processes, it is necessary to grasp smaller scale phenomena. As part of the World Climate Program of the Global Energy and Water Cycle Experiment (GEWEX), this research aims at increasing the knowledge of modelling energy and water balance processes (INAC, 1995).

GEWEX projects, at the North American scale, include the Mississippi and Mackenzie river basins. At the Canadian level, such projects include Trail Valley and Havikpak Creeks near Inuvik, Northwest Territories; Beartrap Creek in Prince Albert National Park, Saskatchewan; and Wolf Creek, Yukon (INAC, 1995). The main aim at the Canadian scale is to model energy and water balance (i.e. main GEWEX goal in general) for northern environments both spatially and temporally at 100 km² and 1 month respectively (INAC, 1995). The following program mission statement has been implemented by the Department of Indian Affairs and Northern Development (DIAND), Water Resources, Yukon Region:

Indian and Northern Affairs Canada (INAC) acts as the overall program manager for the Wolf Creek Research Basin Project, an intradepartmental and university
The Wolf Creek Project was initiated by the DIAND Arctic Environmental Strategy (AES) Program to improve the understanding on northern waters by promoting scientific research in a subarctic mountainous watershed (INAC, 1995: 4).

The hydrometric and climatological stations will provide the input parameters for the SLURP hydrological model. The hydrometric station at the Alaska Highway will be the main outlet for the purpose of this research for three reasons. First, it encompasses the whole basin (i.e. is the largest drainage area representing Wolf Creek). Second, the other two hydrometric stations only have fragmented and limited data since 1994; and thirdly, the SLURP hydrological model has already been used once for this basin (Li et al., 1997).

The research will contribute directly to the Canadian GEWEX goal of identifying and quantifying the critical processes influencing the water and energy cycles by studying the scaling effect of sub-basin size on the accuracy of model simulations. The results of this study will hopefully aid in improving the hydrological modelling of large basins such as the Mackenzie by clarifying the degree to which the basin must be subdivided before the significant hydrological processes can be modelled with acceptable accuracy.

Such a study is also of interest given the importance in linking this type of modelling technique at a global scale with other types of models such as global circulation models (GCMs), oceanographic models, landscape models, and vegetation models. In order for this to be accomplished, hydrologic models have to be applicable at both macro and continental scales (Kite et al., 1994; Kite, 1995). This type of research, being applied in a northern environment, will contribute to the overall understanding of hydrological processes in such environments in hopes of promoting larger scale modelling and greater comprehension of the global water and energy cycles. Thus, this study is potentially beneficial to both sub-basin scale analysis of a specific drainage area, and while expanding the realm of hydrological modelling as we know it, to larger scale analyses (i.e. global).
CHAPTER 4
METHODOLOGY

4.1 Data Sources

A variety of data are required as input to the SLURP hydrological model. The hydrological and climatological parameters are provided from each of the appropriate stations, and the physiographic parameters are derived from a digital elevation model (DEM) and land cover data using TOPAZ and SLURPAZ.

4.1.1 Time Series Data

Hydrological data for the research was provided by the Hydrology Section from the Water Resources Division of INAC. Climatological data were provided by both INAC and Environment Canada’s National Hydrology Research Centre. The necessary climatological inputs of mean areal precipitation, air temperature, dewpoint temperature and net radiation were provided by Li et al. (1997) in Atmospheric Environmental Service (AES) format. Half-hourly data of air temperature, net radiation, relative humidity, snow depth and tipping bucket readings were used from the three meteorological stations in deriving the data into this usable format for SLURP (Li et al., 1997).
4.1.2 Digital Elevation Model (DEM)

The DEM used in this study was derived by manually digitizing 1:50000 scale maps (i.e. NTS 105 D/6; 105 D/7; 105 D/10; 105 D/11) of the area (Zhao, 1996). This information was then taken and gridded (or rasterized) into 30 m cells in order to match the cell size of the satellite image which provides land cover information. There are several gridding methods available (e.g. inverse distance; kriging; minimum curvature; polynomial regression; radial basis functions; triangulation with linear interpolation; etc.). The minimum curvature method was chosen due to its good representation of this size of a data set (i.e. >1000 observations) in reasonably quick processing time (Keckler, 1994).

Determining a suitable DEM resolution that will adequately represent all significant hydrological processes is a difficult task. As a general rule of thumb, Garbrecht and Martz (1996) suggest that the DEM grid size used in hydrologic applications should adequately reflect landscape characteristics, hydrologic model type, and model parameters. Therefore, the optimal grid size will tend to vary with the characteristics and size of the landscape features (Garbrecht and Martz, 1996) and scale of the project. Garbrecht and Martz (1993; 1994) found that from a 30 m DEM, network parameters and network composition in low relief terrain, typically fall within 10% of the ‘blue line’ network derived from USGS 7.5 minute quadrangles (1:24000). Thus, for the purpose of this research, the use of a DEM derived from 1:50000 scale maps in high relief terrain seems very reasonable. Several studies have portrayed optimal grid cell size for various applications in varying areas (Garbrecht and Martz, 1993; 1994; Zhang and Montgomery, 1994; Bruneau et al., 1995; Farajalla and Vieux, 1995).

The accuracy of this DEM is considered to be quite good since it was digitized from 1:50000 scale maps which are fairly large scale maps. Therefore, since the DEM was derived from the largest scale maps available, and even though this scale is slightly smaller than that used by Garbrecht and Martz (1993; 1994), i.e. USGS 7.5-min
quadrangle, it is felt that it more than adequately considers the landscape characteristics for model parameterization.

Although errors are unavoidable (e.g. from source maps; digitizer error), the only way to improve the accuracy of such a DEM would be to conduct ground surveys or scan aerial photographs (or use satellite images (e.g. SPOT)) of the entire basin. Since the latter methods are both costly and time-consuming, manual digitizing was the next best alternative.

4.1.3 The Land Cover Data

The original land cover data was obtained from a 30 metre resolution Landsat TM dataset covering a large area around Whitehorse. Staff at the National Hydrology Research Centre (NHRC) selected a grid encompassing the study area and produced an image with 10 land covers at a pixel size of 30m (Figure 4.1(a)) (Spence, 1996). Two of the land covers within this image encompassed clouds and shadows; thus, these two land classification had to be reclassed using a nearest neighbour methodology to eliminate the cloud and shadow for use in the SLURP hydrologic model (Figure 4.1(b)). A banding effect seemed to occur around the clouds and shadows when first classified (i.e. may be an artifact of the classification method initially used), creating the ‘blocks’ of spruce and tundra in the reclassed image. For the purpose of this study, these ‘blocks’ did not pose any concerns.

4.2 The Hydrologic Model: SLURP

As mentioned in Section 2.7, SLURP requires three types of data: physiographic data (e.g. areas, distances and elevations); time series data (e.g. air temperature, precipitation) and parameters and coefficients (e.g. snowmelt rates, albedos) (Kite, 1997: 39).
Figure 4.1: Land cover: (A) 10 land classes; (B) 8 land classes after reclassifying cloud and shadow.
The physiographic data required by SLURP (Table 4.1) are easily provided using TOPAZ/SLURPAZ (discussed in the following sections).

**Table 4.1:** Physiographic information needed for SLURP. *Source: Kite, 1997: 39.*

<table>
<thead>
<tr>
<th>ASA area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentages of ASA area occupied by different land covers</td>
</tr>
<tr>
<td>Differences in the mean elevations of each land cover and the nearest point on a stream and differences in the mean elevation along the stream to the ASA outlet</td>
</tr>
<tr>
<td>Minimum and maximum distances from each land cover to the nearest point on a stream and maximum and minimum distances along the stream to the ASA outlet</td>
</tr>
<tr>
<td>Mean latitude and altitude of each ASA</td>
</tr>
</tbody>
</table>

The next step needed for the SLURP model, is to estimate model parameters (Table 4.2) in order for the model to be able to transform precipitation into runoff. Once the model parameters are estimated and the physiographic data is known, the model can be run. This data was provided by Li *et al.* (1997) from their original study.

**Table 4.2:** Parameters that transform precipitation into runoff. *Source: Kite, 1997: 39-40.*

<table>
<thead>
<tr>
<th>Maximum capacities for the canopy, detention storage and slow store</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Contents of the snowpack and fast and slow stores</td>
</tr>
<tr>
<td>Interception coefficients, and maximum and minimum LAI</td>
</tr>
<tr>
<td>Surface albedo and maximum soil heat flux</td>
</tr>
<tr>
<td>Snowmelt rates and energy conversion factors</td>
</tr>
<tr>
<td>Conductivity</td>
</tr>
<tr>
<td>Saturated infiltration rate</td>
</tr>
<tr>
<td>Roughness coefficient for each land cover and for the channel within the ASA</td>
</tr>
<tr>
<td>Lapse rate for temperature and precipitation/elevation adjustment rate</td>
</tr>
<tr>
<td>Parameters for specific evapotranspiration methods such as windspeed function, wilting point, field capacity and Priestley-Taylor coefficient</td>
</tr>
</tbody>
</table>
The input files required in running the SLURP hydrological model are as follows: the command file (.cmd), the weights file (.wts) and the Morton evapotranspiration file (.mor). The command file is the ‘key’ file that controls the SLURP model; the weights file is used to compute ASA-average meteorological data from point station data and adjusts for temperature and dewpoint temperature differences due to elevation variations; and the Morton evapotranspiration file contains the mean annual precipitation (mm) used in the Morton CRAE evapotranspiration calculations. Section 4.4 will discuss in more detail how SLURP interacts or is linked with both TOPAZ and SLURPAZ.

4.3 The Digital Terrain Analysis Model: TOPAZ

The basic requirement needed in order to run TOPAZ is a grid DEM. This file is given the name dednm.inp. The dnmcnt.inp file acts as the command file for TOPAZ as does the ‘.cmd’ file for SLURP. An additional input file, the ntgcod.inp, can be used if spatial variability in geophysical landscape properties is to be represented, but this was not included as part of this research.

The raspro.inp file contains the raster processing options needed to produce the necessary raster outputs. An additional module for the purpose of this research was developed, RASPROX (eXtended raster processing), providing additional information such as overland flow distances to both the nearest and closest subwatershed outlet; and elevation change to the nearest channel and subwatershed outlet for each grid cell.

The rasfor.inp file converts the unformatted output files from the various TOPAZ modules to ASCII files which are readily imported to most GIS (Figure 4.2). The actual import procedure will vary with the type of GIS employed by the user. Another additional module was prepared for the purpose of this research, RASFORX (eXtended raster formatting), converting the raster output files generated by the RASPROX module to again facilitate import to GIS systems (Figure 4.2) (see Garbrecht and Martz (1997))
for more details on these input files). The following sections (Section 4.4 and Section 4.5) will discuss the linkages between TOPAZ and SLURP using the SLURPAZ interface.

![Diagram](http://example.com/diagram.png)

**Figure 4.2:** TOPAZ modules used to convert files for GIS import.

### 4.4 Model Linkages Using the SLURPAZ Interface.

SLURPAZ (Lacroix and Martz, 1997; [1]) is an interface between the TOPAZ version 1.20 digital landscape analysis model and the SLURP version 11.0 hydrological model (Figure 4.3). SLURPAZ was written in FORTRAN 90 and the program code is given in Appendix A. The SLURPAZ interface processes the physiographic outputs from TOPAZ together with a raster of land cover data and routing data to generate a SLURP command file (.cmd). The land cover and DEM rasters have to be of the same size and resolution (e.g. 700 rows x 920 columns with 30m cells) to allow the SLURPAZ interface to derive all the necessary information by ASA and by land cover for each ASA. SLURPAZ can process routing data provided by the `ordpm.inp` file which can be used in conjunction with the Muskingum-Cunge channel routing method.
The interface also processes climate station coordinates using the `clmtstns.inp` file in order to generate a SLURP weights (.wts) file and a SLURP Morton evapotranspiration file (.mor). The (.wts) file (see Appendix B for an example with 17 ASAs (i.e. CSA 500)) contains weights used by SLURP to compute the ASA-means of meteorological information from point station data. The (.mor) file contains mean annual precipitation (mm) for each ASA. This data is used in the Morton (1983) CRAE (Complementary Relationship Areal Evapotranspiration) evapotranspiration model which is one of three possible methods used by SLURP to calculate evapotranspiration from vegetation/soil (Kite, 1997). Using the TOPAZ model and SLURPAZ interface, a series of physiographic parameters are derived for input into SLURP.

Figure 4.3: Flow chart illustrating connections between models.

Initially, user-supplied input files (.inp) are required by TOPAZ to allow for model execution (Table 4.3(a)). Afterwards, some selected TOPAZ outputs (.unf; .tab; .out) are used by SLURPAZ to build the SLURP command file (.cmd) (Table 4.3(b)). The name
in brackets indicates the TOPAZ 1.20 modules that generated the file. Table 4.3(c) shows the additional SLURPAZ specific inputs required.

**Table 4.3: Inputs/Outputs for TOPAZ and SLURPAZ.**

<table>
<thead>
<tr>
<th>(a)</th>
<th>TOPAZ Inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>dnmcnt.inp:</td>
<td>File containing parameters describing the DEM raster characteristics, the DEM processing options with corresponding parameters, and the user output options</td>
</tr>
<tr>
<td>dednm.inp:</td>
<td>File containing the digital elevation model (DEM)</td>
</tr>
<tr>
<td>raspro.inp:</td>
<td>File containing raster processing options</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(b)</th>
<th>TOPAZ Outputs; SLURPAZ Inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>outcnt.unf:</td>
<td>General TOPAZ parameters (DEDNM, RASBIN, RASPRO, RASPROX)</td>
</tr>
<tr>
<td>netw.tab:</td>
<td>Table of channel link properties (DEDNM)</td>
</tr>
<tr>
<td>sbct.tab:</td>
<td>Table of subcatchments properties (DEDNM)</td>
</tr>
<tr>
<td>subwth.out:</td>
<td>Raster of subcatchments for each channel link (RASPRO)</td>
</tr>
<tr>
<td>distch.out:</td>
<td>Raster of distances to nearest channel (RASPROX)</td>
</tr>
<tr>
<td>distso.out:</td>
<td>Raster of distances to ASA outlet (RASPROX)</td>
</tr>
<tr>
<td>relief.out:</td>
<td>Raster of relief corrected DEM elevations (DEDNM)</td>
</tr>
<tr>
<td>dzch.out:</td>
<td>Raster of change in elevation to nearest channel (RASPROX)</td>
</tr>
<tr>
<td>dzso.out:</td>
<td>Raster of change in elevation to ASA outlet (RASPROX)</td>
</tr>
<tr>
<td>netwbt.tab:</td>
<td>Channel link properties for the binary drainage network (RASBIN)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(c)</th>
<th>SLURPAZ Inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>iclass.inp:</td>
<td>Raster of land cover classifications</td>
</tr>
<tr>
<td>ordpm.inp:</td>
<td>Routing information (i.e. roughness, width, depth, Alpha and Beta)</td>
</tr>
<tr>
<td>clmtstns.inp:</td>
<td>Climate station number, name, easting, northing, elevation and long-term mean annual precipitation (mm)</td>
</tr>
</tbody>
</table>

The SLURP command file (.cmd) is the ‘key’ file allowing the model to operate (see Appendix C for an example with 5 ASAs (i.e. CSA 2000)). It contains all the model settings and parameter information for each ASA and for each land cover within each ASA. The area of influence of each climate station in each ASA is expressed in the weights (.wts) file. Table 4.4 lists the TOPAZ/SLURPAZ outputs provided as inputs into the SLURP hydrological model. The name in brackets indicates the files from where the information is retrieved and/or derived from. This information varies with sub-basin spatial scale and is applied to the time series data for each ASA. Using these files along with the time series input files, SLURP is able to compute the outflow for individual stream networks.
One of SLURPAZ’s calculations is the derivation of mean UTM Northing and mean UTM Easting (Figure 4.4) for each sub-basin since working with the cells in metres is much simpler. These values are then converted to mean latitude/longitude (with an option of using NAD27 or NAD83) as required by SLURP applying a sub-routine provided by Harrington (1997). Additionally, SLURPAZ is also able to produce the frequency distributions for the distances to channels and ASA outlets if the user wishes to do so. All the user needs to do is change the ‘NOPRINT=1’ option in the code to ‘NOPRINT=0’, and recompile the program. The NOPRINT variable controls whether or not to print out .txt files that contain global variable listings and frequency distribution analysis results necessary if a user wishes to assess variability of particular measures (i.e. frequency distribution for distances to channels and ASA outlets).

Table 4.4: Input needs for the SLURP .cmd, .wts and .mor files provided by TOPAZ/SLURPAZ.

<table>
<thead>
<tr>
<th>(a)</th>
<th>Inputs for .cmd file</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>By ASA:</strong></td>
<td>Area (sbct.tab)</td>
</tr>
<tr>
<td></td>
<td>Mean latitude (subwtb.out)</td>
</tr>
<tr>
<td></td>
<td>Mean elevation (relief.out, subwtb.out)</td>
</tr>
<tr>
<td></td>
<td>% area occupied by each land cover (subwtb.out, lclass.inp)</td>
</tr>
<tr>
<td></td>
<td>Channel length (netw.tab)</td>
</tr>
<tr>
<td></td>
<td>Change of elevation along channel (netw.tab)</td>
</tr>
<tr>
<td></td>
<td>Next ASA downstream (netwb.tab, ordpm.inp)</td>
</tr>
<tr>
<td></td>
<td>Actual number of ASAs (also in the case of complex junctions) (netw.tab)</td>
</tr>
<tr>
<td></td>
<td>Execution sequence, i.e. from upstream to downstream ASA (netwb.tab)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(b)</th>
<th>Inputs for .cmd file</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>By land cover for each ASA:</strong></td>
<td>Mean distance to nearest stream (distch.out, subwtb.out)</td>
</tr>
<tr>
<td></td>
<td>Standard deviation of distances to nearest stream (distch.out, subwtb.out)</td>
</tr>
<tr>
<td></td>
<td>Mean change in elevation to stream (dzch.out, subwtb.out)</td>
</tr>
<tr>
<td></td>
<td>Mean distance to ASA outlet (distso.out, subwtb.out)</td>
</tr>
<tr>
<td></td>
<td>Standard deviation of distances to ASA outlet (distso.out, subwtb.out)</td>
</tr>
<tr>
<td></td>
<td>Mean change in elevation to ASA outlet (dzso.out, subwtb.out)</td>
</tr>
<tr>
<td></td>
<td>Mean elevation of land cover (relief.out, subwtb.out)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(c)</th>
<th>Inputs for .wts file</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>By ASA:</strong></td>
<td>Area of influence for climate stations (clmtstns.inp)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(d)</th>
<th>Inputs for .mor file</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>By ASA:</strong></td>
<td>Mean annual precipitation (clmtstns.inp)</td>
</tr>
</tbody>
</table>
Basic count of cells and sum of rows and sum of cols

\[
\text{do } 260 \text{ ir}=1, \text{ nrow} \\
\text{do } 250 \text{ ic}=1, \text{ ncol}
\]

* IF statement skips cells outside main watershed (* NO 0 [zero] row or col... can't write to 0 row or col; avoids redundant 0 calculations)
* IF statement checks if any landcover values are 0 [zero], and if so, goes to write statement notifying the user that no such value can be used, and program terminates abnormally

\[
\text{if} (\text{lc}(\text{ir}, \text{ic}) \text{ .eq. 0}) \text{ goto 250} \\
\text{if} (\text{lc}(\text{ir}, \text{ic}) \text{ .eq. 0}) \text{ goto 2004}
\]

* Count number of cells in each land cover in each ASA

\[
\text{area\_lc}(\text{isub2(\text{ir}, \text{ic}),lc(\text{ir}, \text{ic}))} = + \text{area\_lc}(\text{isub2(\text{ir}, \text{ic}),lc(\text{ir}, \text{ic})} + 1
\]

* Determine sum of rows and sum of columns for each ASA for later calculations of ASA centroid

\[
\text{rows \_sum(isub2(\text{ir}, \text{ic}))} = \text{rows \_sum(isub2(\text{ir}, \text{ic}) + \text{ir}} \\
\text{cols \_sum(isub2(\text{ir}, \text{ic}))} = \text{cols \_sum(isub2(\text{ir}, \text{ic}) + \text{ic}
\]

250 continue
260 continue

* IF AREA\_ASA is <1, then assign -1 to mean row and to mean col
* ELSE, mean row equals (Sum of rows/ASA area) and mean col equals (Sum of cols/ASA area)

\[
\text{if} (\text{area\_asa(\text{i}).lt.l}) \text{then} \\
\text{rows\_mn (\text{i})} = -1 \\
\text{cols\_mn (\text{i})} = -1 \\
\text{else} \\
\text{rows\_mn (\text{i})} = \text{rows\_sum(\text{i})/area\_asa(\text{i})} \\
\text{cols\_mn (\text{i})} = \text{cols\_sum(\text{i})/area\_asa(\text{i})}
\]

* Mean UTM NORTHING (y or row) and mean UTM EASTING (x or col)

\[
\text{avg utmN= (max y)-(rows\_mn(\text{i})\text{*cell m)}} \\
\text{avg utmE= (min x)+(cols\_mn(\text{i})\text{*cell m}}
\]

\[
\text{utm conversion program: calculating central meridian from utm zone}
\]
\[
\text{deg } = 6 \\
\text{east } = \text{avg utmE} \\
\text{north } = \text{avg utmN} \\
\text{cmerid } = (177.-((\text{zone-1)}*6))
\]

\[
\text{call utm2ll (east, north, cmerid, lon, lat, nad, deg)
}\]

---

**Figure 4.4:** Example code from SLURPAZ calculating mean UTM Northing/Easting. (see Appendix A (i.e. SLURPAZ code) for variable definitions).

### 4.4.1 Complex Node Situations

Using a raster DEM in determining drainage networks often creates situations where more than two channel links flow into one junction node. These are referred to as complex nodes. **TOPAZ** treats such nodes by breaking them up into simple junction nodes (Martz and Garbrecht, 1993b; Garbrecht and Martz, 1997b). This is of importance
in deriving the drainage network, in order to evaluate the channel sequence for cascade type flow routing (Garbrecht and Martz, 1997b).

The SLURPAZ interface had to adjust for complex node situations while determining the next downstream ASA for SLURP. The TOPAZ module RASBIN, allows for source nodes to flow into one node only for calculation purposes. Thus, if one of more source channels flow into the same node, one or more nodes are created to eliminate such complex junctions (Figure 4.5).

![Figure 4.5](image)

**Figure 4.5:** (a) Complex node; (b) Complex node adjusted by TOPAZ.

It was therefore necessary for SLURPAZ to differentiate between downstream ASAs and complex junctions. Thus a series of ‘nested’ loops and ‘IF’ statements were created within the interface in order to by-pass such situations (Figure 4.6). Table 4.5 displays the results from the complex node situations displayed in Figure 4.5. It shows that all upstream nodes or ASAs (i.e. 3, 5, 7 and 8) are corrected to all flow into node #2 or ASA #2.
* Loop to correct complex node situations
*=======================================================================
* Loop for eliminating complex node situations (where flow into a
* complex node does not occur under natural circumstances, it has to
* flow to a node downstream that is an actual sub-basin node). Complex
* nodes are computed by module RASBIN of TOPAZ for calculation purposes.
* do 960 i=2,num asa
* do 950 k=1,num asa
*   if(next asa(k) .eq. i) then
*     next_asa(k)=next_asa(i)
*   endif
* continue
* continue
*Figure 4.6: Example code from SLURPAZ correcting complex node situations (see
* Appendix A (i.e. SLURPAZ code) for variable definitions).
*
*Table 4.5: Corrected downstream (d/s) ASA by SLURPAZ.
*
<table>
<thead>
<tr>
<th>ASA</th>
<th>Actual d/s node (TOPAZ)</th>
<th>Corrected d/s node (SLURPAZ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>8</td>
<td>6</td>
<td>2</td>
</tr>
</tbody>
</table>

4.5 Running the Models

The flow chart in Figure 4.7 shows the order in which the TOPAZ modules and
SLURPAZ interface were executed. Prior to running the SLURP hydrologic model, the
temporary files (i.e. temp.cmd; temp.wts and temp.mor) produced by SLURPAZ are
changed to meaningful or representative names (e.g. Wolf500.cmd (i.e. simulation from
a CSA value of 500)). Also, the user must ensure that the flow data file (ASA00002.flo)
and the climate data files for each climate station (e.g. daily average temperatures; daily precipitation; global solar radiation; daily net radiation; daily dewpoint temperature) are situated in the running directory for the SLURP model. As well, the canopy properties, soil heat flux properties, snowmelt data and the ten hydrologic input parameters for each land cover that are produced in the .cmd file by default from SLURPAZ, are to be replaced by the values from the original data set derived by Li et al. (1997). Running SLURP ‘option 2’ (Compute ASA-average meteorological data from point station data) and the ‘option 1’ (Running the model) were the two final steps in executing all the models fully.

Figure 4.7: Execution sequence of TOPAZ and SLURPAZ.

Wolf Creek was subdivided into a variable number of sub-basins or ASAs by manipulating the CSA parameter in TOPAZ. TOPAZ also allows the MSCL to be
manipulated, however it was left constant for the purpose of this experiment. It was felt that with a MSCL of 100 metres, that this length was short enough to initiate a channel and thus varying the minimum area (i.e. CSA) would suffice in producing sub-basins of varying sizes and numbers. Each resulting set of TOPAZ output data was then processed by SLURPAZ to generate SLURP input files. To analyze the effects of varying sub-basin scale only, the ten hydrologic input parameters based on land covers (Table 4.6) and derived from Li et al. (1997) in previous work for this basin, were used and held constant to allow comparison of the effect varying sub-basin size had on the hydrological model output. This was essentially a ‘meteorologic forcing’ since these parameters more than likely vary with varying levels of detail.

SLURP was initially run for each automated generation using the original hydrologic parameter settings derived by Li et al. (1997) and leaving the input routing parameters of Alpha (α) and Beta (β) constant at 50 and 1 respectively (i.e. α=50, β=1; where the hydrograph is left unchanged). Afterwards, for each scale of parameterization, SLURP was run again while optimizing the routing parameters of Alpha and Beta only. These were optimized using the SCE-UA method with 1000 iterations at 50 steps. These are the maximum number (i.e. 1000) of optimization iterations to be used, and the number of steps (i.e. 50) is the amount of times the optimization technique should go through all the points before having to be re-shuffled and assembled into new sub-complexes (Kite, 1997).

The SLURP output results were then evaluated with the goal of determining the subdivision at which the best hydrological simulation was produced. This was done by comparing the selected SLURP outputs from the varying levels of subdivisions.

The ensuing comparisons followed (see Chapter 5):

- general basin characteristics at all scales;
• a comparative analysis, both with the routing parameters of Alpha and Beta 'non-optimized' and 'optimized', of the original manual method with 19 ASAs against one of the automated generations also having 19 ASAs;
• comparison of water balance components as the number of ASAs increases;
• runoff predictions at varying scales with both routing 'non-optimized' and 'optimized';
• one ASA with shortest possible channel versus longest possible channel;
• a sensitivity of Alpha and Beta routing parameters; and
• a comparison of optimal levels of subdivisions with previous research.

Table 4.6: Hydrological parameters (for each land cover) and routing parameters for each ASA in SLURP.

<table>
<thead>
<tr>
<th>No.</th>
<th>Parameter and coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Initial contents of snow store</td>
</tr>
<tr>
<td>2</td>
<td>Initial contents of slow store</td>
</tr>
<tr>
<td>3</td>
<td>Maximum infiltration rate</td>
</tr>
<tr>
<td>4</td>
<td>Manning roughness surface</td>
</tr>
<tr>
<td>5</td>
<td>Retention constant fast store</td>
</tr>
<tr>
<td>6</td>
<td>Maximum capacity of fast store</td>
</tr>
<tr>
<td>7</td>
<td>Retention constant slow store</td>
</tr>
<tr>
<td>8</td>
<td>Maximum capacity of slow store</td>
</tr>
<tr>
<td>9</td>
<td>Precipitation factor</td>
</tr>
<tr>
<td>10</td>
<td>Snow melt temperature</td>
</tr>
<tr>
<td>11</td>
<td>Alpha (α)</td>
</tr>
<tr>
<td>12</td>
<td>Beta (β)</td>
</tr>
</tbody>
</table>

Measuring the effectiveness of the simulations was done by comparing and contrasting some of the following measures of efficiency provided by SLURP: mean computed flow (m$^3$/s); ratio of the normalized computed discharge (i.e. computed vs. recorded); mean error (m$^3$/s); standard error (m$^3$/s); largest daily error (m$^3$/s); Nash/Sutcliffe criterion; Previous-Day criterion and deviation of volume.
CHAPTER 5
RESULTS AND DISCUSSION

5.1 General Basin Characteristics for All Scales

The subdivisions created by manipulating the CSA parameter in TOPAZ are displayed in Table 5.1. By varying this parameter from 18000 ha to 5 ha, ASAs vary in number from 1 to 1588, respectively. The mean area of the ASAs ranges from 183.3 to 0.12 km$^2$ with 1 to 1588 ASAs, respectively. Figure 5.1a and Figure 5.1b display some TOPAZ generated images of the ASAs and their corresponding networks. This portrays how varying the CSA parameter from a high value to a lower value will represent a drainage area from coarse to fine.

Some of the drainage network composition are listed in Table 5.1 for all scales. For each level of subdivision, the following variables are listed: highest Strahler order; total length of channels; mean length of channels; overall total drainage density; mean channel sinuosity; bifurcation ratio; length ratio and area ratio.

Strahler stream order is the most common approach to quantitatively describe stream networks (Strahler, 1952). Streams having no tributaries are assigned as 1st order streams; two 1st order streams form a 2nd order stream; two 2nd order streams form a 3rd order stream, and so on. When a higher order streams receives flow from a lower order stream, the order remains the same. The basin order (e.g. 3rd order basin) takes on the order of the stream at the outlet. The highest Strahler order listed in Table 5.1, is thus
the order of the basin as a whole for each scale. The orders range from 1 through 6, with the number of ASAs ranging from 1 through 1588, respectively. The ‘blue line’ stream network from the 1:50000 scale topographic maps gives the basin an order of 4. Thus, the generated scales with an order of 4, are said to be the most representative of the ‘blue line’ network from 1:50000 scale topographic maps.

Table 5.1: Drainage network composition for all scales (i.e. for all levels of detail).

<table>
<thead>
<tr>
<th># of ASAs</th>
<th>CSA Value (ha)</th>
<th>Mean Area per ASA (km²)</th>
<th>Highest Strahler Order</th>
<th>Total Length of Channels (km)</th>
<th>Mean Length of Channels (km)</th>
<th>Overall Total Drainage Density (1/km)</th>
<th>Mean Channel Sinuosity</th>
<th>Bifurcation Ratio</th>
<th>Length Ratio</th>
<th>Drainage Area Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18000</td>
<td>183.30</td>
<td>1</td>
<td>2.1</td>
<td>2.1</td>
<td>0.01</td>
<td>1.5</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>3</td>
<td>2500</td>
<td>61.10</td>
<td>2</td>
<td>33.2</td>
<td>7.7</td>
<td>0.18</td>
<td>1.4</td>
<td>3.0</td>
<td>6.3</td>
<td>3.2</td>
</tr>
<tr>
<td>5</td>
<td>2000</td>
<td>36.66</td>
<td>2</td>
<td>38.5</td>
<td>7.6</td>
<td>0.21</td>
<td>1.4</td>
<td>4.0</td>
<td>6.3</td>
<td>7.2</td>
</tr>
<tr>
<td>7</td>
<td>1000</td>
<td>26.19</td>
<td>2</td>
<td>53.0</td>
<td>7.6</td>
<td>0.29</td>
<td>1.4</td>
<td>4.0</td>
<td>6.3</td>
<td>11.2</td>
</tr>
<tr>
<td>11</td>
<td>750</td>
<td>16.66</td>
<td>2</td>
<td>59.1</td>
<td>5.4</td>
<td>0.32</td>
<td>1.3</td>
<td>6.0</td>
<td>5.3</td>
<td>9.3</td>
</tr>
<tr>
<td>15</td>
<td>600</td>
<td>12.22</td>
<td>2</td>
<td>66.3</td>
<td>4.4</td>
<td>0.36</td>
<td>1.3</td>
<td>8.0</td>
<td>5.7</td>
<td>12.9</td>
</tr>
<tr>
<td>17</td>
<td>500</td>
<td>10.78</td>
<td>2</td>
<td>71.2</td>
<td>4.2</td>
<td>0.39</td>
<td>1.3</td>
<td>9.0</td>
<td>6.3</td>
<td>12.9</td>
</tr>
<tr>
<td>19</td>
<td>400</td>
<td>9.65</td>
<td>3</td>
<td>76.8</td>
<td>4.5</td>
<td>0.42</td>
<td>1.3</td>
<td>3.5</td>
<td>1.2</td>
<td>3.5</td>
</tr>
<tr>
<td>33</td>
<td>250</td>
<td>5.55</td>
<td>3</td>
<td>90.8</td>
<td>2.8</td>
<td>0.50</td>
<td>1.2</td>
<td>4.3</td>
<td>3.0</td>
<td>5.3</td>
</tr>
<tr>
<td>77</td>
<td>100</td>
<td>2.38</td>
<td>4</td>
<td>122.4</td>
<td>1.6</td>
<td>0.67</td>
<td>1.2</td>
<td>3.6</td>
<td>2.3</td>
<td>4.0</td>
</tr>
<tr>
<td>162</td>
<td>50</td>
<td>1.13</td>
<td>4</td>
<td>169.2</td>
<td>1.0</td>
<td>0.92</td>
<td>1.1</td>
<td>4.4</td>
<td>2.9</td>
<td>5.2</td>
</tr>
<tr>
<td>308</td>
<td>25</td>
<td>0.60</td>
<td>4</td>
<td>236.2</td>
<td>0.8</td>
<td>1.29</td>
<td>1.1</td>
<td>5.8</td>
<td>2.8</td>
<td>5.9</td>
</tr>
<tr>
<td>413</td>
<td>20</td>
<td>0.44</td>
<td>4</td>
<td>265.0</td>
<td>0.6</td>
<td>1.45</td>
<td>1.1</td>
<td>6.2</td>
<td>3.0</td>
<td>6.6</td>
</tr>
<tr>
<td>447</td>
<td>18</td>
<td>0.41</td>
<td>5</td>
<td>278.0</td>
<td>0.6</td>
<td>1.52</td>
<td>1.1</td>
<td>4.1</td>
<td>2.2</td>
<td>4.4</td>
</tr>
<tr>
<td>525</td>
<td>15</td>
<td>0.35</td>
<td>5</td>
<td>307.6</td>
<td>0.6</td>
<td>1.68</td>
<td>1.1</td>
<td>4.3</td>
<td>2.2</td>
<td>4.5</td>
</tr>
<tr>
<td>571</td>
<td>14</td>
<td>0.32</td>
<td>5</td>
<td>321.4</td>
<td>0.6</td>
<td>1.75</td>
<td>1.1</td>
<td>4.5</td>
<td>2.1</td>
<td>4.5</td>
</tr>
<tr>
<td>615</td>
<td>13</td>
<td>0.30</td>
<td>5</td>
<td>337.2</td>
<td>0.5</td>
<td>1.84</td>
<td>1.1</td>
<td>4.6</td>
<td>2.1</td>
<td>4.6</td>
</tr>
<tr>
<td>682</td>
<td>12</td>
<td>0.27</td>
<td>5</td>
<td>356.1</td>
<td>0.5</td>
<td>1.94</td>
<td>1.1</td>
<td>4.8</td>
<td>2.1</td>
<td>4.7</td>
</tr>
<tr>
<td>744</td>
<td>11</td>
<td>0.25</td>
<td>5</td>
<td>375.1</td>
<td>0.5</td>
<td>2.05</td>
<td>1.1</td>
<td>4.9</td>
<td>2.0</td>
<td>4.7</td>
</tr>
<tr>
<td>824</td>
<td>10</td>
<td>0.22</td>
<td>5</td>
<td>398.7</td>
<td>0.5</td>
<td>2.18</td>
<td>1.1</td>
<td>4.6</td>
<td>2.3</td>
<td>5.0</td>
</tr>
<tr>
<td>1588</td>
<td>5</td>
<td>0.12</td>
<td>6</td>
<td>614.5</td>
<td>0.4</td>
<td>3.35</td>
<td>1.1</td>
<td>4.0</td>
<td>1.9</td>
<td>4.2</td>
</tr>
</tbody>
</table>

The total length of the channels is the length of all stream segments within the basin for that scale. From 1 ASA to 1588 ASA, the total lengths range from 2.1 km (i.e. CSA 18000) to 614.5 km (i.e. CSA 5), respectively. These values, along with total drainage areas, are used in determining the overall total drainage density for the basin. The mean channel length for generated scales of more than 1 ASA ranges from 11.1 km (i.e. CSA 2500) to 0.4 km (i.e. CSA 5), respectively. As can be seen in Figure 5.1a and Figure 5.1b, as there are more and more ASAs, the corresponding channel network also gets finer and finer (i.e. displays more detail).
Figure 5.1a: Example of ASAs and corresponding drainage networks from varying scales, 3 ASAs to 33 ASAs (1 cm equals approximately 3.7 km).
Figure 5.1b: Example of ASAs and corresponding drainage networks from varying scales, 77 ASAs to 308 ASAs (1 cm equals approximately 3.7 km).
The drainage density is defined as the total length of channels divided by the basin area. Drainage densities have been characterized by several researchers. Linsley et al. (1986) suggest that low drainage densities occur in soil materials that are resistant to erosion, very permeable areas and areas of low relief. They also suggest that high values tend to be associated with easily erodable soils or relatively impermeable soils, and with areas of high relief with sparse vegetation. Usually, high drainage density areas can also be associated with higher flood peaks and higher sediment yields (Dunne and Leopold, 1978). Values have been reported to range from less than 2 km\(^{-1}\) to over 100 km\(^{-1}\) (Dingman, 1994); and in some areas even up to 400 km\(^{-1}\) (Linsley et al., 1986). High densities reflect a highly dissected basin. In this study, from 1 ASA to 1588 ASAs, the drainage density ranges from 0.01 km\(^{-1}\) to 3.35 km\(^{-1}\), respectively. Although these values are low and situated within a high relief area, this is difficult to interpret in a meaningful way as the drainage density is manipulated by the user varying the CSA parameter.

Mean channel sinuosity reflects the mean channel length with respect to the valley length. For example, with a sinuosity of 1.5, the stream would be 1.5 times that of the valley length. The results indicate that at low numbers of ASAs the sinuosity is at its highest (i.e. 1.5), and with increasing numbers of ASAs the sinuosities decrease to about 1.1.

In given drainage areas, the number of streams, average lengths and average drainage areas for successive orders display certain consistent characteristics. These are deemed the ‘laws of drainage network composition’ (Knighton, 1998; Dingman, 1994). The bifurcation ratio (R\(_b\)), the length ratio (R\(_L\)) and drainage area ratio (R\(_A\)) are derived from the numbers (N\(_w\)), average lengths (L\(_w\)) and average drainage areas (A\(_w\)) of streams of each order. The law of stream orders (R\(_b\)) is represented inversely (i.e. decreasing number of streams with increasing stream order); and the laws of stream length (R\(_L\)) and drainage areas (R\(_A\)) are of direct form (i.e. mean stream lengths and drainage areas increase with increasing stream order). Logarithmic plots of N\(_w\), 1/L\(_w\) and 1/A\(_w\) tend to be linear in nature with increasing stream orders (Knighton, 1998; Dingman, 1994).
The bifurcation ratio is the ratio of the number of streams of any order to the number in the next highest order. When 3 or more orders appear, the bifurcation ratio is the average of all ratios. Generally, bifurcation ratios for an area remain around the same magnitude, and tend to range between 2 and 5 (Dingman, 1994; Linsley et al., 1986). This data sets shows for all scales that the bifurcation ratio ranges from 2 to 9. With a 2nd order basin, as the number of ASAs increase so does the number of 1st order streams, thus the bifurcation ratio increases from 2 to 9, with 3 ASAs to 17 ASAs, respectively. This trend is also apparent for 3rd, 4th, 5th and 6th order basins for these scales, except between 744 ASAs and 824 ASAs. This slight discrepancy is most likely due to complex node situations occurring at these scales. Also, variations within the same order basins are attributed to an ‘artificial elongation effect’ inherent in models such as TOPAZ. As the CSA value decreases, channels get longer and longer until the order changes. For example, exterior links or 1st order streams get longer, while 2nd order streams remain constant until sufficient numbers of streams appear to necessitate a change within the basin to the next highest order.

The length ratio represents the average length of streams of a particular order to that of the next lowest order. The usual range is between 1.5 and 3.5 (Horton, 1945). The range for this data set is between 1.2 and 6.3. The drainage area ratio is the average drainage area of streams of a particular order to that of the next lowest order. Typical ranges are between 3 and 6 (Schumm, 1956), and this data ranges between 3.2 and 12.9. Again, the higher values here, as CSA value decreases within a same order basin, are attributed to this ‘artificial elongation effect’ of the drainage network created from TOPAZ.

5.2 Original Manual Method vs. New Automated Method

A comparative analysis is presented of an earlier hydrological simulation, for which the physiographic parameters were derived manually using a GIS, with a hydrological
simulation of the same scale, where the physiographic parameters were derived automatically using TOPAZ/SLURPAZ. The automated derivation was based on a CSA value of 400 which yielded 19 ASAs; the same as the earlier, manual derivation of Li et al. (1997). The main purpose of this analysis was to determine if a hydrological simulation based on the new, automated segmentation and parameterization was comparable to a simulation based on the earlier, manual segmentation and parameterization.

The earlier work by Li et al. (1997) used a calibration period of September 1, 1994 to August 31, 1995; and a verification period of September 1, 1995 to August 31, 1996. During the calibration period, the ten hydrological parameters and coefficients, and the storage routing parameters of Alpha (α) and Beta (β) (Table 4.6), were optimized using the built-in Shuffled Complex Evolution global optimization method developed at the University of Arizona (SCE-UA) (Duan et al., 1994). The ten hydrological parameters and coefficients were then kept constant and used in the simulation based on the new automated segmentation and parameterization. The only parameters re-optimized using the SCE-UA method during the automated run, were Alpha (α) and Beta (β). These parameters are used for a hydrological storage routing method between ASAs (Kite, 1997).

Two comparisons were undertaken: first, one where the between-ASA routing parameters were not optimized for either the manual or automated run (Section 5.2.1); and secondly, a comparison where these between-ASA parameters of Alpha and Beta were optimized for both runs (Section 5.2.2). The simulations without optimization of the routing parameters were done initially to see immediate preliminary simulation results since optimizing for the routing parameters is quite time consuming. Optimizing the channel routing parameters however was deemed necessary to fine tune the model for channel characteristics. Although, the ten hydrological input parameters and coefficients remained constant for all runs, it was necessary to re-optimize the routing parameters for the automated run as the ASAs and network structure varied from the
manual run. Albeit that all the parameters, including the ten hydrological input parameters, are more than likely scale sensitive; but in order to try and concentrate this research only on the scaling effects from varying the size and number of the ASAs, as opposed to the sensitivities of the ten hydrologic input parameters, this study focussed only on optimizing for the channel routing parameters.

Figure 5.2 shows the Wolf Creek basin segmentation for the earlier, manual run (Li et al., 1997) and for the new, automated run using the CSA value of 400. Slight differences in the outline of the basin, its area and scale, arose from differences in the segmentation methods. Some ASAs for the automated segmentation are very small (i.e. they are made up of only a few cells). These small ASAs are generated by TOPAZ when two tributaries enter the main channel at close proximity to one another resulting in a small ASA along the main channel.

The SLURP model provides a number of indicators that can be used to assess model performance (See Section 2.7 and Kite (1997)). The ones used in this section and in the comparisons that will follow, are mean error, standard error, largest daily error, Nash/Sutcliffe criterion and previous-day criterion.

5.2.1 Non-Optimized Routing

Simulations based on the manual and automated segmentations were initially compared for the case where the ten hydrologic input parameters and coefficients were taken from Li et al. (1997) and the routing parameters were not optimized (i.e. Alpha=50; Beta=1). Results from both runs are displayed in Table 5.2 and Figure 5.3.
**A) Wolf Creek: Original Run with 19 ASAs**

**B) Wolf Creek: New Run with 19 ASAs**

**Figure 5.2:** 19 ASAs for Wolf Creek: (A) original manual method vs. (B) new automated method.
The normalized computed discharge (i.e. computed/observed discharge) for the manual run is 1.078, or an over-estimate of 7.8%; while for the automated run, the normalized computed discharge is 1.031, or an over-estimate of 3.1%. Relative to the manual run, the mean error, standard error and previous-day criterion of the automated run are slightly better; and the largest daily error slightly worse (i.e. is increased). The Nash/Sutcliffe criterion (where a perfect fit is 1.0) also improves (0.39 vs. 0.25) between the automated and manual runs; so to does the deviation of volume.

**Table 5.2**: Selected hydrological parameters: *non-optimized* routing - original manual method vs. new automated method.

<table>
<thead>
<tr>
<th>NON-OPTIMIZED ROUTING</th>
<th>Original Run</th>
<th>New Automated Run</th>
</tr>
</thead>
<tbody>
<tr>
<td>File Name:</td>
<td>SL1-1T3</td>
<td>400NT3</td>
</tr>
<tr>
<td>Summary statistics for Wolf Creek</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sept '94 to Aug '96</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CSA Value:</td>
<td>N/A</td>
<td>400</td>
</tr>
<tr>
<td>Number of ASAs:</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td>Mean computed flow, m³/s</td>
<td>0.5939</td>
<td>0.5681</td>
</tr>
<tr>
<td>Mean recorded flow, m³/s</td>
<td>0.5508</td>
<td>0.5508</td>
</tr>
<tr>
<td>Ratio of computed vs. recorded flow</td>
<td>1.078</td>
<td>1.031</td>
</tr>
<tr>
<td>Mean error, m³/s</td>
<td>0.043</td>
<td>0.017</td>
</tr>
<tr>
<td>Standard error, m³/s</td>
<td>0.75</td>
<td>0.68</td>
</tr>
<tr>
<td>Largest daily error, m³/s</td>
<td>8.21</td>
<td>8.32</td>
</tr>
<tr>
<td>Nash/Sutcliffe criterion (1)</td>
<td>0.25</td>
<td>0.39</td>
</tr>
<tr>
<td>Previous-Day criterion (1, or &gt;-1)</td>
<td>-5.56</td>
<td>-4.33</td>
</tr>
<tr>
<td>Deviation of volume, % (0)</td>
<td>-7.8</td>
<td>-3.1</td>
</tr>
</tbody>
</table>

### 5.2.2 Optimized Routing

The results presented in this research differ slightly from the earlier run by Li *et al.* (1997) due to some recent improvements made in the water balance components of the SLURP hydrological model. Li *et al.* (1997) used a previous version of the SLURP hydrologic model (i.e. version 10), where this research used a newer and improved
version of the model (i.e. version 11.1). Thus, their original data was reran using the newer version of the model. Simulations based on the manual and automated segmentations were compared for the case where the ten hydrologic input parameters and coefficients were taken from Li et al. (1997) and the routing parameters were optimized. Results from both runs are shown in Table 5.3 and Figure 5.4.

![Stream discharge hydrographs: original manual method vs. new automated method - non-optimized routing.](image)

**Figure 5.3:** Stream discharge hydrographs: original manual method vs. new automated method - *non-optimized* routing.

The normalized computed discharge (i.e. computed/recorded discharge) of the manual run is 1.076, or an over-estimate of 7.6%; while for the new automated run it is 1.029, or an over-estimate of 2.9%. The automated run, relative to the original run, has a slightly better mean error and largest daily error; and a slightly worse standard error and previous-day criterion. The Nash/Sutcliffe criterion (where a perfect fit is 1.0) is also
slightly worse (0.82 vs. 0.84), but the deviation of volume is better by 4.7%. Hydrological simulations using optimized routing parameters (i.e. computed flow (Qcomp)) also give better timing and hydrograph match with the recorded or observed flow (i.e. Qobs).

Table 5.3: Selected hydrological parameters: optimized routing - original manual method vs. new automated method.

<table>
<thead>
<tr>
<th>OPTIMIZED ROUTING</th>
<th>Original Run</th>
<th>New Automated Run</th>
</tr>
</thead>
<tbody>
<tr>
<td>File Name:</td>
<td>MAY2-2</td>
<td>400-1TST</td>
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<tr>
<td>Summary statistics for Wolf Creek</td>
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<tr>
<td>Sept '94 to Aug '96</td>
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<td></td>
</tr>
<tr>
<td>CSA Value:</td>
<td>N/A</td>
<td>400</td>
</tr>
<tr>
<td>Number of ASAs:</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td>Mean computed flow, m³/s</td>
<td>0.5927</td>
<td>0.5668</td>
</tr>
<tr>
<td>Mean recorded flow, m³/s</td>
<td>0.5508</td>
<td>0.5508</td>
</tr>
<tr>
<td>Ratio of computed vs. recorded flow</td>
<td>1.076</td>
<td>1.029</td>
</tr>
<tr>
<td>Mean error, m³/s</td>
<td>0.042</td>
<td>0.016</td>
</tr>
<tr>
<td>Standard error, m³/s</td>
<td>0.34</td>
<td>0.37</td>
</tr>
<tr>
<td>Largest daily error, m³/s</td>
<td>3.89</td>
<td>3.77</td>
</tr>
<tr>
<td>Nash/Sutcliffe criterion (1)</td>
<td>0.84</td>
<td>0.82</td>
</tr>
<tr>
<td>Previous-Day criterion (1, or &gt;-1)</td>
<td>-0.37</td>
<td>-0.59</td>
</tr>
<tr>
<td>Deviation of volume, % (0)</td>
<td>-7.6</td>
<td>-2.9</td>
</tr>
</tbody>
</table>

5.2.3 Summary

The hydrological simulation results are presented for both the calibration and verification period. The hydrographs of the simulations (i.e. for 'non-optimized' and 'optimized' routing) are quite good except for the first peak in the spring of 1996 (Figure 5.3 and 5.4). The model does not simulate the observed peak in late April of 1996 due to SLURP’s inability to model ice jam phenomena. This peak was not caused by
snowmelt or rainfall, but was an outburst flood due to breaking of an ice dam at the Coal Lake outlet (i.e. the main storage component for the basin) (Jasek and Ford, 1997).

Figure 5.4: Stream discharge hydrographs: original manual method vs. new automated method - optimized routing.

In general, outputs from the SLURP model are very similar when comparing the automated and manual runs. The results obtained using the automated segmentation and parameterization were at least as good, if not better, than those obtained using the manual method. Nevertheless, it would take a skilled operator several weeks to manually prepare and parameterize a drainage basin for input into the SLURP
hydrological model at only one scale or level of detail, the new automated techniques can generate SLURP input in only minutes. In the Wolf Creek case, for example, deriving 17 ASAs using TOPAZ, parameterizing those ASAs using SLURPAZ, and conducting a full SLURP simulation requires less than ten minutes.

5.3 Analysis of Varying Scales

Varying sub-basin scale showed interesting trends at two levels of detail. Looking closely at the variation in water balance components as the number of ASAs increases, reveals one scale effect (Section 5.3.1). The second trend of varying the number and size of ASAs is discussed in Section 5.3.2, where an optimal level of subdivision seems to be attained at a certain level of detail and any further subdivision does not enhance model performance significantly.

5.3.1 Water Balance Components

At low levels of detail (i.e. approximately 17 ASAs or less), the water balance components of precipitation, evapotranspiration, storage and computed flow fluctuate slightly.

This was attributed to variations in the areal weighting of time series climate input data with variation in number of ASAs. This is an issue because of the limited number of climate stations in an area of such high variability. A minimum number of ASA subdivisions is required to adequately represent the spatial variability of climatic input data.

In the Wolf Creek basin, the optimal point for the water balance components to be adequately represented is reached at around 20 ASAs, with each representing
approximately 9.2 km² or 5% of the total area (Figure 5.5). The water balance parameters remain constant with further subdivision of the watershed.

![Figure 5.5: Variation in water balance components for 1 to 33 ASAs.](image)

### 5.3.2 Runoff Prediction at Varying Scales

At a higher level of detail, results show that the degree of agreement between the selected indicators, for the 'non-optimized' routing, increases with increasing number of ASAs up to a certain threshold (Table 5.4(a)). Thereafter, further increase in number of ASAs does not substantially improve the agreement between these indicators.

This optimal number of subdivision seems to be reached at or near 525 ASAs (Figure 5.6). As the level of detail increases, the mean error, the standard error, the largest daily error, the Nash/Sutcliffe criterion and the previous day criterion vary minimally. From
this point on, with further subdivision of the basin, agreement between these indicators seems to level off as the number of ASAs increases.

For example, with the 'non-optimized' routing, from about 525 ASAs to 1588 ASAs (an increase of three-fold in number of ASAs), the mean error stays nearly constant (0.022 vs. 0.023); the standard error improves slightly from 0.42 to 0.38; the largest daily error also remains almost constant (3.74 vs. 3.77); the Nash/Sutcliffe improves from 0.76 to 0.81; and the previous day criteria improves slightly from -1.06 to -0.70 (Figure 5.6). The normalized computed discharge for 525 ASAs is 1.041, or overestimates by 4.1%; and the normalized computed discharge for 1588 ASAs is 1.042, or overestimates by 4.2%. Thus, with 525 ASAs, where each ASA represents on average approximately 0.35 km²/ASA or 0.2% of the total area, may suggest that this is the optimal level of subdivision required for a basin of this nature and size when no routing optimization takes place.

The 'optimized' routing runs present similar trends (Figure 5.7) as to be expected with optimization (i.e. as the model is fine tuned or 'tweaked' for varying channel slope characteristics). Slightly improved outputs occur earlier on in the scaling process (i.e. improved outputs are achieved sooner or with coarser subdivisions). Due to computer hardware capabilities and limited time, the optimizations were set to run at a maximum of 1000 iterations with 50 steps (i.e. where a criterion must change after x_number of steps). With these limits set, the model was able to find optimal Alpha and Beta parameters up to 162 ASAs. From this point on and up to 571 ASAs, only Beta was optimized; and beyond 571 ASAs, neither Alpha nor Beta were optimized (i.e. each remained with default values of Alpha=50 and Beta=1). In order to further optimize, these parameters would have to be increased, but due to the computer hardware limitations and time, this was not feasible for the purpose of this study.
As Table 5.4(b) and Figure 5.7 display, the 'optimized' routing runs achieve optimums at lower number of ASAs. The significant improvements, initially, are in the standard error, largest daily error and Nash/Sutcliffe criterion. It would seem that these indicators reach their optimums sooner, but, the same optimums are also reached at finer scales with the 'non-optimized' routing simulations. The mean error seems slightly better with the 'optimized' routing simulations; but the previous day criterion is the only one indicator that worsens with the 'optimized' routing. But, as mentioned in the SLURP
manual, this is the most difficult indicator to achieve a good value when calibrating (Kite, 1997).

![Computed vs Observed flow](image)
![Mean Error](image)
![Standard Error](image)
![Largest Daily Error](image)
![Non/Max effi](image)

**Figure 5.7:** Variations in selected SLURP indicators with number of ASAs: *optimized* routing vs. *non-optimized* routing.

At coarser scales (i.e. CSA 2500 with 3 ASAs) the mean channel length per ASA is around 11.1 km, whereas at finer scales (i.e. CSA 5 with 1588 ASAs) the mean channel length per ASA is approximately 0.4 km. Achieving optimums sooner at coarser scales with the optimized routing portrays an adjustment from the model with regards to storage influences. Thus, at the finer scales with the non-optimized routing, storage influences would appear to become insignificant. The stream hydrographs for a fine
level of subdivision (i.e. CSA (15)) and for a coarser level of subdivision (i.e. CSA (2500)) are shown in Figures 5.8 and 5.9 respectively for both ‘non-optimized’ and ‘optimized’ routing.

Figure 5.8: Stream discharge hydrographs: non-optimized vs. optimized routing with CSA 15 (i.e. fine).

5.3.3 One ASA: Shortest Possible Channel vs. Longest Possible Channel

As mentioned in Section 5.1 with the ‘artificial elongation effect’, the opposite holds true when the CSA parameter is continuously increased. As this occurs, overall channel
lengths and drainage densities decrease (Table 5.1). This portion of the research aims at evaluating the sensitivity of the SLURP hydrological model to a short channel versus a longer channel, when the basin as a whole is used as one ASA. In other words, this is testing SLURP's sensitivity to 'within-ASA' routing.

![Stream discharge hydrographs: non-optimized vs. optimized routing with CSA 2500 (i.e. coarse).](image)

**Figure 5.9:** Stream discharge hydrographs: *non-optimized* vs. *optimized* routing with CSA 2500 (i.e. coarse).

Table 5.4(a) list the indicators for one ASA with the CSA parameter varying from 18000 ha (i.e. short channel) to 2550 ha (i.e. long channel), and the stream hydrographs are
displayed in Figure 5.10. The normalized computed discharge for the short channel run is 1.013, or overestimates by 1.3%; and the longer channel’s normalized computed discharge is also 1.013, or overestimates by 1.35%. The indicators show the following trend when comparing the short channel to the long channel: the mean error remains constant at 0.007; the remaining indicators all worsen to some degree with the long channel: the standard error (0.56 vs. 0.73); the largest daily error (7.23 vs. 9.08); the Nash/Sutcliffe criterion (0.58 vs. 0.30) and the previous day criterion (-2.68 vs. -5.15).

The total routing time for ‘within-ASA’ routing (i.e. to-stream and downstream-to-ASA-outlet), in days, varies anywhere from 1 to 3, 4 or 5 and even 2 to 5 days for the short channel run and all other runs, including the longer channel run with 1 ASA, are 1 to 1 day total routing time. It is safe to assume that SLURP exhibits better ‘within-ASA’ routing when the routing time exceeds 1-day, since any travel times less than 1-day are rounded up to 1-day. This may be an explanation as to why the model’s response with one ASA and a short channel is better represented than that of one ASA with a longer channel.

The discrepancy may also be attributable to the fact that the 10 hydrological parameters used were those derived from the original run using 19 ASAs. Optimizing these input parameters at all scales would more than likely change the outputs of the simulations since their effects would vary with different levels of detail, indicating that these parameters are scale sensitive. Thus, it may not be appropriate to draw any concise conclusions with respect to this specific analysis without otherwise further testing the model’s sensitivities regarding these hydrological parameters.

5.3.4 Sensitivity of Alpha and Beta Routing Parameters

This portion of the research was deemed necessary to fully understand the influence of Alpha and Beta used with the ‘between-ASA’ storage routing method of SLURP. The
comparison was initially made using the first scale where both Alpha and Beta were no longer being optimized (i.e. CSA 13) using set parameters (i.e. 1000 iterations and 50 steps). Five additional simulations were produced using the maximums, minimums and mid-range values of each parameter (i.e. $A_{\text{max}} = 50$, $A_{\text{min}} = 0.2$; $B_{\text{max}} = 2.5$, $B_{\text{min}} = 0.9$) for all the ASAs. Secondly, additional simulations were produced at a coarser scale (i.e. CSA 2500), also in order to determine whether fluctuating these parameters had the same impact on the hydrographs.

![Diagram of stream discharge hydrographs](image)

**Figure 5.10:** Stream discharge hydrographs: one ASA – shortest possible channel vs. longest possible channel, non-optimized.
Table 5.4(a): Selected hydrological parameters: *non-optimized* routing.

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<th>2500NT3</th>
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<th>2500NT3</th>
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<th>400NT3</th>
<th>250NT3</th>
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<td>17</td>
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<td>0.5058</td>
<td>0.5058</td>
<td>0.5058</td>
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Table 5.4(b): Selected hydrological parameters: *optimized* routing.

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<td>0.5058</td>
<td>0.5058</td>
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**NON-OPTIMIZED ROUTING**

**OPTIMIZED ROUTING**
Using the indicators in determining the optimal simulation, proved to be difficult in arriving at a meaningful interpretation (Appendix D). Although, they do portray that the best representation for the fine simulation (i.e. CSA 13 with 615 ASAs) is the default (50,1) run; and for the coarse simulation (i.e. CSA 2500 with 3 ASAs), that the ‘optimized’ routing run is the best.

Appendix E displays the stream hydrographs for these simulations for April 1, 1995 to September 1, 1995. The finer runs (i.e. CSA 13 with 615 ASAs) do indicate changes in the lag time and attenuation of the hydrographs as to be expected. Understandably, the AmaxBmin and default (50,1) simulations (Appendix E(a)) are almost identical due to the closeness of the values. The AmaxBmax and AhlfBhlf (Appendix E(b)) show definite lag and attenuation; and the AminBmin and AminBmax (Appendix E(c)) display unrealistic lag times and attenuation since these values are being applied to all ASAs in a blanket format. This exercise strengthens the argument that at the finer scales, ‘between-ASA’ routing has less of an influence since the storage effect is practically absent; thus re-enforcing why the default run (i.e. Alpha=50; Beta=1) is the better simulation at this level of detail.

The coarser end of the spectrum (i.e. CSA 2500 with 3 ASAs) again acts in accordance with previous analogies where routing and storage effect play more of a pivotal role at this level of detail. The optimal run should prove to be the best run, and it does (Appendix D). Also, fluctuating Alpha and Beta at this scale with the values used displays changes that are more difficult to discern, but nonetheless, still changes affecting the lag time and attenuation in the same manner. At this level of detail, AmaxBmax, AmaxBmin, default (50,1) and AhlfBhlf are practically the same (Appendix E(d)); AminBmax is very close to the default (50,1) but ever so slightly under predicts with minimal delayed timing (Appendix E(e)); and AminBmin under predicts (Appendix E(e)).
5.3.5 Summary

The water balance components (i.e. precipitation, evapotranspiration, storage and computed flow) fluctuate initially from too coarse a subdivision for a basin of this characteristic (i.e. moderately steep). At the lower end or with coarser ASAs, it is necessary to have a sufficient number of ASAs to allow the spatial variability of climatic inputs to be adequately represented. It was found that this basin, having three meteorological stations situated within it, should be subdivided to 5% of the total area to adequately represent the water balance components. In other words, for Wolf Creek, it was necessary to have a minimum 20 ASAs to represent the water balance components adequately. This water balance optimum, is probably very much related to the relief of the basin. Perhaps in the prairies, water balance components may be represented at coarser levels of detail.

The next optimal level of subdivision for this basin occurs approximately where each ASA represents about 0.2% of the total area. This optimum, where model performance is no longer enhanced significantly after this point, takes place with routing ‘non-optimized’ using 500 ASAs giving results that are about the same as for the ‘optimized’ routing. When the routing parameters are ‘optimized’, the optimums reach the same levels as with the ‘non-optimized’ routing simulations, but sooner or, in other words, at a coarser level of subdivision. This suggests that the optimized runs seem to fine tune the model for channel characteristics and thus adjust for storage influences. This scaling relationship for Wolf Creek is most likely attributable to the basin’s own physiography and hypsometry. This higher end threshold, determined without having the between-ASA routing parameters optimized, is representative of the required segmentation needed to adequately account for storage influences. In other words, at this level of detail, it can be assumed that hydrological storage routing influences no longer have an impact on the performance of the hydrological model. If the opportunity exists to allow for a watershed to be subdivided to a level of detail fine enough, then the opportunity
exists to produce results just as good as those with coarser levels of subdivisions with the routing optimized.

The optimum threshold seems to be reached where each ASA has an approximate channel length of 600 metres. This may be viewed as a ‘critical reach length’ where SLURP, operating on a daily time step, is no longer affected by attenuation (i.e. storage influence). Perhaps if SLURP used a smaller time step (e.g. hourly), a different optimum would be attained. Also, as discussed in Section 5.4, it may be that at this level of detail, variance of the hydrologic input parameters is adequately considered with negligible storage influences. This can also be linked with the ‘optimized’ routing simulations, where optimum values of Alpha and Beta are no longer reached (i.e. with the iterations and steps selected) beyond 600 ASAs.

The next segment of this research aimed at evaluating the SLURP hydrological models sensitivity to a short channel versus a long channel with the basin as a whole being used as one ASA. It was found that the model’s performance increased with the short channel simulation versus the long channel simulation. This seemed to be a result of the model’s ability to better exhibit ‘within-ASA’ routing when travel times exceeded 1-day, since the model rounds up any travel time less than a day to 1-day.

The final portion of this research was aimed at evaluating the sensitivity of the Alpha and Beta routing parameters. These parameters are used in the ‘between-ASA’ storage routing method of the SLURP hydrological model. This evaluation also displayed that at finer scales, the ‘between-ASA’ routing played less of a role due to the absence of the storage effect. This portion of the study also portrayed that a coarser levels of detail, the routing and storage effects are more significant.
5.4 Comparison of Optimal Levels of Subdivisions with Previous Research

This section compares optimum segmentations or scales found in previous research to those found in this research. Table 5.5 and Figure 5.11 present the optimal sub-basin size determined in this research and in studies by Wood et al. (1988; 1990), Wood (1995) and Song and James (1992). Both this research and that of Wood et al. (1988; 1990) and Wood (1995) used 30 metre DEMs to derive sub-basins. Song and James (1992) seem to have derived sub-areas manually and the mean sub-basin areas in pixels presented in Table 5.5 were calculated assuming a 30 metre mesh was used.

<table>
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<th>Table 5.5: Comparison of optimums.</th>
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<td>WB (Water Balance components)</td>
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<td>Overall (overall model performance)</td>
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<tr>
<td>Wood et al. (1988; 1990); Wood (1995)</td>
</tr>
<tr>
<td>REA (Representative Elementary Area)</td>
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<td>Song and James (1992)</td>
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<tr>
<td>VS (Very Steep)</td>
</tr>
<tr>
<td>MS (Moderately Steep)</td>
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<td>GR (Gently Rolling)</td>
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</table>

Wood (1995: 335) has also stated that research up to that point has shown that the REA scale for catchment modelling, has ranged anywhere from 0.1 to 25 km$^2$. This large range is likely attributable to various processes varying at different spatial scales and to parameters varying temporally (Wood, 1995). Expressed as percentages with respect to the individual basins, the percentages found in this research for the water balance components fall within the ranges mentioned by Wood et al. (1988; 1990), Wood (1995) and Song and James (1992).
It seems that if the Wolf Creek basin is considered a moderately steep catchment, then the findings of this research are consistent with those of Song and James (1992) for a watershed of similar physiography. Since the overall optimum found in this research (~500 ASAs) is within the finer scales of Wood et al. (1988; 1990) and Wood (1995), it would seem that the variability associated with hydrological variables at this level of detail is being considered appropriately.

**Figure 5.11:** Comparison of optimums (abbreviations correspond to those in Table 5.5).

It was also of interest to examine the grid cell size of the DEM used in this study in the context of the findings of Garbrecht and Martz (1994). They suggest that to obtain about 10% accuracy in reproducing drainage features, the input DEM should have a grid cell size of 5% or less of the average area draining into a channel link. For example, using the 'overall' findings from this research, 5% of the average ASA size at this level of detail is ~0.02 km², which is still much larger than the cell area used (i.e. 0.0009 km²). This suggests that important drainage features are represented to within an accuracy of 10% in this study. The thresholds recognized in this research don't seem to be related to
the level of detail at which we are representing topography (i.e. cell size). Garbrecht and Martz (1994) suggest that with a 30 metre DEM we should still be able to measure network parameters with an accuracy of +/- 10% for up to around 10183 ASAs for this basin.

The average size of land cover area units (or polygons) was compared to the average ASA size at the overall optimum number of ASAs to determine whether land cover controlled model performance. The average area of land cover was around 0.025 km$^2$ (with a standard deviation of +/- 0.516 km$^2$); and the median was 0.002 km$^2$. The average land cover area is much smaller than the average ASA size at the optimum number of ASAs (0.025 km$^2$ vs. 0.37 km$^2$) and also very skewed. Thus, it would seem that the model performance is not determined or controlled by the land cover pattern in this study.
Automated parameterization provides a viable basis for in-depth scaling studies. The use of TOPAZ to provide physiographic parameters for the SLURP hydrological model has the attraction of reducing the cost and time required for parameterization. Both the manual and automated methods of deriving physiographic parameters for inputs to a hydrological model provide equally good results, but the time associated with the manual derivation far exceeds that of the automated method. Thus, the SLURPAZ interface allows for the smooth interaction between TOPAZ and SLURP.

It is necessary to have sufficient number of ASAs to allow the spatial variability of climatic inputs to be adequately represented (e.g. ~20 ASAs for Wolf Creek). This corresponds with the findings in previous research by Wood et al. (1988; 1990), Wood (1995) and Song and James (1992) where sub-areas should be subdivided to about 5% of the total area. Also, results in this research continue to improve as the number of ASAs increases with the ‘non-optimized” routing simulations, up to some threshold (e.g. ~500 ASAs for Wolf Creek). This also corresponds with the REA concept established by Wood et al. (1988; 1990) and Wood (1995) where the variance of the input parameters are being considered in a suitable manner allowing for storage influences to be neglected.

These tools have aided in the long term research goals to examine the spatial scale or level of detail with which sub-basins must be represented for significant processes to be
adequately simulated in hydrological models. The application of these techniques in the field of hydrological modelling will facilitate flood forecasting and flow prediction endeavors for hydrologists and water resources engineers.

These tools can also benefit hydrologists and water resources engineers in the rapid parameterization of watersheds where GIS derived data are not readily available. Such parameterization will allow them to quickly model areas of significant potential hydrological concern. For flow predictions and flood forecasting endeavors, such tools will provide speedier and more accurate parameterization of semi-distributed hydrologic models. Therefore, as mentioned by Tribe (1992), automated physiographic parameterization offers the advantages of speed, precision and reproducibility in drainage basin analyses.

The automated parameterization method also opened up the possibilities of scaling analyses to take place in a reasonable amount of time. With the development of SLURPAZ as an interface between these two models, scaling analyses in hydrological modelling was able to achieve a new level.

6.1 Limitations

The accuracy of the DEM is limited to that of the digitizer himself and to that of the 1:50000 scale maps from which the DEM was digitized. But, as mentioned earlier (Section 4.1.2), for the purpose of this research, due to the availability of 1:50000 source maps and budgetary and time constraints, this manual digitizing was the next best alternative. Also, a limitation of TOPAZ at the moment is its inability to ‘force’ outlets for specific ASAs. This would be a useful asset to TOPAZ when several hydrometric stations are available within a research basin.
Regarding the length of the calibration period (i.e. 1-year) and that of the verification period (i.e. also 1-year), it would be preferable to be able to simulate this basin for a longer period of time. But due to the recent timing of this research area and since this time frame was also the one used in the original research by Li et al. (1997), this was the only time frame usable for this scaling research. Also, due to the varying spatial characteristics of this basin, it may be suitable to add climate stations in the basin in order to allow for a more suitable representation of climatic variables. Additionally, since the 10 hydrologic parameters were optimized at a specific scale (i.e. 19 ASAs) in the original work by Li et al. (1997), one should perhaps consider the variance of these parameters with varying scales and determine at which scale they may be adequately optimized or derived; and/or if the parameters would significantly change if optimized from the automated generation having the same level of detail as in the original work. It may be of interest to evaluate the hydrological model’s performance if it were to be calibrated at each scale or level of detail.

6.2 Recommendations for Future Research

Further research to strengthen scaling analyses should examine varying DEM grid sizes, basins of varying sizes and basins in various geographic areas. Other potential research paralleling this one would be to re-run all the simulations using the Muskingum-Cunge between-ASA routing option while associating channel characteristics to Strahler stream order. This would allow the potential to associate channel characteristics (e.g. stream width, depth and roughness) and their variations, with regards to routing between sub-basins. Using the Muskingum-Cunge routing would also allow a comparison with the Storage routing option of SLURP to compare whether or not similar thresholds exist in the hydrological model’s response. Other potential research could be to evaluate SLURP outputs (e.g. water balance components) for each ASAs at all scales or levels of detail, and determining or associating those relationships with that of the REA concept.
REFERENCES


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Janowicz, R., 1999. Personal communication. Water Resources Division, Indian and Northern Affairs Canada (INAC), Whitehorse, Yukon, Canada.


Appendix A

SLURPAZ code
Program for linking TOPAZ with SLURP
by Martin Lacroix and Lawrence Martz
Last Update: March 27, 1998

Program written and copyrighted by: Mr. Martin Lacroix and
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Slurpaz is an interface (written in FORTRAN 90) between the TOPAZ
version 1.20 (TOpographic Parameterization) (Martz & Garbrecht,
1992; Garbrecht & Martz, 1995) digital landscape analysis model
and the SLURP version 1.1 (Kite, 1997) hydrological model.

TOPAZ processes a raster digital elevation model (DEM) to derive a
wide range of topographic and topologic variables that are physically
meaningful to watershed runoff processes. These variables are output
in both tabular and raster formats.

The SLURPAZ interface processes the physiographic outputs from TOPAZ,
a raster of land cover data and the original DEM into a SLURP command
file (.CMD).

The following TOPAZ outputs are processed by SLURPAZ to build the
SLURP command file (.CMD):

OUTCNT.UNF: General TOPAZ parameters (DEDNM/RASBIN/RASPRO/RASPROX)
NETW.TAB: Table of channel link properties (DEDNM)
SBCT.TAB: Table of subcatchment properties (DEDNM)
SUBWTB.OUT: Aggregated subcatchments for each channel link (RASPRO)
DISTCH.OUT: Raster of distances to nearest channel (RASPROX)
DISTSO.OUT: Raster of distances to ASA outlet (RASPROX)
RELIEF.OUT: Raster of relief corrected DEM elevations (DEDNM)
DZCH.OUT: Raster of change in elevation to nearest channel
DZSO.OUT: Raster of change in elevation to ASA outlet (RASPROX)
NETWB.TAB: Channel link properties for the binary drainage
network (RASBIN)

The following ASCII files are also required by SLURPAZ as inputs:

LCLASS.INP: Raster of land cover classifications
ORDPM.INP: Input file assigning stream order values to variables
ROUGH, WIDTH, DEPTH, ALPHA and BETA
CLMSTNS.INP: Input file with climate station number, name, easting,
northing, elevation and mean annual precipitation

SLURPAZ used the CLMSTNS.INP to calculate the influence of individual
climate stations on each cell of the raster in order to create the
.WTS file (ie file containing weights used to compute ASA-average
meteorological data from point station data and to correct temperature
and dewpoint temperature for differences in elevation).

=======================================================================
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
* THE FOLLOWING PARAMETER STATEMENT IS EXTRACTED FROM TOPAZ 1.20 AND
* SETS THE PARAMETER VALUES REQUIRED BY TOPAZ 1.20.
* DO NOT CHANGE THESE PARAMETERS!
PARAMETER (IOPS = 80, IORD = 10, NMD = 10, INCD = 5)
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
=======================================================================

* Initial variable and array declarations
* Dimension fixed arrays

* ORDPM: Array assigning stream order values to variables ROUGH, WIDTH, DEPTH, ALPHA and BETA

  dimension ordpm (25,5)

* Definition of ALLOCATABLE arrays

  isub2 = array of ASA values
  tmp = temporary array for: DISTCH.OUT, RELIEF.OUT, DZCH.OUT
  tmpl = temporary array for: DISTSO.OUT, DZSO.OUT (to correct SO errors from previous versions)
  lc = array of land cover values
  rows_sum = sum of rows by ASA (row #)
  rows_mn = mean of rows by ASA (row #)
  cols_sum = sum of columns by ASA (col #)
  cols_mn = mean of columns by ASA (col #)
  z_asa_sum = sum of z by ASA (metres)
  z_asa_mn = mean of z by ASA (metres)
  len_strm = channel length by ASA (cells)
  dz_strm = delta z along main channel of ASA (metres)
  asa = ASA # (node index #)
  next_asa = next ASA downstream (node index #)
  area_asa = ASA area (cells)
  order = Strahler stream order
  ex_seq = execution sequence number (ie from upstream to downstream)
  carr3 = character array used to write out land cover properties by number of land covers in .cmd file (G. Kite/B. Li, Aug '97)
  z_lc_sum = sum of elevations by landcover, by ASA (metres)
  z_lc_mn = mean of elevations by landcover, by ASA (metres)
  min_d_ch = minimum distance to nearest channel by LC, by ASA (cells)
  max_d_ch = maximum distance to nearest channel by LC, by ASA (cells)
  min_d_so = minimum distance to ASA outlet by LC, by ASA (cells)
  max_d_so = maximum distance to ASA outlet by LC, by ASA (cells)
  dz_ch_sm = sum of delta z to nearest channel by LC, by ASA (metres)
  dz_ch_mn = mean of delta z to nearest channel by LC, by ASA (metres)
  dz_so_sm = sum of delta z to ASA outlet by LC, by ASA (metres)
  dz_so_mn = mean of delta z to ASA outlet by LC, by ASA (metres)
  area_lc = area of LC by ASA (cells)
  pcent_lc = INTEGER percent of LC by ASA (%) 
  d_ch_sum = sum of distances to channel by LC, by ASA (cells)
  d_ch_mn = mean of distances to channel by LC, by ASA (cells)
  d_ch_dev = sum of deviations (squared) of distances to channel (cells)
  d_ch_sd = standard deviations to channel by LC, by ASA (cells)
  d_so_sum = sum of distances to ASA outlet by LC, by ASA (cells)
  d_so_mn = mean of distances to ASA outlet by LC, by ASA (cells)
  d_so_dev = sum of deviations (squared) of distances to outlet (cells)
  d_so_sd = standard deviations to channel by LC, by ASA (cells)

  NOTE: following two variables used in calculations for deriving means and standard deviations for distances to channels and distances to ASA outlets: distance classes set by D.CL_MAX (range for channels is set by RANGE.CH, and range for ASA outlets is set by RANGE.SO)

  d_cl_ch = distance class widths to channel (25 class widths)
  d_cl_so = distance class widths to outlet (25 class widths)

* Declare ALLOCATABLE arrays
Two-dimensional variable arrays (NROW, NCOL)
(Used for ASA values (ISUB2); for land cover values (LC); and to temporarily store other arrays of the same grid size (TMP); TMP1
used for SO correction from previous versions)

integer*4, allocatable:: isub2 (:,:)
integer*4, allocatable:: tmp (:,:)
integer*4, allocatable:: tmp1 (:,:)
integer*1, allocatable:: lc (:,:)

One-dimensional variable arrays (NUMASA)

integer, allocatable:: rows_sum (:)
real, allocatable:: rows_mn (:)
integer, allocatable:: cols_sum (:)
real, allocatable:: cols_mn (:)
real, allocatable:: z_asa_sum (:)
real, allocatable:: z_asa_mn (:)
real, allocatable:: len_strm (:)
real, allocatable:: dz_strm (:)
integer, allocatable:: asa (:)
integer, allocatable:: next_asa (:)
integer, allocatable:: area_asa (:)
integer, allocatable:: order (:)
integer, allocatable:: ex_seq (:)

One-dimensional variable arrays (NUMLC)

character*10, allocatable:: carr3 (:)

Two-dimensional variable arrays (NUMASA, NUMLC)

real, allocatable:: z_lc_sum (:,:)
real, allocatable:: z_lc_mn (:,:)
real, allocatable:: min_d_ch (:,:)
real, allocatable:: max_d_ch (:,:)
real, allocatable:: min_d_so (:,:)
real, allocatable:: max_d_so (:,:)
real, allocatable:: dz_ch_sm (:,:)
real, allocatable:: dz_ch_mn (:,:)
real, allocatable:: dz_so_sm (:,:)
real, allocatable:: dz_so_mn (:,:)
integer, allocatable:: area_lc (:,:)
integer, allocatable:: pcent_lc (:,:)
real, allocatable:: d_ch_sum (:,:)
real, allocatable:: d_ch_mn (:,:)
real, allocatable:: d_ch_dev (:,:)
real, allocatable:: d_ch_sd (:,:)
real, allocatable:: d_so_sum (:,:)
real, allocatable:: d_so_mn (:,:)
real, allocatable:: d_so_dev (:,:)
real, allocatable:: d_so_sd (:,:)

Three-dimensional variable arrays (NUMASA, D_CL_MAX, NUMLC)

real, allocatable:: d_cl_ch (:,:,:)
real, allocatable:: d_cl_so (:,:,:)

Definition of ALLOCATABLE array used to compute .WTS file

xstns = counts number of climate stations used within an ASA
for .WTS file

stnumbr = climate station number (CLMSTNS.INP)
stname = climate station name (CLMSTNS.INP)
easting = climate station easting (CLMSTNS.INP)
northing = climate station northing (CLMSTNS.INP)
elev = climate station elevation in metres (CLMSTNS.INP)
mmannpccp = climate station mean annual precipitation (CLMSTNS.INP)
wts = array used to calculate weight of climate stations by ASA
nnstns = array of total climate stations by number by ASA
Declare ALLOCATABLE arrays used in calculating .WTS file

1) One-dimensional variable arrays (NUM_ASA)
   integer, allocatable:: xstns (:)

2) One-dimensional variable arrays (NSTAT)
   integer, allocatable:: stnnbr (:)
   character*8, allocatable:: stnname (:)
   real, allocatable:: easting (:)
   real, allocatable:: northing (:)
   real, allocatable:: elev (:)
   real, allocatable:: mnannpcp (:)

3) Two-dimensional variable arrays (NUM_ASA, NSTAT)
   integer, allocatable:: wts (:,:) 
   integer, allocatable:: nnstns (:,)

Definition of variables used as CONSTANTS throughout the program

TOPAZ variables used in SLURPAZ:

NUM_ASA: # of ASAs
CELL_M: cell size in metres
MAX_Y: maximum UTM NORTING (ie max row)
MIN_X: minimum UTM EASTING (ie max col)
NROW: # of rows
NCOL: # of cols

**NOTE: NUM_ASA is dependent on TOPAZ runs with varying CSA and MSCL values.**

TOPAZ variables converted to SLURP units:

CELL_KM: cell size in km
CEL_AREA: cell area in square km

Variables that are CONSTANT within the program (ie can only be changed in the code itself and recompiled)

D_CL_MAX: maximum number of distance class widths (set at 25)
RANGE_CH: class width for distances to channel (set at 10*cell_m)
RANGE_SO: class width for distances to ASA outlets (set at 30*cell_m)
FLPSE_RT: 0.75
FPCP_RT: 5.0

**NOTE: the user can change the LAPSE RATE (FLPSE_RT) and the PRECIPITATION RATE (FPCP_RT) in the code but would have to re-compile the program; or these rates can be adjusted via SLURP OPTION 2.**

User supplied variables:

NUM_LC: number of land covers used in LCLASS.INP
ROUGH: Strahler stream order value (ORDER)
WIDTH: Strahler stream order value (ORDER)
DEPTH: Strahler stream order value (ORDER)
ALPHA: 50
BETA: 1

**NOTE: NUM_LC will depend on the number of land covers used in LCLASS.INP (has to start from 1, i.e. lc(1), lc(2), ...); and ROUGH, WIDTH, DEPTH, ALPHA and BETA can be modified in the ORDPM.INP file or via SLURP OPTION 2.**

Declaration of misc variables
integer d_cl_max, asa_act, nstat
integer sumwts, max, sav
real sumcpp

C UTM conversion program: variable declaration
integer*2 nad, deg, zone
real*8 east, north, cmerid, lon, lat

* CARR2 : character array used to print out last line of optimization
* parameters in .cmd file (G. Kite & B. Li, Jul '97)
* *-----------------------------------------------------------------------
* * CARR2 : character array used to print out last line of optimization
* parameters in .cmd file (G. Kite & B. Li, Jul '97)
* *-----------------------------------------------------------------------
* THE FOLLOWING CODE IS EXTRACTED FROM THE TOPAZ SUBROUTINE IOCNT
* AND IS USED TO READ JOB CONTROL INFORMATION FROM THE TOPAZ OUTPUT FILE
* OUTCNT.UNF
* *
* VERSION 1.02: 11 JANUARY 1996
* *
* COMMON /CNT1/
* **** VARIABLES ORIGINATED FROM MODULE DEDNM:
* + IRSV, ICSV, IASV, ICHSV, IORDV, IOPSV, NMDV, INCDV, ICLSV,
* + KLOCK(8), IKD(9, 2), IMDL(NMD),
* + IUTMZ, IUTMX, IUTMY, VLPIX, APIX, IGOR,
* + NROW, NCOL, NROWI, NCOLI, NNODE, IDR, IDC, IDRI, IDC1,
* + ELMIN, ELMAX, IELMI, IELMAI, IELMIN, IELMAX,
* + VELMAX, VELMIN, JELMAX, JELMIN, IUND, VUND, IUNDT, INDELT,
* + IOP7(IOPS), NTIM, IW1, IW2, IW3,
* + ARMIN(INCD), DISMIN(INCD), ITSHLD(INCD),
* + IFRMEL, ICNTC, ICAOUT, ICadem, MAXNOD, ISBMAX, NSTOR,
* **** VARIABLES ORIGINATED FROM MODULE RASBIN:
* + ICHSV, NORDBN, IOUTJC, ITRITB, ITRIBB(IORD), ITRBTT,
* **** VARIABLES ORIGINATED FROM MODULE RASPRO:
* + ISFMIN, ISFMAX, ISHMIN, ISHMAX, ISTMIN, ISTMAX
* COMMON /CNT2/ TITLE1, TITLE2, TITLE3
* *
* DOUBLE PRECISION VELMAX, VELMIN
* *
* CHARACTER*79 TITLE1, TITLE2, TITLE3
* *
* OPEN I/O FILE.
* WRITE/READ ALL VARIABLES IN COMMON BLOCK /CNT1/ AND COMMON BLOCK/CNT2/
* FROM/TO UNFORMATTED SEQUENTIAL FILE OUTCNT.UNF.
* *
* OPEN (UNIT = 34, FILE = 'OUTCNT.UNF', STATUS = 'OLD',
* + ACCESS = 'SEQUENTIAL', FORM = 'UNFORMATTED')
* *
* IRCNM = 1
* READ (34, ERR=110, END=120)
* + IRSV, ICSV, IASV, ICHSV, IORDV, IOPSV, NMDV, INCDV,
* + ICLSV, KLOCK, IKD, IMDL,
* + IUTMZ, IUTMX, IUTMY, VLPIX, APIX, IGOR,
* + NROW, NCOL, NROWI, NCOLI, NNODE, IDR, IDC, IDRI, IDC1,
* + ELMIN, ELMAX, IELMI, IELMAI, IELMIN, IELMAX,
* + VELMAX, VELMIN, JELMAX, JELMIN, IUND, VUND, IUNDT, INDELT,
* + IOP7, NTIM, IW1, IW2, IW3, ARMIN, DISMIN, ITSHLD,
* + IFRMEL, ICNTC, ICAOUT, ICadem, MAXNOD, ISBMAX, NSTOR
* IRCNM = IRCNM + 1
* READ (34, ERR=110, END=120)
* + ICHSV, NORDBN, IOUTJC, ITRITB, ITRIBB, ITRBTT
* IRCNM = IRCNM + 1
* READ (34, ERR=110, END=120)
* + ISFMIN, ISFMAX, ISHMIN, ISHMAX, ISTMIN, ISTMAX
* IRCNM = IRCNM + 1
* READ (34, ERR=110, END=120)
* + TITLE1, TITLE2, TITLE3
* CLOSE (UNIT = 34)
* *
* THE PRECEDING CODE IS EXTRACTED FROM THE TOPAZ SUBROUTINE IOCNT
* *
* - 117 -
* Assign values to local variables:
*---------------------------------------------------------------*

* NOPRINT variables controls whether or not to print out .TXT files that
  contain global variable listings and frequency distribution analysis
  results. The default is not to print out these text files. This can be
  turned on by changing NOPRINT to 0 (zero) and recompiling the program.
*---------------------------------------------------------------*

NOPRINT=1
* TOPAZ variables used in SLURPAZ
* num_asa = MAXNOD
  cell_m = VLPIX
  max_y = IUTMY
  min_x = IUTMX
*---------------------------------------------------------------*

* TOPAZ variables converted to SLURP units
*---------------------------------------------------------------*

cell_km = cell_m/1000
cel_area = cell_km**2
*---------------------------------------------------------------*

Distance class widths used for frequency distribution analysis of
distances to channels and distances to ASA outlets
*---------------------------------------------------------------*

d_cl_max = 25
range_ch = 10*cell_m
range_so = 30*cell_m
*---------------------------------------------------------------*

* Prompts user for number of land classes (num_lc) in LCLASS.INP
*---------------------------------------------------------------*

write (*,*), 'Please enter number of LAND COVERS used in LCLASS', +' and press ENTER'
read (*,*) num lc
write (*,*), ' '*

* IF statement checks if num lc equals zero; if yes program ends; if no
  * program continues normally
*---------------------------------------------------------------*

if (num lc.eq.0) then
  goto 10
else
  goto 20
endif
*---------------------------------------------------------------*

10  write (*,*), '!!!!Cannot have 0 value for NUM LC!!!!', +' ...Range has to be between 1 and number of land covers', +' in LCLASS.INP...'
  stop
*---------------------------------------------------------------*

20  continue
*---------------------------------------------------------------*

* Dynamic Memory allocation for arrays
*---------------------------------------------------------------*

allocate (isub2 (nrow,ncol))
allocate (lc (nrow, ncol))
allocate (tmp (nrow, ncol))
allocate (tmp1 (nrow, ncol))

allocate (rows_sum (num_asa))
allocate (rows_mn (num_asa))
allocate (cols_sum (num_asa))
allocate (cols_mn (num_asa))
allocate (z_asa_sum (num_asa))
allocate (z_asa_mn (num_asa))
allocate (len_strm (num_asa))
allocate (dz_strm (num_asa))
allocate (asa (num_asa))
allocate (next_asa (num_asa))
allocate (area_asa (num_asa))
allocate (order (num_asa))
allocate (ex_seq (num_asa))

allocate (carr3 (num_lc))
allocate (z lc_sum (num_asa, num_lc))
allocate (z lc_mn (num_asa, num_lc))
allocate (min_d_ch (num_asa, num_lc))
allocate (max_d_ch (num_asa, num_lc))
allocate (min_d_so (num_asa, num_lc))
allocate (max_d_so (num_asa, num_lc))
allocate (dz_ch_sm (num_asa, num_lc))
allocate (dz_ch_mn (num_asa, num_lc))
allocate (dz_so_sm (num_asa, num_lc))
allocate (dz_so_mn (num_asa, num_lc))
allocate (area lc (num_asa, num_lc))
allocate (pcent lc (num_asa, num_lc))
allocate (d ch_sum (num_asa, num_lc))
allocate (d ch_mn (num_asa, num_lc))
allocate (d ch_dev (num_asa, num_lc))
allocate (d ch_sd (num_asa, num_lc))
allocate (d so_sum (num_asa, num_lc))
allocate (d so_mn (num_asa, num_lc))
allocate (d so_dev (num_asa, num_lc))
allocate (d so_sd (num_asa, num_lc))

allocate (d cl_ch (num_asa, d cl_max, num_lc))
allocate (d cl_so (num_asa, d cl_max, num_lc))

* Initialize arrays to zero
* 1) Arrays by NUM_ASA
*  
do 50 i=1,num_asa
rows_sum (i) = 0
rows_mn (i) = 0
cols_sum (i) = 0
cols_mn (i) = 0
z_asa_sum(i) = 0
z_asa_mn (i) = 0
len_strm (i) = 0
dz_strm (i) = 0
asa (i) = 0
next_asa (i) = 0
area_asa (i) = 0
order (i) = 0
ex_seq (i) = 0
* 2) Arrays by NUM_ASA & NUM_LC
*  
do 40 j=1,num_lc
z lc_sum(i,j) = 0
z lc_mn (i,j) = 0
min_d_ch(i,j) = 0
max_d_ch(i,j) = 0
min_d_so(i,j) = 0
max_d_so(i,j) = 0
dz_ch_sm(i,j) = 0
dz_ch_mn(i,j) = 0
dz_so_sm(i,j) = 0
dz_so_mn(i,j) = 0
area_lc (i,j) = 0
pcnt_lc(i,j) = 0
d_ch_sum(i,j) = 0
d_ch_mn (i,j) = 0
d_ch_dev(i,j) = 0
d_ch_sd (i,j) = 0
d_so_sum(i,j) = 0
d_so_mn (i,j) = 0
d_so_dev(i,j) = 0
d_so_sd (i,j) = 0
*
3) Arrays by NUM_ASA, D_CL_MAX and NUM_LC
* do 30 k=1,d_cl_max
d_cl_ch [i,k,j] = 0
d_cl_so [i,k,j] = 0
30 continue
40 continue
50 continue
*
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
* Open "NETW.TAB" file outputted from DEDNM for ASA information
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
* Read in lines(rows) that aren't essential to the program
* (i.e. first 25 lines/rows are 'junk')
* open (32,file='netw.tab',status='old')
* write(*,*),'Processing network table...'
* do 60 i=1, 25
read (32,70) junk
60 continue
70 format (a1)
* Read in values (iv1,iv2,iv3,etc...) where IVs are INTEGERS; and Vs are REALS (in FORTRAN, I-N are integers)
* iv16 from 'NETW.TAB' is node# (i.e. subwatershed code or ASA #); this value is assigned as the 'x-value or row or ASA#' for len_strm and
* dz_strm, for e.g. if iv16=8, the corresponding values for ASA 8 will be written in the 8th row
* the value of v9 (channel length in number of cell widths) is assigned to len_strm
* v10-v11 ((upstream elevation of channel in metres)-(downstream elevation of channel in metres)) is assigned dz_strm
* therefore, ASA_ACT = ACTUAL number of ASAs (in case COMPLEX JUNCTIONS occur)
* LEN_STRM = Channel length in cell widths by ASA
* DZ_STRM = Change of elevation (m) along stream by ASA
80 read (32,90) iv1,iv2,iv3,iv4,iv5,iv6,iv7,iv8,
  + v9,v10,v11,
  + iv12,iv13,iv14,iv15,iv16
90 format (8i5,f10.0,2f7.0,i10,i11,2i10,i7)
* if (iv1.eq.-1) goto 100
  asa_act = iv1
  len_strm (iv16) = v9
dz_strm (iv16) = v10-v11
* goto 80
100 close (32)
* Writes information to screen for user to use as a check
* WRITE(*,*),'NUMBER OF ROWS:     ', nrow
* WRITE(*,*),'NUMBER OF COLUMNS:  ', ncol
* WRITE(*,*)
WRITE(*,*),'NUMBER OF LANDCOVERS:', num lc
WRITE(*,*),'NUMBER OF ASAs: ', (asa_act-1)
WRITE(*,*),'UTM MAXIMUM NORTHERN:', max_y
WRITE(*,*),'UTM MINIMUM EASTING: ', min_x
WRITE(*,*),'CELL SIZE (m): ', cell_m
WRITE(*,*),'CELL AREA (sq km): ', cel_area
WRITE(*,*),'JOB TITLE:', TITLE1, TITLE2, TITLE3
GOTO 140
110 WRITE(*,*),'READ ERROR (IOCNT)'
GOTO 130
120 WRITE(*,*),'EOF ERROR (IOCNT)'
GOTO 130
130 STOP '!!PROGRAM NOT COMPLETED SUCCESSFULLY!!'
140 pause 'Press ENTER to continue ...'

*=======================================================================*
Open 'SBCT.TAB' file outputted from DEDNM for ASA info
*=======================================================================*

* Read in lines(rows) that aren't essential to the program (i.e. first 27 lines/rows are 'junk')
* open (32,file='sbct.tab',status='old')
* write(*,*),'Processing subwatershed table...
* do 150 i=1, 27
* read (32,70) junk
* continue
* when reading, if -1 is encountered for iv1 (i.e. ASA#), then whole file has been read, therefore CLOSE
* iv8 (subcatchment area in number of cells) is assigned to area_asa
* therefore, AREAASA = Subcatchment(or ASA) area in number of cells
* read (32,170)iv1,iv2,iv3,iv4,iv5,iv6,iv7,iv8
* format(i5,i6,i7,i10,4i8)
* if (iv1.eq.-1) goto 180
* area_asa (iv3)=iv8
* goto 160
180 close (32)
*=======================================================================*
* RASTER DATA LAYERS ANALYSIS
*=======================================================================*

* Initialize MINIMUM distances and MAXIMUM distances for the distance-to-channel and the distance-to-subwatershed-outlet
* do 200 i=2,num asa
* do 190 k=1,num lc
* min_d_ch (i,k) = 999999999.9
* max_d_ch (i,k) = 0.0
* min_d_so (i,k) = 999999999.9
* max_d_so (i,k) = 0.0
* continue
200 continue
* write(*,*),'Reading subwatershed raster...
* Open subwatershed raster and read values for ASA information
* ISUB2 is assigned ASA values (once divided by 10)
* open (32,file='subwtb.out', status = 'OLD', ACCESS = 'SEQUENTIAL', FORM = 'UNFORMATTED')
* READ (32) ((isub2 (I,J),I=1,nrow),J=1,ncol)
close(32)
* Convert subwatershed codes by dividing by 10
* do 220 ir=1,nrow
  do 210 ic=1,ncol
    isub2(ir,ic)=int(float(isub2(ir,ic))/10)
    continue
  continue
* Open landcover raster and read in values of land covers
* write(*,*) 'Reading land cover raster...'
  open (32,file='lclass.inp',status='old')
  do 240 ir=1,nrow
    do 230 ic=1,ncol
      read(32,*) lc(ir,ic)
      if(lc(ir,ic).eq.0) goto 250
      if(isub2(ir,ic).eq.0) goto 2004
      area lc(isub2(ir,ic),lc(ir,ic)) =
      area lc(isub2(ir,ic),lc(ir,ic)) + 1
      rows_sum(isub2(ir,ic)) = rows_sum(isub2(ir,ic)) + ir
      cols_sum(isub2(ir,ic)) = cols_sum(isub2(ir,ic)) + ic
      continue
  continue
* Basic count of cells and sum of rows and sum of cols
* do 260 ir=1,nrow
  do 250 ic=1,ncol
    * IF statement skips cells outside main watershed (* NO 0 (zero) row or
      * col...can't write to 0 row or col; avoids redundant 0 calculations)
    * IF statement checks if any landcover values are 0 (zero), and if so,
      * goes to write statement notifying the user that no such value can
      * be used, and program terminates abnormally
    * if(isub2(ir,ic) .eq. 0) goto 250
    if(lc(ir,ic) .eq. 0) goto 2004
    * Count number of cells in each land cover in each ASA
    * area lc(isub2(ir,ic),lc(ir,ic)) =
      area lc(isub2(ir,ic),lc(ir,ic)) + 1
    * Determine sum of rows and sum of columns for each ASA for later
      * calculations of ASA centroid
    * rows_sum(isub2(ir,ic)) = rows_sum(isub2(ir,ic)) + ir
    * cols_sum(isub2(ir,ic)) = cols_sum(isub2(ir,ic)) + ic
    250 continue
    260 continue
* Distance to channel analysis
* write(*,*) 'Distance-to-channel analysis...'
open (32, file='distch.out',
  + STATUS = 'OLD', ACCESS = 'SEQUENTIAL', FORM = 'UNFORMATTED')
READ (32) ((tmp (I,J),I=1,nrow),J=1,ncol)
close(32)

* Loop through raster domain
* do 280 ir=1,nrow
   do 270 ic=1,ncol
   * Skip cells outside main watershed
   * if(isub2(ir,ic) .eq. 0) goto 270
   * Assign raster cell value to DIST variable
   * dist = tmp(ir,ic)
   * IDCLASS is a distance class calculated as the truncated value of
   * distance to channel divided by the distance-to-channel class width
   * (range_ch). IF statement value greater than distance class 25,
   * then assign to 25
   * idclass = aint(dist/range_ch) + 1
   * Count number of cells in each distance class in each landcover
   * d_cl_ch(isub2(ir,ic),idclass,lc(ir,ic)) =
     + d_cl_ch(isub2(ir,ic),idclass,lc(ir,ic)) + 1.0
   * Sum distance-to-channel by landcover
   * d_ch_sum(isub2(ir,ic),lc(ir,ic)) =
     + d_ch_sum(isub2(ir,ic),lc(ir,ic)) + dist
   * Assign MINIMUM distance-to-channel
   * if (dist .lt. min_d_ch(isub2(ir,ic),lc(ir,ic))) then
     min_d_ch(isub2(ir,ic),lc(ir,ic)) = dist
   * Assign MAXIMUM distance-to-channel
   * if (dist .gt. max_d_ch(isub2(ir,ic),lc(ir,ic))) then
     max_d_ch(isub2(ir,ic),lc(ir,ic)) = dist
   270 continue
280 continue

* Calculate mean distance-to-channel by land cover and ASA
* do 300 i=1,num_asa
   do 290 j=1,num_lc
      if (area_lc(i,j).gt.0) then
         d_ch_mn(i,j) = d_ch_sum(i,j)/area_lc(i,j)
      endif
   290 continue
300 continue

* Calculate sum of deviations from the mean for each value by
* land cover
* do 320 ir=1,nrow
   do 310 ic=1,ncol
   * if(isub2(ir,ic) .eq. 0) goto 310
   * dist = tmp(ir,ic)
   * d_ch_dev(isub2(ir,ic),lc(ir,ic)) =
     + (d_ch_dev(isub2(ir,ic),lc(ir,ic)) +
     + ((dist-(d_ch_mn(isub2(ir,ic),lc(ir,ic))))**2))
   310 continue
320 continue
* Calculate standard deviation of distance-to-channel for each landcover
*  
do 340 i=1,num_asa
do 330 j=1,num_lc
   if (area_lc(i,j).gt.0) then
      d_ch_sd(i,j)=sqrt(d_ch_dev(i,j)/area_lc(i,j))
   endif
330 continue
340 continue
* Distance to subwatershed outlet analysis
*-----------------------------------------------------------------------
* Read the distance to ASA outlet raster into the TMP1 array (TMP 1
* to correct SO errors...)
*  
write(*,*) 'Distance-to-subwatershed-outlet analysis ... '
open (32,file='distso.out', STATUS = 'OLD', ACCESS = 'SEQUENTIAL', FORM = 'UNFORMATTED')
READ (32) ((tmp1 (I,J),I=1,nrow),J=1,ncol)
close(32)
* Loop through raster domain
*  
do 360 ir=1,nrow
   do 350 ic=1,ncol
      * Skip cells outside main watershed
      *  
      if(isub2(ir,ic) .eq. 0) goto 350
      *  
      * Assign raster cell value to DISTSO variable
      *  
      distso = tmp1(ir,ic) - tmp (ir,ic)
      *  
      * IDCLASS is a distance class calculated as the truncated value of
* distance to outlet divided by the distance-to-outlet class width
* (range_so). IF statement value greater than distance class 25,
* then assign to 25.
*  
      idclass = aint(distso/range_so) + 1
      if (idclass.gt.d_cl_max) then
         idclass=d_cl_max
      endif
*  
      * Count number of cells in each distance class in each landcover
*  
      d_cl_so(isub2(ir,ic),idclass,lc(ir,ic)) =
      d_cl_so(isub2(ir,ic),idclass,lc(ir,ic)) + 1.0
*  
      * Sum distance-to-outlet by landcover
*  
      d_so_sum(isub2(ir,ic),lc(ir,ic)) =
      d_so_sum(isub2(ir,ic),lc(ir,ic)) + distso
*  
      * Assign MINIMUM distance-to-outlet
*  
      if (distso .lt. min_d_so(isub2(ir,ic),lc(ir,ic))) then
         min_d_so(isub2(ir,ic),lc(ir,ic)) = distso
      endif
*  
      * Assign MAXIMUM distance-to-outlet
*  
      if (distso .gt. max_d_so(isub2(ir,ic),lc(ir,ic))) then
         max_d_so(isub2(ir,ic),lc(ir,ic)) = distso
      endif
350 continue
360 continue
*  
* Calculate mean distance-to-outlet by land cover and ASA
*  
do 380 i=1,num_asa
   do 370 j=1,num_lc
      if (area_lc(i,j).gt.0) then
         d_so_mn(i,j) = d_so_sum(i,j)/area_lc(i,j)
      endif
370 continue
380 continue
* Calculate sum of deviations from the mean for each value by land cover
* do 400 ir=1,nrow
  do 390 ic=1,ncol
    if(isub2(ir,ic) .eq. 0) goto 390
    distso = tmp1(ir,ic) - tmp(ir,ic)
    dso_dev(isub2(ir,ic),lc(ir,ic)) =
      dso_dev(isub2(ir,ic),lc(ir,ic)) +
      (distso-(dso_mn(isub2(ir,ic),lc(ir,ic))))**2)
  continue
400 continue
* Calculate standard deviation of distance-to-outlet for each landcover
* do 420 i=1,num_asa
  do 410 j=1,num_lc
    if (area_lc(i,j) .gt. 0) then
      dso_sd(i,j) = sqrt(dso_dev(i,j)/area_lc(i,j))
    endif
  continue
420 continue
*-----------------------------------------------------------------------
* Elevation analysis
*-----------------------------------------------------------------------
* Reads the elevation raster values into the TMP array
* write(*,*) 'Elevation analysis...' 
  open (32,file='relief.out', STATUS='OLD', ACCESS='SEQUENTIAL', FORM='UNFORMATTED')
  READ (32) ((tmp (I,J),I=1,nrow),J=1,ncol)
  close(32)
* Loop through raster domain
* do 440 ir=1,nrow
  do 430 ic=1,ncol
    if(isub2(ir,ic) .eq. 0) goto 430
    z = tmp(ir,ic)/100000
    z_lc_sum(isub2(ir,ic),lc(ir,ic)) =
      z_lc_sum(isub2(ir,ic),lc(ir,ic)) + z
  continue
440 continue
* Elevation change to channel analysis
*-----------------------------------------------------------------------
* Read the elevation change to channel raster into the TMP array
* write(*,*) 'Elevation-change-to-channel analysis...' 
  open (32,file='dzch.out', STATUS='OLD', ACCESS='SEQUENTIAL', FORM='UNFORMATTED')
  READ (32) ((tmp (I,J),I=1,nrow),J=1,ncol)
  close(32)
* Loop through raster domain
* do 460 ir=1,nrow
  do 450 ic=1,ncol
    if(isub2(ir,ic) .eq. 0) goto 450

* Divide raster cell value by 100,00 to convert to meter units and
* assign result to DZCH variable
*  
dzch=tmp(ir,ic)/100000
  dzch_sm (isub2(ir,ic),lc(ir,ic))
  = dzch_sm (isub2(ir,ic),lc(ir,ic)) + dzch

450  continue
460  continue

Elevation change to subwatershed outlet analysis

Read the elevation change to outlet raster into the TMP1 array (TMP1
array created to correct for SO error)

write('*,*)'Elevation-change-to-subwatershed-outlet analysis...'
open (32, file='dzso.out', +
  STATUS = 'OLD', ACCESS = 'SEQUENTIAL', FORM = 'UNFORMATTED')
READ (32) ((tmp1 (I,J),I=1,nrow),J=1,ncol)
close(32)

* Loop through raster domain
  do 480 ir=1,nrow
    do 470 ic=1,ncol
      * Divide raster cell value by 100,000 to convert to meter units and
      * assign result to DZSO variable
      *  
dzso=tmp1(ir,ic)/100000 - tmp(ir,ic)/100000
      dzso_sm (isub2(ir,ic),lc(ir,ic))
      + dz_so_sm (isub2(ir,ic),lc(ir,ic)) + dzso

470  continue
480  continue

Open "NetwB.tab" file outputted from RASBIN module of TOPAZ

Open "NETWB.TAB" and "ORDPM.INP" file

***NOTE: ORDPM.INP is limited to 25 stream orders***

* Read in lines(rows) that aren't essential to the program (i.e. first
  24 lines/rows are 'junk')
  do 490 i=1,24
    read (32,70) junk
490  continue

* Read in values from ORDPM.INP file (iv1...iv7), where
  iv1 = node # or ASA #
  iv7 = next ASA downstream
  iv2 = Strahler stream order
  iv4 = Execution Sequence (i.e. from upstream to downstream)
  do 510 i=1,num_asa
    read (32,500) iv1,iv2,iv3,iv4,iv5,iv6,iv7
500  format (5x,2i7,i8,i7,i6,i8)
    asa (iv1) iv1
    next_asa (iv1) = iv7
    order (iv1) = iv2
    ex_seq (iv1) = iv4
510  continue

Assigns values from input file to ordpm array by ASA,
* by climate station
  * do 520 i=1,25
     read (33,*),(ordpm(i,j),j=1,5)
  520  continue
  *
  close (32)
  close (33)
  *
* Writes to TABLE_CH output file (Table of distances to channels
  in cells)
*=======================================================================
* Opens TABLE_CH.txt file
* IF(NOPRINT.EQ.0) THEN
  * open(32,file='table_ch.txt',status='unknown')
  * write(32,530) '**************************************************'
  * write(32,530) '*********************** TABLE 1 ******************'
  * write(32,530) '************** DISTANCES TO CHANNELS ************'
  * write(32,530) '********************** (in cells) ***************'
  * write(32,530) '**************************************************'
  530  format (5x,a65)
  * write(32,540) cell_m
  * write(32,550) nint(range_ch/cell_m)
  * format (5x, 'Cell Size (m): ',f4.1)
  540  format (5x, 'Distance Class Width (cells): ',i4)
  * do 700 i=2,num_asa
  * write (32,*)
  * write (32,560)
  560  format (5x,80('='))
  * do 570 k=1,num_lc
     if (mind_ch(i,k).eq.999999999.9) then
     mind_ch(i,k)=0
     endif -
  570  continue
  write (32,610)
  write (32,580) ((k), k=1,num_lc)
  write (32,620) (nint(d_cl_ch(i,j,k)), k=1,num_lc)
  write (32,630) ( (k), k=1,num_lc)
  write (32,640) (mind_ch(i,k)/cell_m,k=1,num_lc)
  write (32,650) (max_d_ch(i,k)/cell_m,k=1,num_lc)
  write (32,660) (d_ch_mn(i,k)/cell_m,k=1,num_lc)
  write (32,670) (d_ch_sd(i,k)/cell_m,k=1,num_lc)
  write (32,590)
  write (32,580)
  580  format (5x,80('-'))
  590  format (5x,10('-'))
  600  format(5x, 'Dist Class')
  * do 680 j=1,d_cl_max
  * write (32,620) j, (nint(d_cl_ch(i,j,k)), k = 1,num_lc)
  610  format (12x,<num_lc>i7)
  620  format (5x,17,<num_lc>i7)
  630  format (5x,' ASA:',i4,28x,'Land Classes')
  640  format (5x,' Min: ',<num_lc>f7.1)
  650  format (5x,' Max: ',<num_lc>f7.1)
format (5x, ' Mean: ',<num_lc>f7.1)
format (5x, ' SD: ',<num_lc>f7.1)

write (32,580)
write (32,690) (area_lc(i,k),k=1,num_lc)
format (6x, 'Total: ',<num_lc>i7)

continue close (32)

*=======================================================================
* Writes to TABLE_SO output file (Table of distances to outlets in cells)
*=======================================================================
*
* Opens TABLE_SO.txt file
*
open(32,file='table_so.txt',status='unknown')
write(32,530) '**************************************************'
write(32,530) '*********************** TABLE 2 ******************'
write(32,530) '************* DISTANCES TO ASA OUTLETS ***********'
write(32,530) '****************** (in cells) ******************'
write(32,530) '**************************************************'
write(32,540) cell_m
write(32,550) nint(range_so/cell_m)

1700 continue

* IF STATEMENT, assigns a value of 0 to variable MIN_D_SO if there is no minimum distance to outlet (ie if lc is not present)
* do 710 k=1,num_lc
  if (mind_so(i,k) .eq.999999999.9) then
    mind_so(i,k)=0
  endif - -
  continue

write (32,610) ((k), k=1,num_lc)
write (32,580)
write (32,640) (min_d_so(i,k)/cell_m,k=1,num_lc)
write (32,650) (max_d_so(i,k)/cell_m,k=1,num_lc)
write (32,660) (d_so_min(i,k)/cell_m,k=1,num_lc)
write (32,670) (d_so_sd(i,k)/cell_m,k=1,num_lc)
write (32,590)
write (32,620)

write (32,580)

* do 720 j=1,d_cl_max
  write (32,620) j, (nint(d_cl_so(i,j,k)),k=1,num_lc)
  continue

write (32,580)
write (32,690) (area_lc(i,k),k=1,num_lc)

730 continue close (32)

*=======================================================================
* Writes to MSD_CH output file (Frequency distribution of distance class widths to channels)
*=======================================================================
*
* Opens MSD_CH output file
*
open (32,file='msd_ch.txt',status='unknown')

- 128 -
**********

FREQUENCY DISTRIBUTION FOR

DISTANCES TO CHANNELS

**********

Cell Size (m): ,f4.1
Distance Class Width (cells):',i4)

Every X is equal to: 1%

Landcover Type:','i3,'
Area (cells)='',i7,''
Mean Distance (cells)='',f7.2,''
Std. Dev. = ',f6.2)

Minimum Distance (cells)='',f6.2,
Maximum Distance (cells)='',f7.2)

DO LOOP, gives percentage of cells within each distance class widths

IF statement, assigns min and max distance class widths;
and determines percentage per distance class widths

do 830 j=1,d_cl_max
if (d_cl_ch(i,j,k).gt.0.1) then
maxclass=j
if (minclass.lt.1) then
minclass=j
endif
endif
if (area_lc(i,k).gt.0.1) then
    d_cl_ch(i,j,k)=(d_cl_ch(i,j,k)/area_lc(i,k))
else
    d_cl_ch(i,j,k)=0.0
endif
continue
* 
write(32,840)
format (5x,110(''))

DO LOOP, assigns minclass and maxclass to variable KOUNT, and
distribution is plotted (x) if KOUNT is greater than 0

do 870 j=minclass,maxclass
    kount=nint(d_cl_ch(i,j,k))
    if (kount.eq.0) then

write(32,860) j, d_cl_ch(i,j,k)
else
write(32,850) j, d_cl_ch(i,j,k)
endif

format (5x,i4,<kount>('X'),f6.1, '%%')
format (5x,i4,f6.1, '%%')
continue

write(32,880)
format (5x,110('=1'))
continue
continue
close (32)

*=======================================================================
* Writes to MSD_SO output file (Frequency distribution of distance class
* widths to outlets)
*=======================================================================
*
* Opens MSD_SO output file
*  
* open (32,file='msd_so.txt',status='unknown')
*  
* write (32,740) '**************************** FREQUENCY DISTRIBUTION FOR ***********
* write (32,740) '************ DISTANCES TO ASA OUTLETS **********
* write (32,740) '****************************
*  
* write (32,750) cell_m
* write (32,760) mint(range_so/cell_m)
* write (32,770)
* write(32,780)
* do 940 i=2,num_asa
* write(32,*) ' ' write (32,790)
* write(32,800) i
*  
do 930 k=1,num_lc
* if(area_lc(i,k).lt.1) goto 930
*     write(32,810) k, area_lc(i,k), d_so_mn(i,k)/cell_m,
*     + d_so_sd(i,k)/cell_m
*     write(32,820) min_d_so(i,k)/cell_m, max_d_so(i,k)/cell_m
* minclass=0
* maxclass=0
*  
* DO LOOP, gives percentage of cells within each distance class widths
*  
* IF STATEMENT, assigns min and max distance class widths; and determines percentage per distance class widths
*  
do 910 j=1,d_cl_max
*   
* if(d_cl_so(i,j,k).gt.0.1) then
*    maxclass=j
*    if(minclass.lt.1) then
*      minclass=j
*    endif
* endif
*   
* if (area_lc(i,k).gt.0.1) then
*    d_cl_so(i,j,k)=(d_cl_so(i,j,k)/area_lc(i,k))*100
* else
*    d_cl_so(i,j,k)=0.0
* endif
*  
do 910 contiue
*  
* write(32,840)
*  
* - 130 -
DO LOOP, assigns minclass and maxclass to variable KOUNT, and
distribution is plotted (x) if KOUNT is greater than 0

   do 920 j=minclass,maxclass
      kount=nint(d_cl_so(i,j,k))
      if(kount.eq.0) then
         write(32,860) j, d_cl_so(i,j,k)
      else
         write(32,850) j, d_cl_so(i,j,k)
      endif
   continue
   write(32,880)
   continue
   continue
   close (32)
   END IF

*=======================================================================
* Loop to correct complex node situations
*=======================================================================

* Loop for eliminating complex node situations (where flow into a
* complex node does not occur under natural circumstances, it has to
* flow to a node downstream that is an actual sub-basin node). Complex
* nodes are computed by module RASBIN of TOPAZ for calculation purposes.

   do 960 i=2,num_asa
      if (len strm(i) .lt. 1) then
         do 950 k=1,num_asa
            if(next asa(k) .eq. i) then
               next asa(k)=next asa(i)
            endif
         continue
      endif
   continue
   continue
*=======================================================================
* Thiessen loop for .wts file (Martin Lacroix & Uwe Haberlandt, Aug '97)
*=======================================================================

* Read all climate station information

* write (*,*), 'Please enter number of climate stations to be used',
* 'for calculating .wts file,'
* 'and press Enter,'
* 'or enter 0 to skip .wts calculations:'
* read (*,*) nstat
* IF statement skips .wts calculations
* if (nstat.eq.0) then
goto 1180
endif
* Allocate climate station weights analysis arrays
* allocate (xstns  (num_asa))
* allocate (stnnmbr (nstat))
* allocate (stnnname (nstat))
* allocate (easting  (nstat))
* allocate (nortjng (nstat))
* allocate (elev (nstat))
* allocate (mnnnppcp (nstat))
* allocate (wts  (num_asa, nstat))
* allocate (nnstns  (num_asa, nstat))
* Initialize .wts variables
do 980 i=1,num_asa
   xstns(i)=0
980 continue

do 970 j=1,nstat
   nnstns(i,j)=0
   wts(i,j)=0
970 continue

do 990 i=1,nstat
   easting(i)=0
   northing(i)=0
   elev(i)=0
   stnnmbr(i)=0
   stnname(i)=0
   mnannpcp(i)=0
990 continue

* Read variables for each climate station from input file CLMSTNS.INP
* open (40,file='clmstns.inp',status='old')
* do 1000 i=1,nstat
*   read (40,*) stnnmbr(i),stnname(i),easting(i),northing(i),
+   elev(i),mnannpcp(i)
* close (40)

* Loop through raster to find Nearest Neighbour
*-----------------------------------------------------------------------
write (*)
write (*) 'Computing weights (.wts) file...'

* do 1030 ir=1,nrow
  do 1020 ic=1,ncol
  * Skip cells outside main watershed
  * if (isub2(ir,ic).eq.0) goto 1020
  * utm_E=min_x+cell_m*(ic-1)-(0.5*cell_m)
  * utm_N=max_y-cell_m*(ir-1)-(0.5*cell_m)
  * Calculate distances to climate stations and select closest one
  * do 1010 is=1,nstat
    dist2 = sqrt((utm_E- easting(is))**2 + (utm_N- northing(is))**2)
    if (is.eq.1) then
      mindist=dist2
      near=is
      goto 1010
    endif
    if (dist2.lt.mindist) then
      mindist = dist2
      near=is
    endif
    continue
  * 1010 continue
  * Sum number of cells nearest each climate station for each ASA
  * nnstns(isub2(ir,ic),near)=
    nnstns(isub2(ir,ic),near)+1
  * 1020 continue
  1030 continue
* Assigns ASA # to ia
* do 1050 ia=2,num_asa
* Initializes SUMWTS to 0; and XSTNS (as an array) to NSTAT
* (XSTNS is used to count number of climate stations used
* within an ASA for .wts file); max to 0; and sav to 0
* number by ASA)
* Assigns climate station number to IS
* if(area_asa(ia).lt.1) goto 1050
  do 1040 = 1, nstat
* Calculates the weights (WTS); and assigns the highest weight to
* variable MAX and the associated station number to SAV
  wts(ia,is) = nint((real(nnstns(ia,is))/
             real(area_asa(ia)))*100)
*   if (wts(ia,is).gt.max) then
*       max = wts(ia,is)
*       sav = is
*   endif
*   IF statement includes number of climate stations only if station
*   has a weight greater than 1%; if not, subtracts 1 from xstns(ia);
* SUMWTS sums the weights of the climate stations by ASA
*   if (wts(ia,is).lt.1) then
*     xstns(ia) = xstns(ia)-1
*     goto 1040
*   endif
*   SUMWTS sums the weights of the stations used by ASA (i.e. the stations
*   with greater than 1% influence)
*   sumwts = sumwts + wts(ia,is)
1040 continue
*   IF statement adds the difference of (100 - SUMWTS) to the
*   highest weight by ASA if SUMWTS is less than 100
*   if (sumwts.lt.100) then
*     wts(ia,sav) = wts(ia,sav) + (100 - sumwts)
*   endif
*   IF statement subtracts the difference of (100 - SUMWTS) to the
*   highest weight by ASA if SUMWTS is greater than 100
*   if (sumwts.gt.100) then
*     wts(ia,sav) = wts(ia,sav) - (100 - sumwts)
*   endif
1050 continue
* Writes to TEMP.WTS file
*-----------------------------------------------------------------------
*-----------------------------------------------------------------------
*-----------------------------------------------------------------------

* IF statement goes to write statement that assign a weight to
* NET RADIATION
if (sun.eq.1) then
  goto 1060
endif

* IF statement goes to write statement that assigns a weight to
* SUNSHINE HOURS
* if (sun.eq.2) then
  goto 1120
endif

*-----------------------------------------------------------------------
1060 continue

* Assigns execution sequence value to nex (ie from upstream
* to downstream)
  do 1110 nex=1,num_asa-1
* Assigns ASA # to ia
  do 1100 ia=2,num_asa
* IF statement continues through loop until execution sequence
* equals nex
  if (ex_seq(ia) .ne. nex) goto 1100
* IF statement skips over any ASAs with an area of less than 1 (e.g.
* in COMPLEX NODE situations)
  if (area_asa(ia).lt.1) goto 1110
* Writes ASA name and number of climate stations used in .wts file
  write (340,1070) ia, xstns(ia)
  format ('ASA',i5.5,i2)

* Initializes sumpcp to 0
  sumpcp=0.0

* Assigns climate station number to is
  do 1090 is=1,nstat
* IF statement writes values only if WTS is greater than 1% (and
* values are rounded up to nearest percent in write statement ie f10.0)
* if (wts(ia,is).lt.1) goto 1090
  write (340,1080) stname(is), elev(is),
  real(wts(ia,is)),
  if (real(wts(ia,is)).lt.1) format ('ASA',i5.5,i2)

* Sums mean annual precip by ASA (by climate station influence
* (ie wts (ia, is))) for Morton evapotranspiration calculations
* (ie .mor file)
  sumpcp = sumpcp + (wts(ia,is)*mnannpcp(is))

* Writes temp.mor file
  write (341,1081) ia, sumpcp/100, '  0.00'
  format ('ASA',i5.5,2x,f10.2,a10)
  goto 1110
1100 continue
1110 continue
  close (340)
  close (341)
  goto 1180
C THIS LOOP NO LONGER NEEDED IF WEIGHTS ARE TO BE WRITTEN TO BOTH C RADIATION AND SUNSHINE COLUMNS OF .WTS FILE
1120 continue
*
* Assigns execution sequence value to nex (ie from upstream
* to downstream)
*
* do 1170 nex=1,num_asa=1
*
* Assigns ASA # to ia
*
* do 1160 ia=2,num_asa
*
* IF statement continues through loop until execution sequence
* equals nex
*          if (ex_seq(ia) .ne. nex) goto 1160
*
* IF statement skips over any ASAs with an area of less than 1 (e.g.
* in COMPLEX NODE situations)
*      if (area_asa(ia).lt.1) goto 1170
*
* Writes ASA name and number of climate stations used in .wts file
*
write (340,1130) ia, xstns(ia)
format ('ASA',i5.5,i2)
*
* Initializes sumpcp to 0
*
sumpcp=0.0
*
* Assigns climate station number to is
*
* do 1150 is=1,nstat
*
* IF statement writes values only if WTS is greater than 1% (and
* values are rounded up to nearest percent in write statement ie f10.0)
*      if (wts(ia,is).lt.1) goto 1150
*
write (340,1140) stname(is),elev(is),
+ real(wts(ia,is)),
+ real(wts(ia,is)),
+ real(wts(ia,is)),
+ real(wts(ia,is)),
+ '0.'
format (a7,3x,5f10.0,a10)
*
* Sums mean annual precip by ASA (by climate station influence
* (ie wts (ia, is))) for Morton evapotranspiration calculations
* (ie .mor file)
*  sumpcp = sumpcp + (wts(ia,is)*mnannpcp(is))
1150 continue
*
* Writes temp.mor file
*
write (341,1081) ia, sumpcp/100, ' 0.00'
goto 1170
1160 continue
1170 continue
*
* close (340)
* close (341)
goto 1180

*-----------------------------------------------------------------------
*=======================================================================
*Opens output file (used to check if parameters are correct...)
*=======================================================================
*
* Opens PARAM.txt file (NOTE: not needed for SLURP .cmd file)
IF(NOPRINT.EQ.0) THEN
  open(32, file='param.txt', status='unknown')
  write(*,*) 'Writing PARAM.txt file'
END IF

* Do LOOP, assigns ASA# to i
  do 1210 i=2,num_asa
  IF AREAASA is <1, then assign -1 to mean row and to mean col
  ELSE, mean row equals (Sum of rows/ASA area) and mean col equals
  (Sum of cols/ASA area)
  if(area_asa(i).lt.1)then
    rows Mn (i) = -1
    cols Mn (i) = -1
  else
    rows Mn (i) = rows_sum(i)/area_asa(i)
    cols Mn (i) = cols_sum(i)/area_asa(i)
  endif

  * Initializes sum of elevations by ASA to 0
  z_asa_sum(i)=0

  * Do LOOP, assigns landcover values to k; and adds up all landcover
  * cells by ASA
  do 1190 k=1,num_lc
    continue
  continue
  if(area_asa(i).lt.1)then
    z_asa Mn(i) = 0
  else
    z_asa Mn(i) = z_asa_sum(i) / area_asa(i)
  endif

  * Do LOOP, assigns landcover values to k
  * IF ASA area by landcover is <1, THEN assigns mean z by ASA to ZLCMn
  * and 0 to all other land cover related variables; ELSE assigns (sum of
  * z by LC/ASA area by LC) to ZLCMn, (sum of delta z to channel/ASA
  * area by LC) to DZCHMn, (sum of delta z to outlet/ASA area by LC)
  * to DZCHMn
  do 1200 k=1,num_lc
    if(area_lc(i,k).lt.1)then
      z_lc_mn (i,k) = z_asa_mn(i)
      min_d_ch (i,k) = 0
      max_d_ch (i,k) = 0
      min_d_so (i,k) = 0
      max_d_so (i,k) = 0
      dz_ch Mn (i,k) = 0
      dz_so Mn (i,k) = 0
      d_ch Mn (i,k) = 0
      d_so Mn (i,k) = 0
      d_ch_sd (i,k) = 0
      d_so_sd (i,k) = 0
    else
      z_lc_mn (i,k) = zlc_sum(i,k)/area_lc(i,k)
      dz_ch Mn (i,k) = dz_ch_sm(i,k)/area_lc(i,k)
      dz_so Mn (i,k) = dz_so_sm(i,k)/area_lc(i,k)
    endif
  continue
1210 continue
*-----------------------------------------------------------------------
* PARAM.txt not needed for SLURP .cmd file
*-----------------------------------------------------------------------
* DO LOOP, assigns ASA# to i
* IF(NOPRINT.EQ.0) THEN
 do 1220 i=2,num_asa
* * Writes to PARAM.txt file
 num lc7 = 7*num lc
 num lc61 = 61*num lc
 * write(32,1230) i, len strm(i), dz strm(i), area asa(i),
 + (area lc(i,k),k=1,num lc),rows mn(i),cols mn(i),
 + (z lc mn(i,k),k=1,num lc),
 + (min_d_ch(i,k),k=1,num lc), (max_d_ch(i,k),k=1,num lc),
 + (dz_ch mn(i,k),k=1,num lc), (dz so mn(i,k),k=1,num lc),
 + asa(i), next_asa(i), order(i),
 + ((mint(d cl_ch(i,m,k)),m=1,d cl_max),k=1,num lc),
 + ((mint(d cl_so(i,m,k)),m=1,d cl_max),k=1,num lc)
* 1220 continue
* 1230 format(i4,2f8.1,i8,<num_lc>i8,2f8.1,<num_lc7>f8.1,3i8,
 <num_lc61>i8)
 close(32)
 ENDTIF
*=======================================================================
*=======================================================================
* "TEM.CMD" file
*=======================================================================
*=======================================================================
c&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
 write (*,*) 'Enter UTM Zone:'
 read (*,*) zone
 write (*,*), 'Enter 27 (NAD27) or 83 (NAD83) :'
 read (*,*) nad
 c&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
* Opens temp.cmd file
* open (34, file='temp.cmd', status='unknown')
* write (*,*) 'Writing temp.cmd file...
* !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
* Writes out 1st line of .cmd file (Brian Li, July'97)
* write (34,1240) asa act-l,num lc
1240 format (i5,i5,') 10 9 1994  8 1996 5000MSNSNNBFFYNYYN')
*!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
* * Assigns execution sequence value to nex (ie from upstream
to downstream)
* do 1310 nex = 1,num asa-1
* * Assigns ASA # to i
* do 1300 i=2,num asa
* * IF statement continues through loop until execution sequence
* * equals nex
* if(ex_seq(i) .ne. nex) goto 1300
* * IF statement skips over any ASAs with an area of less than 1 (e.g.
in COMPLEX NODE situations)
* if (area asa(i).lt.1) goto 1310
* - 137 -
area_km2 = area_asa(i)*cel_area
* Mean UTM NORTHING (y or row) and mean UTM EASTING (x or col)
* are calculated for each ASA
* avg_utmN = (max y) - (rows mn(i)*cell m)
avg_utmE = (min x) + (cols mn(i)*cell m)
c
* utm conversion program; calculating central meridian from utm zone
deg = 6
  east = avg_utmE
  north = avg_utmN
c
  cmerid = (177. - (zone-1)*6)
c
  call utm2ll (east, north, cmerid, lon, lat, nad, deg)
c
* Writes out UTM EASTING & NORTHING to a file to allow for converting
to LATITUDES using a conversion program
* Open (35, file='utm.txt', status='unknown')
write (35,1249) i, east, north, lon, lat
1249 format ('ASA',i5.5, f10.0, 'E', 1x, f10.0, 'N', 1x, f10.3, 'Lon', 1x, +
  f10.3, 'Lat')
c
* DO loop, assigns landcover values to k
* PCENT derives percent of landcover for each ASA and converts from REAL
to an INTEGER (NINT)
* do 1250 k=1,num lc
  atmp1=area lc(i,k)
  atmp2=area-asa(i)
  pcent lc(i~k) = nint((atmp1/atmp2)*100)
continue
*
* Initializes ILCMAX, ILCSUM, KSAV to 0
*
* LAPSE RATE (FLPSE_RT) and PCP RATE (FPCP_RT) are set as constants
* (**NOTE: have to be changed by the user manually within SLURP if
* different values are required**)
* ilcmax = 0
  ilcsum = 0
  ksav = 0
  flpse_rt = 0.75
  fpcp_rt = 5.0
*
* DO loop, assigns landcover values to k
*
* Integer land cover sum (ILCSUM) (i.e. 0) plus integer land cover
* (PCENT_LC) by LC by ASA, equals ILCSUM
* do 1260 k=1,num lc
  ilcsum=ilcsum + pcent lc(i,k)
* if (pcent lc(i,k) .gt. ilcmax) then
  ilcmax=pcent lc(i,k)
  ksav=k
endi
continue
*
* ILCHECK checks that percentage of landcovers by ASA add up to 100%
*
* IF statement: - IF ILCHECK equals 0 goto write statement
* - ELSE MAXIMUM percentage of landcover equals maximum
*   percentage of landcover plus ILCHECK
*   e.g. if ILCHECK = 99, then MAX. % of LC equals MAX. % of LC + 1
*   e.g. if ILCHECK = 101, then MAX. % of LC equals MAX. % of LC + (-1)
* ilcheck=100-ilcsum
if (ilcheck.eq.0) then
  goto 1270
else
  pcent_lc(i,ksav)=pcent_lc(i,ksav)+ilcheck
endif

*-----------------------------------------------------------------------
* Writes out ASA#, Area km2, mean latitude, avg z and % of land cover
*-----------------------------------------------------------------------
1270  write (34,1280) i, area km2, lat, 
   zb, asa_mm, flpse_rt, fpcp_rt
write (34,1290) pcent hc(i,k), k=1,num lc
1280  format ('ASA',i5.5,2x,5es10.3)  
1290  format ( 10x,10i5)

*-----------------------------------------------------------------------
1300  continue
1310  goto 1310

* DO loop, assigns ASA# to i
* do 1380 nex=1,num asa-1
  do 1370 i=2,num_asa
* IF statement continues through loop until execution sequence
* equals nex
  if(ex_seq(i) .ne. nex) goto 1370
* IF statement skips over any ASAs with an area of less than 1 (e.g. 
in COMPLEX NODE situations)
  if (area_asa(i) .lt. 1) goto 1380
* STRM_KM converts stream length from cells to km
* strm_km=len_strm(i)*cell km
* Assigns values from ORDPM.INP file to the variables ROUGH, WIDTH,
* DEPTH, ALPHA, BETA
* rough = ordpm(order(i),1)
width = ordpm(order(i),2)
depth = ordpm(order(i),3)
alpha = ordpm(order(i),4)
beta = ordpm(order(i),5)
* If statement writes zero values for ALPHA & BETA for 
* last ASA downstream
* if (next_asa(i) .eq. 1) then
  write (34,1320) i, strm_km, dz strm(i),rough,width,depth
  format ('ASA',i5.5,2x,5es10.3,' .000E+00',' .000E+00')
goto 1340
endif
*-----------------------------------------------------------------------
* Writes upstream ASA, channel length(km), delta z along stream(m),
* roughness or Manning n (constant set as stream order), channel
* width(m; constant set as stream order), channel depth(m; constant set 
as stream order), and 0 values for ALPHA and BETA when next d/s ASA 
is main basin outlet (i.e. next_asa = 1)
*-----------------------------------------------------------------------
write (34,1330) i, strm_km, dz strm(i), rough, width, depth, alpha, beta
 End
*-----------------------------------------------------------------------
*-----------------------------------------------------------------------
*-----------------------------------------------------------------------
* DO loop, assigns land cover values to k
*  
do 1360 k=1,num lc
  
    if (pcent lc (i,k) .eq. 0) then
      dchmn_km = 0
      dchmx_km = 0
      avg_dich = 0
      dsomn_km = 0
      dsmx_km = 0
      avg_dzso = 0
      avg_z_lc = z_lc_mn (i,k)
      fmean_ch = 0
      fmean_so = 0
      stdev_ch = 0
      stdev_so = 0
    else
      /1000 to get in km
      
      dchmn_km = min_d_ch (i,k)/1000
      dchmx_km = max_d_ch (i,k)/1000
      avg_dich = dz_ch_mn (i,k)
      dsomn_km = min_d_so (i,k)/1000
      dsmx_km = max_d_so (i,k)/1000
      avg_dzso = dz_so_mn (i,k)
      avg_z_lc = z_lc_mn (i,k)
      fmean_ch = d_ch_mn (i,k)/1000
      fmean_so = d_so_mn (i,k)/1000
      stdev_ch = d_ch_ad (i,k)/1000
      stdev_so = d_so_ad (i,k)/1000
      
    endif

*-----------------------------------------------------------------------
* Writes out ASA#, Land Cover, mean dist. to channel(km), standard
* deviation to channel(m), avg. dz to channel(m), avg. dist. to ASA
* outlet(km), standard deviation to outlet(m), avg. dz to ASA outlet(m),
* avg. z by land cover for each ASA(m)
*-----------------------------------------------------------------------

  c&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
  c IF statements: writes out a value of 1 for avg dzch and avg dzso if
c value is less than 0.5 when land cover is present (ie pcent_lc)
c
  c  if (pcent lc(i,k).ge.1) then
  c    if (avg_dzch.lt.1) avg_dzch=1
  c    if (avg_dzso.lt.1) avg_dzso=1
  c  endif
  c&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
   
  write (34,1350) i, k, fmean_ch, stdev_ch, avg_dzch,
  
  + fmean_so, stdev_so, avg_dzso, avg_z_lc
  
format ('ASA',i5.5,2x,'LC_',i5.5,2x,7es10.3)
  
1350  
1360  continue
*  
go to 1380
1370  continue
1380  continue
*  
* Initializes knt to 0
*  
  knt=0
*  
* Assigns execution sequence to nex (ie from upstream to downstream)
*  
do 1400 nex=1,num_asa-1
*  
* Assigns ASA # to i
*  
do 1390 i=2,num_asa
*  
* IF statement continues through loop until execution sequence
*  
equals nex
*  
* - 140 -
if(ex_seq(i) .ne. nex) goto 1390
*
* IF statement skips over any ASAs with an area of less than 1
* (eg in COMPLEX NODE situations); and execution sequence is assigned
* a value of 0
*
if (area_asa(i).lt.1) then
  ex_seq(i)=0
  goto 1400
endif
*
* knt is the ACTUAL number of ASAs to be executed (ie COMPLEX NODES
* will not be counted in number of executions); knt is then assigned to
* equal execution sequence
*
knt = knt+1
ex_seq(i) = knt
1390  continue
1400  continue
*
* Maximum execution sequence is assigned to equal knt
*
  max_ex=knt
*
* Assigns ACTUAL EXECUTION SEQUENCE to nex
* (ie from upstream to downstream)
*  do 1440 nex=1,max_ex
*
* Assigns ASA # to i
*  do 1430 i=2,num_asa
*
* IF statement continues through loop until execution sequence
* equals nex
*  if(ex_seq(i) .ne. nex) goto 1430
*
* IF statement skips over any ASAs with an area of less than 1
* (eg in COMPLEX NODE situations)
*  if (area_asa(i).lt.1) goto 1440
*
* IF statement writes out info in ACTUAL EXECUTION SEQUENCE until it
* reaches last ASA (ie most d/s ASA); ELSE goes to next write statement
*  if(nex .lt. max_ex) then
*-------------------------------------------------------------------------------------------------  
*  Writes out ASA#(ie ex_seq), ASA name, and next_asa d/s(ie ex_seq of
*  next_asa d/s)
*-------------------------------------------------------------------------------------------------  
*     write (34,1410) ex_seq(i), asa(i), 'N', ex_seq(next_asa(asa(i))),
*          + 'S', 'N', 'N'
* 1410 format (i5,'ASA',i5.5,1x,a1,i5,3a1)
*    else
*-------------------------------------------------------------------------------------------------  
*  Writes out ASA#(ie ex_seq), ASA name, and a value of 0 for next_asa
*  d/s (ie ex_seq of next_asa d/s) for last ASA downstream(ie flowing in
*  main watershed outlet)
*-------------------------------------------------------------------------------------------------  
*     write (34,1420) ex_seq(i), asa(i), 'Y', 0,
*          + 'S', 'N', 'Y'
* 1420 format (i5,'ASA',i5.5,1x,a1,i5,3a1)
*  endif
1430  continue
1440  continue
*
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
* Additional output for SLURP CMD file 'TEMP.CMD' is done by Brian Li
* on July 11, 1997. (new variables 'carr2(i)' are introduced)
* Write out each land cover properties, 10 parameters with default value of 0, and the last line of optimization setting

```plaintext
do 1450 i=1,num lc
   write (34,1460) i, carr3(i) = ' 0.000E+00'
1450 continue
1460 format (' LC ',i5.5,2x,' 0.000E+00',' 8','','1',
       +6' ' 0.000E+00')
   carr2(1) = "Initial contents of snow store (mm) N '
   carr2(2) = "Init. contents of slow store (%) N '
   carr2(3) = "Maximum infiltration rate (mm/day) N '
   carr2(4) = "Manning roughness, n N '
   carr2(5) = "Retention constant for fast store (day) N '
   carr2(6) = "Maximum capacity for fast store (mm) N '
   carr2(7) = "Retention constant for slow store (day) N '
   carr2(8) = "Maximum capacity for slow store (mm) N '
   carr2(9) = "Precipitation factor N '
   carr2(10) = "Rain/snow division temperature (deg C) N '
write (carr2(11),1480) 2
   do 1470 i=1,11
      write (34,carr2(11)) i, carr2(i)
      write (34,1490) (carr3(k), k=1,num_lc)
   continue
1480 format ('(i5,a4S, ',i3.3,' (" O.OOOE+00"))
1490 format ('Sx,10a10

* Deallocate dynamic memory allocation for arrays

deallocate (isub2, tmp, lc, rows_sum, rows_mm, cols_sum, cols_mm, 
 + z_asa_sum, z_asa_mm, len_strm, dx_strm, asa, next_asa, 
 + area_asa, order, ex_seq, carr3, z_lc_sum, z_lc_mm, 
 + min_d_ch, max_d_ch, min_d_so, max_d_so, dz_ch_sm, 
 + dz_ch_mm, dz_so_sm, dz_so_mm, area_lc, pcent_lc, 
 + d_ch_sum, d_ch_mm, d_ch_dev, d_ch_sd, d_so_sum, 
 + d_so_mm, d_so_dev, d_so_sd, d_cl_ch, d_cl_so, tmp1)
   if (nstat.ne.0) then
      deallocate (stnnumbr, nnstns, xstns, easting, northing, 
       + elev, wts, stname)
   endif
   close (34)
   close (35)
   stop 'Program completed normally'

* Program termination if land cover value less than 1 encountered within 
* the watershed

2004 write(*,'')
   write(*,2000)
   write(*,2001)
   write(*,2002)
   write(*,2003)
   write(*,2006)
   write(*,2007)
   write(*,'')
   write(*,2005) ir,lc
   write(*,'')
   STOP '!!!! Program terminated on error !!!'
2000 format(1x,'!!!!!!!!!!!!!!!!!!!!!! FATAL ERROR !!!!!!!!!!!!!!!!!!!!!!!!')
2001 format(1x,'!! A cell with landcover value of 0 (zero) !')
2002 format(1x,'!! encountered within the watershed. Adjust the !')
2003 format(1x,'!! ICLASS.INP file so that all cells within the !')
2006 format(1x,'!! watershed have a landcover value of 1 or greater. !')
2007 format(1x,'!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!')
2005 format(1x,'!!!! First error at row ',i5, ' & column ',i5,' !!!')
```

END
UTM

Converts UTM easting northing to lat long

Converts lat long to UTM easting and northing

Good for NAD27/83 north west quadrisphere (metric)

Uses 3, 6 or 8 degree UTM zones

(Pretty obviously converted from C)

R.A. Harrington

raharrin@sentex.net

(519) 822 4192 fax (519) 822 9667

September 1997

----------------------------------------------------------

SUBROUTINE UTM2LL(EAST,NORTH,CMERID,LON,LAT,NAD,DEG)

REAL*8 EAST,NORTH,CMERID,LON,LAT
REAL*8 A,B,C,D,E,SCALE,RAD,ECC,E2,NU,NURHO
REAL*8 NX,NY,DLON,FEAST,TORAD
INTEGER*2 NAD,DEG

Parameters for meridian distance

Eccentricity, radius, e squared

Change for NAD 83

IF(NAD.EQ.83) THEN
  A = 1.005052501804153
  B = 0.00253153702240046
  C = 0.000000110098250
  D = 0.000000000617806
  RAD = 6378206.4
  ECC = 0.081819191043
  E2 = ECC * ECC
  AE = RAD*(1.-E2)
END IF
C SCALE = 0.9996
IF(DEG.EQ.3) SCALE=0.999
IF(DEG.EQ.8) SCALE=0.9994

C TORAD = 3.141592653589791180.
FEAST = 500000.
IF(DEG.EQ.8) FEAST = 1500000.

C DOLON = 0.
LAT = 0.
NU = 0.
NURHO = 0.

C LAT = NORTH / ( SCALE * AE * A)
CALL SETRAD(E2,LAT,NU,NURHO,RAD)

C DLON = (FEAST-EAST) / ( SCALE*NU*DCOS(LAT) )
CALL NRTHNG(NY,AE,A,B,C,D,E,NU,NURHO,LAT,DLON,SCALE)
LAT = LAT + ( NORTH - NY) / (AE * A * SCALE)
CALL SETRAD(E2,LAT,NU,NURHO,RAD)

C Calculate an easting to adjust long
CALL EASTNG(NX,NU,NURHO,LAT,DLON,SCALE)
IF(DABS(FEAST-EAST).GT.0.) THEN
   DLON = DLON - (EAST-FEAST+NX)/NU/DCOS(LAT)
ELSE
   DLON = 0.
END IF

C DO 100 I=1,10
C Now iterate to final answer
C Same procedure as above except
C simplify the lat correction
C
C CALL ESTLAT(LAT,DLON,NU,NURHO,NORTH,SCALE,AE,A,B,C,D,E)
CALL NRTHNG(NY,AE,A,B,C,D,E,NU,NURHO,LAT,DLON,SCALE)
LAT = LAT * NORTH / NY
CALL SETRAD(E2,LAT,NU,NURHO,RAD)

C CALL ESTLON(LAT,DLON,NU,NURHO,EAST,SCALE,FEAST)
CALL EASTNG(NX,NU,NURHO,LAT,DLON,SCALE)
IF(DABS(FEAST-EAST).GT.0.) THEN
   DLON = DLON * (FEAST-EAST)/NX
ELSE
   DLON = 0.
END IF

C CALL EASTNG(NX,NU,NURHO,LAT,DLON,SCALE)
CALL NRTHNG(NY,AE,A,B,C,D,E,NU,NURHO,LAT,DLON,SCALE)
IF(DABS(EAST-FEAST+NX).GT.0.0001) GO TO 100
IF(DABS(NORTH-NY).GT.0.0001) GO TO 100
GO TO 200

100 CONTINUE

200 LON = CMERID + DLON/TORAD
LAT = LAT/TORAD

RETURN
END

C---------------------------------------------------------------------
SUBROUTINE LL2UTM(EAST,NORTH,CMERID,LON,LAT,NAD,DEG)
REAL*8 EAST,NORTH,CMERID,LON,LAT
REAL*8 A,B,C,D,E,SCALE,RAD,ECC,E2,AE,NU,NURHO
REAL*8 DLON,FEAST,TORAD
INTEGER*2 NAD,DEG
Parameters for meridian distance
Eccentricity, radius, e squared

A = 1.005108920378148
B = 0.002559864669165
C = 0.00002702240046
D = 0.00000113812139
E = 0.000000000645685
RAD = 6378206.4
ECC = 0.08227185422
E2 = ECC * ECC
AE = RAD * (1. - E2)

Change for NAD 83

IF(NAD.EQ.83) THEN
  A = 1.005052501804153
  B = 0.00253153703236
  C = 0.000002643065580
  D = 0.000000110098250
  E = 0.000000000617806
  RAD = 6378137.
  ECC = 0.081819191043
  E2 = ECC * ECC
  AE = RAD * (1. - E2)
END IF

Scale factor defaults to 6 degree
SCALE = 0.9996
IF(DEG.EQ.3) SCALE = 0.9999
IF(DEG.EQ.8) SCALE = 0.9994

Convert to radians, false easting
TORAD = 3.141592653589791180.
FEAST = 500000.
IF(DEG.EQ.8) FEAST = 1500000.

Initialize the rest
DLON = (CMERID - LON) * TORAD
LAT = LAT * TORAD
NU = 0.
NURHO = 0.

Get radii of curvature
CALL SETRAD(E2, LAT, NU, NURHO, RAD)
CALL NRTHNG(NORTH, AE, A, B, C, D, E, NU, NURHO, LAT, DLON, SCALE)
CALL EASTNG(EAST, NU, NURHO, LAT, DLON, SCALE)

EAST = EAST + FEAST
RETURN
END

Calculates radii of curvature and frequently used terms

SUBROUTINE SETRAD(E2, LAT, NU, NURHO, RAD)
REAL*8 E2, LAT, NU, NURHO, TEMP, RAD
TEMP = (1. - E2 * DSIN(LAT) * DSIN(LAT))
NU = RAD / DSQRT(TEMP)
NURHO = TEMP / (1. - E2)
RETURN
END

Estimates latitude with terms of northing equation

SUBROUTINE ESTLAT(LAT, DLON, NU, NURHO, NORTH, SCALE, AE, A, B, C, D, E)
REAL*8 LAT, DLON, NU, NURHO, NORTH, SCALE, AE, A, B, C, D, E
REAL*8 NT1, NT2, NT3, NT4

Get terms in northing equation
CALL NTERMS(AE, A, B, C, D, E, NT1, NT2, NT3, NT4, NU, NURHO, LAT, DLON)
LAT = ( ( NORTH / SCALE - NT2 - NT3 - NT4 ) / AE 
+ B*DSIN(2.*LAT) - C*DSIN(4.*LAT)  
+ D*(DSIN(LAT)**5)*DCOS(LAT)  
+ E*(DSIN(LAT)**7)*DCOS(LAT) ) / A
RETURN
END

C--------------------------------------------------------------------
C Estimates longitude with first few terms of easting equation
SUBROUTINE ESTLON(LAT,DLON,NU,NURHO,EAST,SCALE,FEAST)
REAL*8 LAT,DLON,NU,NURHO,EAST,SCALE,FEAST
REAL*8 ET1,ET2,ET3,ET4
C Get terms in easting equation
Then estimate longitude
C Signs account for easting and latitude going in opposite directions
CALL ETERMS(ET1,ET2,ET3,ET4,NU,NURHO,LAT,DLON)
DLON = ( (FEAST-EAST)/SCALE + ET2 + ET3 + ET4  
* ) / ( NU * DCOS(LAT) )
RETURN
END

C---------------------------------------------------------------------
C Calculates the northing
SUBROUTINE NRTHNG(NY,AE,A,B,C,D,E,NU,NURHO,LAT,DLON,SCALE)
REAL*8 NY,AE,A,B,C,D,E,NU,NURHO,LAT,DLON,SCALE
REAL*8 NT1,NT2,NT3,NT4
C Get each term in the northing equation
Calculate northing
C CALL NTERMS(AE,A,B,C,D,E,NTl,NT2,NT3,NT4,NU,NURHO,LAT,DLON)
NY = (NT1 + NT2 + NT3 + NT4) * SCALE
RETURN
END

C---------------------------------------------------------------------
C Calculates the easting
SUBROUTINE EASTNG(NX,NU,NURHO,LAT,DLON,SCALE)
REAL*8 NX,NU,NURHO,LAT,DLON,SCALE
REAL*8 ET1,ET2,ET3,ET4
C Get each term in the easting equation
Calculate easting
C CALL ETERMS(ET1,ET2,ET3,ET4,NU,NURHO,LAT,DLON)
NX = (ETl + ET2 + ET3 + ET4) * SCALE
RETURN
END

C---------------------------------------------------------------------
C Terms in the northing equation
SUBROUTINE NTERMS(AE,A,B,C,D,E,NT1,NT2,NT3,NT4,NU,NURHO,LAT,DLON)
REAL*8 AE,A,B,C,D,E,LAT,DLON,NU,NURHO
REAL*8 NT1,NT2,NT3,NT4
REAL*8 D2,D4,D6,S1,S5,S7,C1,C3,C5,T1,T2,T4,SR,UR2,UR3,UR4
D2 = DLON * DLON
D4 = D2 * D2
D6 = D4 * D2
S1 = DSIN(LAT)
S5 = S1 * S1 * S1 * S1 * S1
S7 = S5 * S1 * S1
C1 = DCOS(LAT)
C3 = C1 * C1 * C1
C5 = C3 * C1 * C1
T1 = DTAN(LAT)
T2 = T1 * T1
T4 = T2 * T2
NR = NURHO
NR2 = NR * NR
NR3 = NR2 * NR
NR4 = NR2 * NR2

NT1 = AE * ( A*LAT - B*DSIN(2.*LAT) + C*DSIN(4.*LAT) * - D*S5*C1 - E*S7*C1 * )

NT2 = D2*NU/2.*S1*C1

NT3 = D4*NU/24.*S1*C3 * ( 4.*NR2-NR-T2 )

NT4 = D6*NU/720.*S1*C5 * ( 6.*NR4*(11.-24.*T2) - 28.*NR3*(1.-6.*T2) * + NR2*(1.-32.*T2) - 2.*NR*T2 + T4 * )

RETURN
END

C---------------------------------------------------------------------
C Terms in the easting equation
C
SUBROUTINE ET TERMS(ET1,ET2,ET3,ET4,NU,NURHO,LAT,DLON)
REAL*8 ET1,ET2,ET3,ET4,NU,NURHO,LAT,DLON
REAL*8 D1,D3,D5,D7,C1,C3,C5,T1,T2,T4,NR,NR2,ET4

D1 = DLON
D3 = D1 * D1 * D1
D5 = D3 * D1 * D1
D7 = D5 * D1 * D1
C1 = DCOS(LAT)
C3 = C1 * C1 * C1
C5 = C3 * C1 * C1
C7 = C5 * C1 * C1
T1 = DTAN(LAT)
T2 = T1 * T1
T4 = T2 * T2
T6 = T4 * T2
NR = NURHO
NR2 = NR * NR
NR3 = NR2 * NR
NR4 = NR2 * NR2
ET1 = D1*NU*C1
ET2 = D3*NU/6.*C3*(NR-T2)

ET3 = D5*NU/120.*C5 * ( 4.*NR3*(1.-6.*T2) + NR2 *(1. + 8.*T2) - 2.*NR*T2 + T4 )

C This compiler is fussy
C Doesn't like this term - pretty small

ET4 = 0.0

ET4 = D7*NU/5040.*C7 * ( 61. - 479.*T2 + 179.*T4 - T6 )

RETURN
END

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Appendix B

Weights (.wts) file (for CSA 500)
<table>
<thead>
<tr>
<th>ID</th>
<th>Type</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
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<td>taiga</td>
<td>1250</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>0</td>
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<td>taiga</td>
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<td>100</td>
<td>0</td>
<td>100</td>
</tr>
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<td>taiga</td>
<td>1250</td>
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<td>100</td>
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<td>0</td>
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<td>1</td>
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<td>1</td>
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<td>77</td>
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<td>4</td>
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<td>0</td>
<td>4</td>
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<td>96</td>
<td>96</td>
<td>0</td>
<td>96</td>
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<td>46</td>
<td>46</td>
<td>0</td>
<td>46</td>
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<td>spruce</td>
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<td>54</td>
<td>54</td>
<td>54</td>
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<td>54</td>
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<td>ASA00003</td>
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<td>747</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>ASA00002</td>
<td>spruce</td>
<td>747</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>0</td>
<td>100</td>
</tr>
</tbody>
</table>
Appendix C

Command (.cmd) file (for CSA 2000)
<table>
<thead>
<tr>
<th>Column</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial contents of snow store (mm)</td>
<td>1.000E+00</td>
</tr>
<tr>
<td>Initial contents of slow store (% of max)</td>
<td>1.000E+01</td>
</tr>
<tr>
<td>Maximum infiltration rate (mm/day)</td>
<td>7.970E+01</td>
</tr>
<tr>
<td>Manning roughness, n</td>
<td>1.000E-04</td>
</tr>
<tr>
<td>Retention constant for fast store (day)</td>
<td>1.000E+00</td>
</tr>
<tr>
<td>Maximum capacity for fast store (mm)</td>
<td>1.787E+02</td>
</tr>
<tr>
<td>Retention constant for slow store (day)</td>
<td>1.000E+01</td>
</tr>
<tr>
<td>Maximum capacity for slow store (mm)</td>
<td>1.308E+02</td>
</tr>
<tr>
<td>Precipitation factor</td>
<td>1.420E+00</td>
</tr>
<tr>
<td>Rain/snow division temperature (deg C)</td>
<td>-9.00E+00</td>
</tr>
</tbody>
</table>

1.000E+00 5.000E+00 1.000E+01 1.000E+02 8.000E+03 1.000E+00 1.000E+01 1.000E+02 1.000E+03

1.000E+00 5.000E+00 1.000E+01 1.000E+02 8.000E+01 4.000E+01

1.000E+00 5.000E+00 1.000E+01 1.000E+02 8.000E+00 1.000E+01 1.000E+00 8.000E-01 4.000E+01

1.000E+00 5.000E+00 1.000E+01 1.000E+02 8.000E+00 1.000E+01 1.000E+00 8.000E-01 4.000E+01

1.000E+00 5.000E+00 1.000E+01 1.000E+02 8.000E+00 1.000E+01 1.000E+00 8.000E-01 4.000E+01

1.000E+00 5.000E+00 1.000E+01 1.000E+02 8.000E+00 1.000E+01 1.000E+00 8.000E-01 4.000E+01

1.000E+00 5.000E+00 1.000E+01 1.000E+02 8.000E+00 1.000E+01 1.000E+00 8.000E-01 4.000E+01

1.000E+00 5.000E+00 1.000E+01 1.000E+02 8.000E+00 1.000E+01 1.000E+00 8.000E-01 4.000E+01

1.000E+00 5.000E+00 1.000E+01 1.000E+02 8.000E+00 1.000E+01 1.000E+00 8.000E-01 4.000E+01

1.000E+00 5.000E+00 1.000E+01 1.000E+02 8.000E+00 1.000E+01 1.000E+00 8.000E-01 4.000E+01

1.000E+00 5.000E+00 1.000E+01 1.000E+02 8.000E+00 1.000E+01 1.000E+00 8.000E-01 4.000E+01

1.000E+00 5.000E+00 1.000E+01 1.000E+02 8.000E+00 1.000E+01 1.000E+00 8.000E-01 4.000E+01

1.000E+00 5.000E+00 1.000E+01 1.000E+02 8.000E+00 1.000E+01 1.000E+00 8.000E-01 4.000E+01
Appendix D

Indicators for Alpha/Beta sensitivity analysis
### TESTING ALPHA & BETA

<table>
<thead>
<tr>
<th>File Name:</th>
<th>13-1TST</th>
<th>AmaxBmax</th>
<th>AmaxBmin</th>
<th>AminBmax</th>
<th>AminBmin</th>
<th>AhlfBhlf</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ALPHA</strong></td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>0.2</td>
<td>0.2</td>
<td>25</td>
</tr>
<tr>
<td><strong>BETA</strong></td>
<td>1</td>
<td>2.5</td>
<td>0.9</td>
<td>2.5</td>
<td>0.9</td>
<td>1.7</td>
</tr>
</tbody>
</table>

**Summary statistics for Wolf Creek Sept '94 to Aug '96**

<table>
<thead>
<tr>
<th>CSA Value:</th>
<th>13</th>
<th>13</th>
<th>13</th>
<th>13</th>
<th>13</th>
<th>13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of ASAs:</td>
<td>615</td>
<td>615</td>
<td>615</td>
<td>615</td>
<td>615</td>
<td>615</td>
</tr>
</tbody>
</table>

| Mean computed flow, m³/s | 0.5728 | 0.5597 | 0.6254 | 0.4413 | 0.4115 | 0.5654 |
| Mean recorded flow, m³/s | 0.5508 | 0.5508 | 0.5508 | 0.5508 | 0.5508 | 0.5508 |
| Ratio of computed vs. recorded flow | 1.040 | 1.016 | 1.135 | 0.801 | 0.747 | 1.027 |
| Mean error, m³/s | 0.022 | 0.009 | 0.075 | -0.109 | -0.139 | 0.015 |
| Standard error, m³/s | 0.40 | 0.62 | 0.45 | 0.92 | 0.90 | 0.58 |
| Largest daily error, m³/s | 3.74 | 6.04 | 3.74 | 10.23 | 10.33 | 5.70 |
| Nash/Sutcliffe criterion (1) | 0.78 | 0.48 | 0.73 | -0.14 | -0.09 | 0.54 |
| Previous-Day criterion (1, or >1) | -0.92 | -3.54 | -1.35 | -8.99 | -8.55 | -2.99 |
| Deviation of volume, % (0) | -4.00 | -1.61 | -13.54 | 19.87 | 25.28 | -2.65 |

### TESTING ALPHA & BETA

<table>
<thead>
<tr>
<th>File Name:</th>
<th>2500nt3</th>
<th>2501tst</th>
<th>AmaxBmax</th>
<th>AmaxBmin</th>
<th>AminBmax</th>
<th>AminBmin</th>
<th>AhlfBhlf</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ALPHA</strong></td>
<td>50</td>
<td>optimized</td>
<td>50</td>
<td>50</td>
<td>0.2</td>
<td>0.2</td>
<td>25</td>
</tr>
<tr>
<td><strong>BETA</strong></td>
<td>1</td>
<td>optimized</td>
<td>2.5</td>
<td>0.9</td>
<td>2.5</td>
<td>0.9</td>
<td>1.7</td>
</tr>
</tbody>
</table>

**Summary statistics for Wolf Creek Sept '94 to Aug '96**

<table>
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<tr>
<th>CSA Value:</th>
<th>2500</th>
<th>2500</th>
<th>2500</th>
<th>2500</th>
<th>2500</th>
<th>2500</th>
<th>2500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of ASAs:</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

| Mean computed flow, m³/s | 0.5603 | 0.5594 | 0.5601 | 0.5603 | 0.5584 | 0.5587 | 0.5602 |
| Mean recorded flow, m³/s | 0.5508 | 0.5508 | 0.5508 | 0.5508 | 0.5508 | 0.5508 | 0.5508 |
| Ratio of computed vs. recorded flow | 1.017 | 1.017 | 1.017 | 1.017 | 1.014 | 1.014 | 1.017 |
| Mean error, m³/s | 0.010 | 0.009 | 0.010 | 0.008 | 0.008 | 0.009 |
| Standard error, m³/s | 0.72 | 0.71 | 0.72 | 0.60 | 0.48 | 0.70 |
| Largest daily error, m³/s | 8.68 | 4.84 | 8.70 | 7.17 | 5.58 | 8.52 |
| Nash/Sutcliffe criterion (1) | 0.32 | 0.79 | 0.33 | 0.52 | 0.69 | 0.34 |
| Previous-Day criterion (1, or >1) | -4.98 | -0.87 | -4.84 | -5.00 | -3.23 | -1.68 | -4.79 |
| Deviation of volume, % (0) | -1.74 | -1.57 | -1.70 | -1.74 | -1.39 | -1.43 | -1.72 |
Appendix E

Stream hydrographs for Alpha/Beta sensitivity analysis
(a)

(b)
CSA 2550

Flow (m³/s)

Date

24-Mar-95  24-Apr-95  25-May-95  26-Jun-95  26-Jul-95  26-Aug-95  26-Sep-95

--- AmnMax
--- AmnMin
Default(50,1)
Qobs

(e)