Current Limitations of Hydrologic Modeling In B.C.: An Examination of the HSPF, TOPMODEL, UBCWM and DHSVM Hydrologic Simulation Models, B.C. Data Resources and Hydrologic-Wildfire Impact Modeling

by

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We accept the thesis as conforming
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ABSTRACT

This thesis examines current problems and limitations of hydrologic modeling in British Columbia with respect to operational forestry use and hydrologic-wildfire modeling. A comparative review of the HSPF, TOPMODEL, UBCWM and DHSVM hydrologic simulation models and the availability and limitations of B.C. data resources in relation to hydrologic modeling are provided. Also discussed are a review of hydrologic-wildfire impacts, criteria for the development of a hydrologic-wildfire model and a description of an attempt to apply the DHSVM to a B.C. interior watershed.

The model review indicates that none of the four hydrologic models are optimally suited for widespread operational use in B.C. forest management. This is due to limitations of the hydrologic models in addressing a wide range of forestry modeling goals as each model has been created for a specific purpose, in a specific locale. The data resources review indicates that many different agencies in B.C. collect data that could be used in hydrologic modeling. However, it appears that the most limiting factor of B.C. data resources, for hydrologic modeling purposes, is the sparseness of meteorological, snow and streamflow data on a spatially distributed basis. The attempt to apply the DHSVM to a B.C. interior watershed illustrates the importance of being prudent in matching hydrologic modeling goals to the available data and hydrologic model. This attempt also highlights the necessity of allowing ample time in a modeling project for data preparation and model calibration when using a hydrologic model for the first time. The review of hydrologic-wildfire impacts indicates that wildfire has the potential to create earlier and larger peakflows, higher than average soil moisture levels and deeper and earlier melting snow-packs in a forested watershed. A physically-based, distributed hydrologic model was determined to be the most optimal candidate for development into a hydrologic-wildfire model.

The conclusion is reached that the absence of a hydrologic model specifically designed for operational use in B.C. limits widespread hydrologic modeling in forest management. Despite these results, hydrologic models possess a great potential for use in B.C. forest management.

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CHAPTER 1
INTRODUCTION

1.1 Introduction

Recently, there have been many important changes in the way forests are managed in British Columbia. The implementation of new legislation, including the Forest Practices Code, has lead to a stricter regulation of all forest activities in the province. Associated with these stricter regulations is an increased responsibility of forest managers to be able to accurately assess and predict the possible effects that forest disturbance (e.g., timber harvesting, wildfire, bark beetles, windthrow) will have on the landscape. The alteration of the normal hydrologic regime of an area is often at the forefront of these concerns. Forest activities that create changes in streamflow, water chemistry, water temperature and snow-pack depth may have repercussions on features such as flooding, water supply, water quality, fish habitat and fish survival. Yet, due to the complexity of many hydrologic systems, the ability to accurately predict the changes that may result from forest disturbance is a difficult task.

Hydrologic simulation models can be used as a tool to quantify forest disturbance impacts and, subsequently, aid forest management in B.C. Hydrologic models can be used to investigate a variety of forestry scenarios to assess the hydrologic impacts of many different treatments before those activities are initiated. In addition, some hydrologic models have the potential to incorporate climate change and natural disturbance into simulations providing for a greater degree of realism. However, the use of hydrologic models in forest management is not widespread as most applications have historically been in the fields of hydrologic research and engineering. There are many reasons why hydrologic simulations models have not gained popularity in forest management that may include: model complexity, model esotericism, lack of suitable data, user unfriendliness and excessive time consumption. Ultimately, the absence of a hydrologic model specifically designed for operational use in B.C. presents a significant barrier to widespread hydrologic modeling in forest management. Despite these concerns, hydrologic simulation models have a great potential for use in forest management in B.C.

This thesis was initiated with an attempt to apply the Distributed Hydrology-Soils-Vegetation Model (DHSVM) to a watershed located in the interior of British Columbia. The goal was to investigate whether or not the DHSVM could be used successfully as a tool to predict the effects of both forest harvesting and wildfire on the hydrologic regime of a small watershed. Unforeseen circumstances, limitations in the obtained modeling data and difficulties with the DHSVM resulted in the eventual termination of the modeling project. This experience provided valuable insight on potential limitations of hydrologic modeling in B.C. As a result, the modeling problems encountered are important to convey to other prospective model users as many of these limitations can be avoided or solved if known about before modeling projects commence.

In order to continue with the theme of the original research, the thesis topic was expanded to augment this modeling attempt to include a review of four popular hydrologic models that have potential for application in B.C. This review includes an assessment of model suitability for use in B.C., a discussion of data availability and limitations in B.C. and some ideas on the development of a hydrologic-wildfire simulation model.

This thesis topic is unique in that it presents B.C. modeling issues from a model users perspective. Hence, issues that may seem trivial to hydrologic model creators will be illustrated and issues that may seem esoteric to model users will be explained in an attempt to provide a more holistic discussion of hydrologic modeling. The modeling attempt described could be considered representative of what first-time hydrologic model users with adequate computer skills might experience in B.C. Overall, the thesis topics covered should provide the reader with a comprehensive understanding of what is required, what is limiting and what resources are available in order to successful apply hydrologic models in B.C.

1.2 Goals and Objectives

The purpose of this thesis is twofold: first to provide a basic understanding of the issues surrounding hydrologic modeling and, second, to highlight the current problems and limitations of hydrologic modeling in B.C. with respect to operational forestry use and hydrologic-wildfire modeling. To accomplish these goals, five main objectives were established:

1) to define hydrologic models, in general, and describe some of the different model classification schemes used;

2) to document the background and limitations of the following four hydrologic simulation models: Hydrologic Simulation Program-FORTRAN (HSPF), TOPMODEL, UBC Watershed Model (UBCWM), and the Distributed Hydrology-Soils-Vegetation Model (DHSVM);

3) to document the data resources currently available in B.C. and illustrate the general limitations of such data with respect to hydrologic modeling;

4) to illustrate by way of a case study, the inherent limitations first time hydrologic modelers may encounter and;

5) to discuss hydrologic-wildfire impacts and simulation.

1.3 Thesis Outline

Each one of these objectives represents a chapter in this thesis that will be examined and discussed in the above order. Chapter 2 provides a discussion on what hydrologic models represent and why they are important in B.C. Also included is background information on four model classification categories. Chapter 3 documents the background of four popular hydrologic simulation models: HSPF, TOPMODEL, UBCWM and DHSVM. Chapter 3 also compares these four models, documenting the strengths and weaknesses of each model in relation to suitability for operational forestry use in B.C. Chapter 4 documents the availability and general limitations of B.C. data resources for hydrologic modeling purposes. Chapter 5 illustrates some inherent limitations that first time hydrologic modelers might encounter when attempting to use a hydrologic model in B.C. Chapter 5 also provides details on the original thesis topic and the problems that were encountered. Chapter 6 discusses the impacts that wildfire can impose on the hydrologic regime of a watershed. Chapter 6 also discusses some current limitations of hydrologic models in simulating hydrologic-wildfire impacts as well as criteria for the selection of a candidate model that could be modified and used as a hydrologic-wildfire impact simulator. Chapter 7 provides the summary and concluding remarks for this thesis.

CHAPTER 2
CLASSIFICATION OF HYDROLOGIC SIMULATION MODELS

2.1 Introduction

This chapter will provide background information on model classification that will allow the reader to better understand discussion topics presented later in the thesis. Four model classification categories are examined that include model characteristics, model processes, temporal characteristics and spatial characteristics. To begin, this chapter discusses what a hydrologic model represents and details some possible goals of using hydrologic models in forest management in B.C.

2.2 What is a Hydrologic Model?

In general, hydrologic models represent simplifications of reality and are based upon our interpretation and understanding of hydrologic processes. Hydrologic models employ numerous mathematical equations containing parameters and variables meant to represent hydrologic processes. A variable can be defined as any characteristic of a system that varies temporally or spatially in numeric value (Singh, 1988). Some examples of hydrologic variables include daily precipitation, evaporation and temperature (Singh, 1988). A parameter is a quantity characterizing a hydrologic system, which for the most part is constant over time (Clarke, 1973; Singh, 1988). Some examples of hydrologic model parameters include: hydraulic conductivity, time of concentration and Manning's roughness factor (Singh, 1988).

Many hydrologic models represent a culmination of hydrologic knowledge that is at the cutting edge; constantly evolving as research gains new insights on hydrologic concepts. Historically, concepts in hydrology have preceded our ability to incorporate them into computer models due to computer limitations. Today, advances in computer technology have allowed for the development of highly complex computerized hydrologic models (Beven, 1989; Blöschl et al., 1992). In addition, new technologies such as remote sensing and geographic information systems (GIS) have changed the way data are collected and processed in many hydrologic modeling packages.

Hydrologic models are often used to simulate the quantity and/or quality of water in a watershed (also called a drainage basin or catchment). Water quantity and quality are a function of the interplay between climate, soil, vegetation and topography within each ecosystem in the watershed unit. Any change in one of these components will invoke changes in the others and, hence, may create altered water quantity and water quality regimes. It is thus important to manage the effects humans have on each of these features holistically, although watersheds are rarely managed in a holistic manner (Singh, 1995). Hydrologic computer models are thus important as they can be used as an aid to this holistic forest management concept.

2.3 Operational Use of Hydrologic Models

While hydrologic models have great potential for use in B.C. forest management, all hydrologic models possess limitations that can either decrease or negate their suitability for use in certain modeling scenarios. One of the biggest limitations that a majority of hydrologic models currently possess is that many models have been designed around solving specific hydrologic problems, often in distinct geographic locales. As such, the range of applications that many models can address may be limited depending upon model capabilities. Some examples of the potential applications of hydrologic models in forestry might include:

- to determine the maximum expected changes in peak flows resulting from timber harvesting;
- to determine the percentage of a watershed that could be harvested before changes in streamflow occur;
- to obtain accurate estimates of peak flow and water yield from a watershed;
- to derive simplistic rainfall-runoff relationships;
- to determine the impacts of forest disturbance in altering the flood regime of a regional watershed (i.e., Fraser River);
- to calculate peak flows for bridge, culvert and road drainage design;
- to determine the long term affects of forest management (fire suppression, timber

harvesting and silviculture) on water yield, peak flow and peak flow timing in municipal watersheds;

- to determine the affects of timber harvesting on late summer low flows;
- to determine the affects of wildfire on water yield and;
- to determine the impacts of climate change on altering the hydrologic regime of a watershed (i.e., snow accumulation and melt, glacier melt, water yield) and interplay with forest harvesting.

These are only some of the many possible goals of using hydrologic models in forest management in B.C. In considering these modeling goals, the suitability of any given hydrologic model will vary depending upon the spatial scale of the modeling exercise (global vs. regional vs. local), the modeling time frame (long term or short term) and the accuracy of simulation results required (precise or crude). For example, a modeling problem requiring long term, accurate simulation results on a local scale, would not be appropriately addressed by a hydrologic model capable of providing only short term, crude simulation results on a regional basis. The capabilities and, hence, characteristics of a hydrologic model, therefore, define the data inputs required, the simulation results produced and ultimately what goals may be satisfactorily achieved by a model. It is therefore prudent that the goals of a hydrologic modeling exercise be efficiently matched to the capabilities of the hydrologic model selected.

The utility of using hydrologic models operationally in B.C. will vary depending upon forest management objectives and planning scale. The hierarchical planning structure of B.C. forest management is complex and varies depending upon locale (i.e., coast vs. interior). As such, a detailed description of this planning process will not be provided. It is important, however, to highlight the place within this planning structure where hydrologic models would have the greatest utility. Ideally, there are five levels in the provincial forest management planning system: provincial, regional, sub-regional, local and operational/site. Most of the specific planning (what this thesis terms ‘operational’) in B.C. occurs at the sub-regional level (Land and Resource Management Plans - LRMPs), local level (Landscape level plans) and site level (Operational plans). LRMPs are 10 year management plans, approximately the size of a forest district. LRMPs are higher level plans that are strategic; providing direction but not specifics on land use. Hydrologic models could be used in the LRMP planning process to investigate and supplement management decisions that affect large scale features of the LRMP and its subdivisions; the resource management zone (RMZ). For example, at this scale a hydrologic model could be used to determine the impacts of forest disturbance in altering the flood regime of a regional watershed (i.e. Fraser River).

Landscape level planning is local planning that focuses on intermediate sized watersheds or areas that may include several small watersheds. This level of planning provides more specific direction to the operational plans than do LRMPs. Wildlife and biodiversity objectives in the Forest Practices Code guidelines are implemented at this scale. Landscape level planning is well suited to holistic forest management and as such, hydrologic models can supplement planning decisions on a scale congruent with timber and non-timber land use objectives. For example, at this scale a hydrologic model could be used to determine the long term affects of forest management (fire suppression, timber harvesting and silviculture) on water yield, peak flow and peak flow timing in a municipal watershed. These results could in turn be used to investigate further effects on non-water related land use objectives (e.g., biodiversity, wildlife, etc.).

Operational plans are a form of lower level planning that are used to prescribe the specifics of land use (e.g. timber extraction) that are to occur on a site scale. Operational plans are site specific and must be consistent with the objectives of higher level plans (LRMPs). Examples of operational plans include: forest development, range use, silviculture, access management, logging and stand management plans. In many instances, the objectives of using a hydrologic model at this planning scale would be similar to landscape level planning. However, because operational planning occurs on a smaller scale (site to sub-basin), smaller units within a watershed would be investigated with a hydrologic model. For example, a hydrologic model could be used to investigate changes in peak flows resulting from timber harvesting (proposed cut-block layout or harvest method) or calculate peak flows for bridge, culvert and road drainage design.

Despite the enormous potential for use at present, hydrologic computer models have yet to become a commonly used tool in practical hydrologic applications (Singh, 1995). As will be discussed in Chapters 3 and 4, there are many limitations that create barriers to the operational implementation of hydrologic models in B.C. To better understand these limitations, it is important to understand the many different hydrologic model classification schemes available.

2.4 Hydrologic Model Classification

A survey of the literature reveals a number of different classification schemes for categorizing hydrologic models. In this chapter, background information on four model classification categories are provided that include model characteristics, model processes, temporal characteristics and spatial characteristics. Hydrologic models may also be classified in many other ways such as by land-use (i.e., agricultural, urban, forest, range, desert, mountainous, coastal, wetlands and mixed) or by model use (i.e., planning, management and prediction) (Singh, 1995).

2.4.1 Model Characteristics

For this category, models are classified according to basic descriptive criteria. Seven classification distinctions are made which include: theoretical, empirical, conceptual, complete, partial, calibrated and measured parameter models. These classification distinctions are not mutually exclusive as models can be described by more than one of the above mentioned criteria (i.e., a complete, fitted parameter empirical model).

Many of the mathematical models found in the literature can be described as being either theoretical or empirical models. By definition, theoretical (physically-based) models simplify hydrologic processes and are comprised of general laws and theoretical principles that often incorporate empirical equations into their modeling structure (Woolhiser and Brakensiek, 1982; Singh, 1988). Empirically based models, on the other hand, can be viewed solely as representations of data as they often are not based upon any laws (Woolhiser and Brakensiek, 1982; Singh, 1988). The division between these categories, however, is ambiguous as what is one person's theory is another's empiricism (Singh, 1988; Clarke, 1973). For example, Darcy's law (a physical law) was derived by observation and, hence, could be considered empirical (Singh, 1988; Clarke, 1973). Yet, some models based firmly in physics may also contain empirical components. Therefore, the distinction between the two classes is arbitrary according to one's viewpoint. When speaking of theoretical and empirical models, some authors periodically make reference to conceptual models. Conceptual models are intermediate between theoretical and empirical models, often containing highly simplified physical laws (Singh, 1988).

Hydrologic models can also be classified as either complete or partial according to the depth by which they model the hydrologic cycle. A complete model would, in most cases, create a simulated hydrograph to represent all hydrologic processes (Larson et al., 1982). Complete models are comprehensive, as they calculate values to represent each process in the hydrologic cycle. In contrast, a partial model only simulates a portion of the hydrologic cycle and, hence, is not as comprehensive.

Models can also be classified as calibrated (fitted) parameter or measured parameter models according to the method by which their parameters are derived. Calibrated models have one or more parameters that have been derived by fitting simulated hydrographs to observed flow data (Larson et al., 1982). Most models can be classified as calibrated parameter models if they contain empirical components. Measured parameter models have all their parameters derived "from known watershed characteristics, either by estimation or measurement" (Larson et al., 1982: 412). These models are unique in that they can feasibly be applied to ungauged watersheds. The development of such a model that is both continuous and accurate, however, has yet to be achieved (Larson et al., 1982).

2.4.2 Model Processes

Hydrologic models can also be classified according to the characteristics of the model's processes. Four classification distinctions are made which include: lumped, distributed, deterministic and stochastic. The most popular distinction made between hydrologic models is whether or not a model is lumped or distributed. Lumped models typically use average values to represent various processes over an entire watershed (lumped) in order to obtain an overall output at the basin outlet (Rosso, 1992). A lumped model does not account for the spatial variability of model parameters, variables, hydrologic processes and geometric characteristics within a watershed (Singh, 1995; Singh, 1988; Woolhiser and Brakensiek, 1982; Clarke, 1973).

Distributed models are mathematical models that maintain and account for the spatial variation of model parameters, variables, hydrologic processes and geometric characteristics over the modeled watershed (Rosso, 1992; Singh, 1995; Woolhiser and Brakensiek, 1982; Clarke, 1973). In general, distributed models require more information and usually contain more parameters than do lumped models (Singh, 1995). Distributed models usually divide a drainage basin into units or pixels of a defined size. For each of these units, a unique set of variables and parameters are assigned which are maintained throughout the simulation. However, data limitations often prevent the realization of fully distributed models, as certain system characteristics may have to be lumped within many distributed models. Hence, many distributed models may more appropriately be classified as semi or quasi-distributed in cases where the lumping of certain watershed characteristics exists (Singh, 1995).

Hydrologic models can also be classified as either deterministic or stochastic according to the way in which processes are described in the model. A deterministic model is one whose variables are generally free from random variation (Woolhiser and Brakensiek, 1982; Clarke, 1973). A stochastic model, however, has one or more variables that are randomly distributed in probability (Woolhiser and Brakensiek, 1982; Clarke, 1973). Singh (1995) describes variants of these as quasi-stochastic, quasi-deterministic and hybrid model or stochastic-deterministic depending upon the respective mixture of deterministic and stochastic components.

2.4.3 Temporal Characteristics

Models may also be classified temporally as either event or continuous based according to the number of hydrologic events simulated. An event based model only simulates a single hydrologic event (hours to days). A continuous model calculates flow rates and watershed conditions continuously over longer periods of time usually from several years to decades. Continuous based hydrologic models simulate more than one hydrologic event as well as the period between hydrologic events.

2.4.4 Spatial Characteristics

Models may also be classified according to their spatial characteristics. Singh (1995) outlined three classes of models that are distinct depending upon the capabilities and requirements of the model in simulating the hydrology of different sized watersheds: namely, small, medium and large. Song and James (1992) reviewed five scales used in hydrologic simulation that could be used to delineate a more appropriate model classification scheme based upon spatial scale. The five scales are: laboratory, hillslope, catchment, basin and continental or global scale. In general, the complexity of each model category increases with the associated scale. Laboratory scale hydrologic models can be defined as one dimensional models that use hydrodynamic equations (Song and James, 1992). Hillslope scale models are two or three dimensional models that incorporate information that can only be gathered *in situ*; for example, soil macroporosity (Singh, 1995; Song and James, 1992). Hillslope models also incorporate surface and subsurface flow routing schemes in their simulations (Singh, 1995). Catchment scale models include topography in the modeling of surface runoff and geologic information in the simulation of subsurface runoff (Song and James, 1992; Singh, 1995). Basin scale models use storage and translation routing schemes to simulate watershed runoff (Song and James, 1992; Singh, 1995). Continental and/or global scale models concentrate on modeling atmospheric processes that influence evapotranspiration and precipitation (Song and James, 1992).

2.5 Conclusion

As reflected by the numerous classification schemes, there are many different types of hydrologic models available. Knowledge of the differences between hydrologic model types is important as it can be used to efficiently match modeling objectives to the most appropriate hydrologic model available. However, while knowledge about a hydrologic model can be derived from its classification grouping, more specific information about the model is usually required to determine its overall suitability. Specific hydrologic model information can be gained from two main sources. Model users can personally research each model under consideration, which can prove to be time consuming or model users can consult comparative model reviews in which many hydrologic models have been compared on a structured basis. Obtaining information from comparative model reviews is frequently more efficient than personal model reviews as a wealth of information on many different models can be gained with minimal time expenditure.

CHAPTER 3
COMPARATIVE REVIEW OF FOUR HYDROLOGIC SIMULATION MODELS: HSPF, TOPMODEL, UBCWM AND DHSVM

3.1 Introduction

Over the last 30 years, there has been a proliferation in the production of hydrologic simulation models. With this variety comes the difficult and sometimes daunting task of matching hydrologic model capabilities to modeling objectives. Hydrologic model reviews can be useful sources of information to aid the model selection process. Unfortunately, few model reviews examine more than one model on a consistent, systematic basis. Additionally, many reviews focus on the esoteric limitations of the model and often do not acknowledge the trivial problems that are also of concern to model users.

This chapter systematically reviews the HSPF, TOPMODEL, UBCWM and DHSVM hydrologic simulation models. This review will include background descriptions, model comparisons and an outline of each model's potential for use in forested areas of B.C. Information for this chapter has been gathered from literature sources, interviews with model creators and users and through the personal experiences of the author, a first time hydrologic model user. Contact addresses have been provided (Appendix A) should the reader require further information on any of these models.

3.2 Hydrologic Simulation Program-FORTRAN (HSPF) Model

3.2.1 HSPF Model Background

The Hydrological Simulation Program - FORTRAN (HSPF) is a comprehensive digital computer model that can simulate both the quantity and quality of water in streams, in mixed impoundments as well as on pervious and impervious land surfaces (Bicknell et al., 1993). Depending upon application, the HSPF can be classified as a semi-distributed to lumped, continuous or event-based hydrologic model. The HSPF is based upon three previously developed models: the Hydrologic

Simulation Program-HSP, the EPA Nonpoint Source Runoff Model-NPS and the EPA Agricultural Management Model-ARM (Donigian et al., 1995). The HSPF model was first released to the public in 1980 (release 5) and now is currently in its 11th release.

The HSPF model can simulate the "continuous, dynamic event, or steady-state behavior of both hydrologic/hydraulic and water quality processes in a watershed, with an integrated linkage of surface, soil and stream processes" (Donigian et al., 1995: 396). For model operation, watersheds are divided into homogenous land units called segments (Bicknell et al., 1993) that contain the same soil, vegetation and topographic properties as well as precipitation and potential evapotranspiration rates. The HSPF is capable of providing estimates of streamflow, nutrient concentrations, pesticide concentrations, sediment load and many other water quantity and quality estimates at any given point in a modeled watershed (Donigian et al., 1983).

The HSPF has a modular design comprised of three application modules and six utility modules. The utility modules include: COPY, PLTGEN, DISPLY, DURANL, GENER and MUTSIN. These modules are used in the analysis and manipulation of data. The three application modules include: PERLND, IMPLND and RCHRES. The PERLND module is used to simulate water quality and runoff processes on pervious land surfaces (Donigian et al., 1995). The IMPLND module is used to simulate water quality and runoff on impervious land surfaces. The RCHRES module is used to simulate runoff and water quality in stream channels and reservoirs.

Several supplemental programs have been developed for the HSPF (i.e., ANNIE, HSPEXP, WDM and Scenario Generator) that are used primarily for data processing and result analysis (Donigian et al., 1995). Of particular interest to hydrologic model users may be the HSPEXP program, which is a stand-alone version of the land surface hydraulics found in the HSPF (Donigian et al., 1995). The HSPEXP is an attempt to bring the knowledge of hydrologic modeling experts to the general model user. It is a program that contains a set of hierarchical rules that guides model users through the model calibration process, thereby aiding in the identification of parameters for which adjustment is required.

The HSPF model has enjoyed a wide following since its release in 1980 and throughout its ‘life’, has constantly undergone improvements and additions. An excellent discussion of the current state of the HSPF model and proposed future enhancements can be found in Donigian (et al., 1995). An in-depth discussion of HSPF model background can be found in Bicknell (et al., 1993) and Donigian (et al., 1995). Further information on the HSPF model can be obtained from the U.S. Geological Survey, Hydrologic Analysis Software Support Team or the Environmental Protection Agency, Center for Exposure Assessment Modeling (CEAM) (Appendix A). A listing of HSPF related websites are provided in Appendix B.

3.2.2 HSPF Data Requirements

Data requirements for the HSPF are dependent upon model application (i.e., water quantity simulations and/or water quality simulation) and the characteristics of the watershed (i.e., presence or absence of snow). In general, the HSPF requires “a time history of rainfall, temperature, evaporation and parameters related to land-use patterns, soil characteristics and agricultural practices to simulate the processes that occur in a watershed” (Donigian et al., 1995: 396). To simulate snow-melt, the HSPF requires additional measurements of wind, solar radiation and dew point. Data pertaining to tillage practices, pesticide application and pollution point sources can be required for water quality simulations. Streamflow measurements and sometimes pollution concentrations are required for model calibration. Data time steps used by the HSPF generally range from one minute to daily.

3.2.3 HSPF Computer Requirements

The HSPF model can be run on either DOS or UNIX operating systems. The USGS distributes the HSPF specifically for Data General AViiON and Sun SPARCstation, UNIX based computers (Donigian et al., 1995). DOS based computers should have at least a 386 processor with at least, 4 mega-bytes of extended memory.

3.2.4 Historical HSPF Applications

The HSPF has been successfully applied hundreds of times in a variety of climates around the world (Donigian et al., 1995). Applications of the HSPF have ranged from using the model in its most basic mode to using the model as the basis for the creation of more complex models. Many of the published applications of the HSPF model have been in the U.S.A. The HSPF has been used extensively in Washington, Iowa, Tennessee, Maryland, Virginia, Nebraska, Nevada, Pennsylvania, Illinois, New York and Georgia (K. Flynn per. comm., 1997). Donigian et al. (1983) discussed evaluating the HSPF's capabilities in examining the effect of agricultural best management practices on water quality in two watersheds in Iowa. Some of the more significant and complex applications of the HSPF in the U.S. have been in Chesapeake Bay, Patuxent River, Carson-Truckee River Basin and Seattle (Donigian et al., 1995). In British Columbia, data from Carnation Creek, on the West Coast of Vancouver Island, have been used in a test calibration of the HSPF for use in forested watersheds (Hetherington et al., 1995). A listing of selected HSPF model references are provided in Appendix C.

3.2.5 HSPF Model Availability

A UNIX version of the HSPF is available from the website "http://h2o.usgs.gov/software/surface_water.html". A DOS version of HSPF is available from the website "ftp://ftp.epa.gov/epa_ceam/wwwhtml/hspf.htm".

3.2.6 HSPF Model Training

HSPF training is available through a variety of organizations that include: EPA, US Geological Survey, Hydrocomp Inc. and AQUATERRA Consultants. Training costs vary depending upon organization. The USGS offers a one week training course at a cost of $1,700.00 (U.S. currency) for foreign students and $1,500.00 for U.S. students. AQUATERRA Consultants offer HSPF training at the convenience of the student's workplace. A two-day, AQUATERRA HSPF hydrology workshop with up to six people, costs $2,000 plus travel expenses (from Everett, Washington). Contact information for these organizations are provided in Appendix

A.

3.3 TOPMODEL

3.3.1 TOPMODEL Background

The development of the first version of the TOPMODEL hydrologic simulation program was initiated in 1974 by Mike Kirkby at the University of Leeds, United Kingdom. The model was developed for landscape types in the U.K. TOPMODEL can be classified as a distributed to semi-distributed, event or continuous, hydrologic computer model. TOPMODEL's creators view it not as a modeling package, but rather as a set of conceptual tools that can be used to simulate the hydrologic behavior of a watershed (Beven et al., 1995). Because of this, TOPMODEL has been adapted and applied in a variety of ways by many different model users since the original version was created. This diversity is reflected in TOPMODEL's lengthy bibliography.

TOPMODEL is programmed in FORTRAN and the structure of the model has been purposely kept simple by its creators. An advantage of this simplicity is the relative ease with which TOPMODEL can be modified to suit model user needs. The number of physical parameters in TOPMODEL also has been kept to a simple minimum. This ensures that the physically interpretable parameters "do not become merely the statistical artifacts of a calibration exercise" (Beven et al., 1995: 627). At a minimum, four effective catchment parameters are required in TOPMODEL; namely saturated zone, saturated transmissivity, root zone and channel routing velocity parameters. The components of the hydrologic cycle simulated by TOPMODEL vary by model version. In general, TOPMODEL can predict streamflow, overland flow, subsurface flow, soil moisture, evapotranspiration and water-table discharge.

Like the HSPF model, TOPMODEL has enjoyed a wide following in the hydrologic modeling community. However, unlike the HSPF model, there has not been a "standard" version of the model available as most users have adapted the model to suit their own particular research needs. These adaptations have lead to the development of an abundance of different versions of TOPMODEL as well as other models based on TOPMODEL. A listing of these variants can be found on page 16 of the TOPMODEL user's manual, Version-95.02 which is available from the website: http://www.es.lancs.ac.uk/es/Freeware/ Freeware.html. Further information on the TOPMODEL can be obtained from Keith Beven, Lancaster University, United Kingdom (Appendix A). A listing of TOPMODEL related websites are provided in Appendix B.

3.3.2 TOPMODEL Data Requirements

Data requirements for TOPMODEL are dependent upon application and the version of TOPMODEL used. In general, the data required for TOPMODEL include a time series of precipitation, evapotranspiration, daily maximum and minimum temperature, soil data and digital elevation data. Typically, one hour to three hour data time steps are optimal for TOPMODEL.

3.3.3 TOPMODEL Computer Requirements

The demonstration version of TOPMODEL distributed by Lancaster University, U.K., requires a computer with, at minimum, a 386 CPU with a math co-processor, MS-DOS operating system and EGA graphics. TOPMODEL is programmed in Lahey FORTRAN 77 and supplied in this format as well as in an executable format.

3.3.4 Historical TOPMODEL Applications

TOPMODEL was originally applied in 1979 to the Crimple Beck catchment in northern England (Beven and Kirkby, 1979). Since TOPMODEL is viewed not as a modeling package, but rather as a set of conceptual tools used to simulate the hydrologic behavior of a watershed (Beven et al., 1995), there have been many adaptations and applications around the world. Beven et al. (1995) noted applications of TOPMODEL in the humid temperate climates of New Zealand, Scotland and the Eastern United States (Hornberger et al., 1985) as well as in the dry Mediterranean-type climates in France. TOPMODEL has also been used in flood frequency forecasting and within a GIS framework (Beven et al., 1995). Widespread use of TOPMODEL continues today and a special issue of the journal *Hydrological Processes* entitled "TOPMODEL Special Issue 1997" that details many other current applications and limitations of TOPMODEL has recently become available (December 1997). A book version of the special issue entitled "*Distributed Modelling in Hydrology: Application of the TOPMODEL concepts* is also available (Beven, 1997). Unfortunately, this special issue was released too late to be used in this thesis. A listing of selected TOPMODEL references are provided in Appendix C.

3.3.5 TOPMODEL Availability

Many different versions of TOPMODEL have been created and are currently in use by the hydrologic modeling community. A version of TOPMODEL, distributed by Lancaster University, U.K., can be downloaded from the website: http://www.es.lancs. ac.uk/es/Freeware/Topmodel/software.html.

3.3.6 TOPMODEL Training

Currently, no formal training in TOPMODEL use is available. However, a TOPMODEL seminar was offered in 1995 in Lancaster, U.K. at a price of £400 (K. Beven per. comm., 1997). Additional seminars, possibly taking place in the United States, are currently under consideration. Contact Keith Beven for more information.

3.4 UBC Watershed Model (UBCWM)

3.4.1 UBCWM Background

The UBC Watershed Model (UBCWM) was developed at the University of British Columbia, Vancouver, B.C. The model can be classified as a lumped to semi-distributed, continuous or event, hydrologic simulation computer model. The UBCWM was originally designed for short term river flow forecasting (Quick et al., 1995) in mountainous terrain where runoff is generated by a combination of rainfall, snow-melt and glacier melt (Quick, 1995). In B.C., orography can have a strong influence on temperature and precipitation patterns. The UBCWM incorporates the influences of these processes within its modeling structure through the use of elevation zones (bands).

The UBC Watershed Model can provide estimates of streamflow, "...accumulation and depletion of snow-pack, soil moisture budget, soil and groundwater storage values, contributions to runoff from various portions of the watershed and surface and subsurface components of runoff" (Quick, 1995: 234). The model is divided into seven major modules which include: a meteorological sub-module, soil moisture sub-module, watershed routing sub-module, output and evaluation sub-module, semi-automatic calibration sub-module, updating sub-module and a routing sub-module (Quick, 1995). Descriptions of the functions of these sub-models can be found in Quick (1995) and Quick et al. (1995). Overall, water is routed through four storage reservoirs in the UBCWM that include: fast (surface runoff), medium (interflow), slow (upper groundwater) and very slow (deep groundwater) (Hudson, 1995; Quick, 1995).

The UBCWM has a user's manual and a user's interface that incorporates a semi-automatic calibration routine (Quick et al., 1995). The user's interface for the model includes a main program, graphics and statistical utilities along with parameter optimization and sensitivity analysis options (Quick, 1995). The UBCWM has the unique ability to directly convert AES, BC Hydro and Water Survey Canada data formats into a format recognized by the model. Further information on the UBCWM can be obtained from Dr. Michael C. Quick, University of British Columbia (Appendix A). A listing of UBCWM related websites are provided in Appendix B.

3.4.2 UBCWM Data Requirements

Data requirements for the UBC Watershed Model include: time series precipitation and temperature records as well as historical streamflow records for model calibration. The model can accept up to five meteorological stations per watershed (Quick, 1995). Other descriptive information commonly available from topographic maps and aerial photographs must also be obtained for each delineated elevation band in the model. This information includes: "mean elevation, mean area, forested fraction of the band, the density of the forest canopy, north-south orientation, glaciated area of the band, the fraction of any glacier with south orientation, the impermeable fraction of band, precipitation adjustment and station temperature, precipitation and evapotranspiration indices" (Quick et al., 1995:10). Most applications of the UBCWM in the past have used a daily time step (M. Quick per. comm., 1997).

3.4.3 UBCWM Computer Requirements

The UBC Watershed Model was developed for IBM and IBM compatible personal computers that use the MS-DOS operating system. The model requires a computer with, at minimum, a 386-33 MHz CPU with a math co-processor and EGA graphics card. The model also requires approximately 20 Mb of hard drive space with at least 2 Mb free after installation (Quick et al., 1995).

3.4.4 Historical UBCWM Applications

The earliest version of the UBCWM dates back to 1963 where it was used as a flood forecasting tool on Fraser River in British Columbia (Quick, 1995). Historically, most applications of the model have been in British Columbia, although Quick (1995) noted applications of the UBCWM in India and Pakistan. The UBCWM has been successfully applied to both fast response type watersheds typical of coastal B.C. as well as snow-melt dominated watersheds typical of interior B.C. The model has been applied to the Illecillewaet river in the Upper Columbia River basin in the B.C. interior to estimate seasonal snow-melt and glacier melt runoff volumes along with the probability of seasonal distribution of flow (Quick, 1995). The UBCWM has also been applied by B.C. Hydro to the Upper Campbell River basin on Vancouver Island to simulate inflows to the Strathcona reservoir (Weiss, 1995). BC Hydro has also used the UBCWM as an operational tool on the Peace River (M. Quick per. comm., 1997).

Since the UBCWM was primarily designed for flow forecasting, there have been limited experiments in its use as a water quality simulator. However, Hudson

(1995) applied the UBC Watershed Model to four small, subalpine catchments near Penticton, British Columbia to investigate the response of water chemistry under different forest cover types. Hudson and Quick (1997) detailed the development of a component based water quality simulator using the UBCWM as a basis for the model. A listing of selected UBCWM references are provided in Appendix C.

3.4.5 UBCWM Availability

The UBC Watershed Model is not available from any website. The standard version of the UBCWM runs on the MS-DOS operating system. A Windows 95 version of the model has been developed and is currently undergoing testing and validation. Further information on UBCWM availability can be obtained from Dr. Michael C. Quick.

3.4.6 UBCWM Training

UBC Watershed Model training is available at the University of British Columbia. The cost for a detailed demonstration of the model is $300.00. Further information on model training can be obtained from Dr. Michael C. Quick (Appendix A).

3.5 Distributed Hydrology Soils- Vegetation Model (DHSVM)

3.5.1 DHSVM Background

The Distributed Hydrology Soils-Vegetation Model (DHSVM) is a physically based, distributed hydrologic computer model that can account for the spatial variability of topographic, hydrologic, soil and vegetation components within a watershed. The DHSVM was developed for use in the mountainous terrain of the Pacific Northwest of the United States. The model was created by the joint effort between researchers at the University of Washington and modelers at Battelle Laboratories in Richland, Washington (M. Wigmosta per. comm., 1997).

The DHSVM utilizes grid cells (pixels) to maintain the spatial heterogeneity of a modeled watershed, as each cell is assigned individual watershed characteristics (i.e., soil, vegetation, climate, topographic). Forest cover types ranging from closed, two canopy forests to bare soil can be accurately represented within the model (Wigmosta et al., 1994).

The energy and water balance equations used in the DHSVM are coupled through five sub-models that include: evapotranspiration, solar radiation, snow accumulation and melt, unsaturated soil moisture and saturated soil moisture (Wigmosta et al., 1994). The DHSVM incorporates: "a two-layer canopy model for evapotranspiration, an energy balance model for snow accumulation and melt, a two layer rooting zone model and a saturated subsurface flow model" (Wigmosta et al., 1994: 1666). On every iteration (time step) the model calculates separate energy balance and water balance equations for each grid cell in the watershed. Grid cells in the model are linked in a "quasi three-dimensional saturated subsurface transport scheme" which allows water to be transferred pixel by pixel down-slope (Wigmosta et al., 1994: 1666). Further discussion of the DHSVM background can be found in Wigmosta (et al., 1994). Further information on the DHSVM can be obtained from Dennis P. Lettenmaier, University of Washington or Mark S. Wigmosta, Battelle Pacific Northwest Laboratory (Appendix A). A listing of DHSVM related websites are provided in Appendix B.

3.5.2 DHSVM Data Requirements

The DHSVM is a distributed model; thus, its data requirements are extensive in comparison to lesser complex models. Meteorological data required by the model include: precipitation, temperature, relative humidity, wind speed, solar radiation and cloud cover estimations. The DHSVM requires streamflow and snowfall data for model calibration and validation. Elevation data are required for modeling the topographic controls on "incoming solar radiation, air temperature, precipitation and down-slope water movement" (Wigmosta et al., 1994:1666).

The DHSVM also requires detailed distributed information on many soil and vegetation parameters. These parameters will vary depending upon application. The DHSVM potentially requires the following soils information: saturated hydraulic conductivity, soil depth, average rooting depth of overstory and understory vegetation, soil porosity, field capacity, vertical saturated conductivity, saturated moisture content and vegetation wilting point. Vegetation information required by the model include: overstory and understory species composition, height and density; vegetation roughness length; fraction of the ground surface covered by the overstory and understory; overstory root fraction; summer and winter leaf area index of the understory and overstory; and species dependent information such as: reflectance coefficient (α), minimum stomatal resistance (Rsmin, s/cm) and maximum cuticular resistance (Rsmax, s/cm). All of these data types are required for DHSVM model operation. Where soil and vegetation data of this nature are not available, reasonable estimates have been used by DHSVM users in the past. Data time steps used by the DHSVM generally range from three to 24 hours.

3.5.3 DHSVM Computer Requirements

The DHSVM has been programmed in the C programming language. Knowledge of this computer language in addition to FORTRAN is essential in order to use the model effectively. The DHSVM is most efficiently run on UNIX based micro-computer systems which are well suited to handling the large data sets that are produced by the model. The DHSVM can be run on personal computers, however, depending on computer processing speed, computer run time may be unacceptably long if large watersheds with numerous pixels are to be modeled.

3.5.4 Historical DHSVM Applications

The DHSVM was originally applied to the Middle Fork Flathead River basin in Northwestern Montana (Wigmosta et al., 1994). Since then, the model has been applied (unpublished applications) to numerous sites in Washington and Montana by researchers at the University of Washington. The model has also been used in the Boreal Ecosystem-Atmosphere Study (BOREAS) in the boreal forest of Saskatchewan and Manitoba. A listing of these and further application references can be found on the website: http://maximus.ce.washington.edu/%7Enijssen/docs/DHSVM. A listing of selected DHSVM references are provided in Appendix C.

3.5.5 DHSVM Availability

Because the DHSVM has undergone continual model development, a standard version of the model has only recently been developed (1996/1997). Version 1 of the DHSVM can now be obtained from the above mentioned model contacts. For further information on model availability, contact Dennis Lettenmaier or Mark Wigmosta or visit the website: http://maximus.ce. washington.edu/%7Enijssen /docs/DHSVM/.

3.5.6 DHSVM Training

No model training or DHSVM user's manual are currently available. Limited documentation is available from the website: http://maximus.ce.washington.edu/ %7Enijssen/docs/DHSVM/.

3.6 Comparison of the HSPF, TOPMODEL, UBCWM and DHSVM Hydrologic Simulation Models

The remainder of this chapter comparatively reviews the HSPF, TOPMODEL, UBCWM and DHSVM hydrologic simulation programs. The objective of this review is to highlight the strengths and weaknesses of each model in order to illustrate their suitability for operational forestry use in B.C. Information has been gathered through interviews with each model's creator and/or those responsible for model maintenance, in cases where the original model creator(s) could not be contacted. For each model, a series of basic to open-ended questions were submitted to the model experts. Unfortunately, for unknown reasons, many of the open-ended questions posed to these model experts could not be answered. Because of this, some important topics could not be thoroughly examined as in the best case, only incomplete information were available. Subsequently, a discussion of the following were dropped from the review: the theoretical base of each model, major assumptions of each model and scale issues associated with each model.

For each model, this review will focus on discussing the following topics:

modeling unit range, watershed size range, modeling time requirements, variability of modeling time step, roads and vegetation removal modeling, parameter modification, computer programming requirements, unsuitable landscape types and benefits and drawbacks for operational forestry use in B.C.

3.6.1 Modeling Unit Range

The type of modeling unit used by a hydrologic simulation model is important to consider as it ultimately defines whether a model is distributed, semi-distributed or lumped. A hydrologic modeling unit is a division of a watershed that can represent unique soil, vegetation, climate and topographic characteristics. These divisions are created within the model by using evenly spaced grids, segments that follow natural boundaries or even to uneven spaced elevation bands. The type and range of hydrologic modeling units varies considerably for each of the hydrologic models reviewed. Two of the four models reviewed are grid-based models; these being TOPMODEL and the DHSVM. These grid-based models use pixels, regularly distributed over the landscape, to maintain the spatial heterogeneity of a modeled watershed. Unfortunately, only incomplete information were available on the range of maximum and minimum pixel sizes for these two models. The maximum pixel size typically used in TOPMODEL is 100 meters while the minimum pixel size is unknown (K. Beven per. comm., 1997). In the DHSVM, the smallest pixel that has been used, in practice, has been 30 meters although the use of smaller pixel sizes are possible, yet remain untested (M. Wigmosta per. comm., 1997). The maximum pixel size that can be used in the DHSVM is unknown.

The HSPF and UBCWM are not grid-based models. These models use land segments and elevation bands, respectively, to represent the spatial characteristics of a modeled watershed. In the HSPF model, the study watershed is divided into homogenous land units called segments (Bicknell et al., 1993). Segments are assumed to contain the same soil, vegetation and topographic properties as well as precipitation and potential evapotranspiration rates. Segments in the HSPF have no theoretical minimum or maximum size, although model performance may vary with the size of segments delineated. Past applications of the HSPF in the Potomac River basin illustrate the range of land segments that can be used in the HSPF model as segments varied in size from one acre up to 155,100 acres (K. Flynn per. comm., 1997).

The UBCWM utilizes elevation bands to represent orographic influence on the spatial distribution of vegetation, climate and soil features in a watershed. In the UBCWM, elevation bands can be evenly or unevenly distributed in the watershed and range in size from one meter and up. Elevation band widths of 100 to 300 meters are commonly used in UBCWM (M .Quick per. comm., 1997).

Overall, of the four models reviewed, the DHSVM is the only model known to have the ability to model and maintain the spatial heterogeneity of a watershed at a fine resolution, on a pixel by pixel basis. In theory, TOPMODEL should also be able to model at a fine pixel resolution. However, cell by cell output is only available in TOPMODEL if model users keep track of where the topographic index values come from in the landscape (K. Beven per comm., 1997). These two distributed models are best suited to applications where a model user requires point by point hydrologic information in a watershed. Technically, the UBCWM and HSPF models are considered to be semi-distributed models as their modeling unit size is frequently coarser (larger) than what is typically used in the DHSVM and TOPMODEL. These semi-distributed models provide more of a "lumped" simulation result than the above mentioned distributed models and, hence, are most suitable for applications that required less distributed results.

3.6.2 Watershed Size Range

The theoretical range of the sizes of watersheds that can be modeled by each of the simulation models is unknown. None of the model creators interviewed were able to provide a precise or approximate range of watershed sizes that could be modeled in theory. Many of the interviewees stated that, theoretically, any size watershed can be modeled using their model. However, very large and very small watersheds may contain characteristics that are not represented adequately by each model. Unfortunately, these upper and lower boundaries seem to be largely unknown to the model creators.

The closest information available on watershed size limitations, per model, can be inferred through past applications. The HSPF has been applied to watersheds ranging in size from 0.1 acre up to 40,000 square miles (K. Flynn per. comm., 1997). The DHSVM has been applied to watersheds ranging in size from one to two square kilometers up to 30,000 square kilometers. (M. Wigmosta per. comm., 1997). TOPMODEL has been applied to watersheds ranging in size from 0.0063 square kilometers to 456 square kilometers (K. Beven per. comm., 1997). The UBCWM has been applied to watersheds ranging in size from one to 8000 square km (M. Quick per. comm., 1997).

3.6.3 Modeling Time Requirements

Estimations of the time required to obtain acceptable simulation results are difficult to determine for each model as these estimations will vary depending upon the scale of application and model user competency and experience. It is possible however to estimate the time required to "mechanically" run the model for the first time, ignoring any significance of model results. The following estimates were created assuming that the first time model user is under the guidance of an experienced modeler during initial modeling attempts. These estimates do not include the time required for data preparation which, for example, can account for roughly 50-90% of the time spent calibrating the HSPF model (K. Flynn per. comm., 1997). These estimates also do not include the time required to obtain acceptable simulation results nor the time necessary to gain a competent understanding of the model. These estimates are also impossible to derive due to the variability of each modeling scenario.

HSPF model experts estimate that it would take approximately two to five days to achieve results from the HSPF model (D. Beyerlein per. comm., 1997; K. Flynn per. comm., 1997). Simulation results produced under these circumstances would rarely be satisfactory and more time would be required to obtain acceptably realistic results. Although TOPMODEL is a distributed model, it requires less time to run than the HSPF. On average, it takes approximately one day to run after data preparation has been completed (K. Beven per. comm., 1997). The UBCWM is also a relatively quick model in that can be run in one day after data preparation is complete. The data requirements for TOPMODEL and the UBCWM are not as extensive as the HSPF and DHSVM models. One could therefore assume that the use of TOPMODEL and the UBCWM, overall, will be quicker than for the HSPF or DHSVM. Of the four models, the DHSVM demands the most time and usually requires, at minimum, one work week (40 hours) to run under the guidance of an experienced DHSVM user (M. Wigmosta per. comm., 1997). As with the HSPF, initial simulation results produced in this manner will rarely be satisfactory and, hence, will require further time inputs.

Overall, one can expect that those models with extensive data requirements (e.g., DHSVM, HSPF) will require much longer time commitments than models that are less data intensive (e.g., UBCWM, TOPMODEL). Models that take minimal time to use would be more desirable for operational forestry use in B.C. However, the simulation results produced by these quicker models may not be acceptably realistic depending upon modeling objectives. These factors must be taken into account when selecting a model and/or planning a hydrologic modeling exercise.

3.6.4 Variable Modeling Time Step

There are many advantages to incorporating a variable iteration time step within a hydrologic model. The range of time steps a model can use is much different from possessing a variable time step. A variable time step is the ability of a model to change its iteration time during a simulation run (e.g., from hourly to daily). A fixed time step model thus cannot change its iteration time step during a simulation run. The benefits of a variable time step are usually decreased computer run times and reduced data preparation time. For example, during the winter snow accumulation period, B.C. snow data are frequently collected at two week intervals. The hourly hydrologic regime of this time period is often not of great interest to the model user. However, in order to use fixed time step models, synthetic hourly or daily data must be first be fabricated from the two week data observations. This process can be time consuming and the extra work required is often not justified for these winter periods as the results produced, in many cases, will lack significance. If the model iteration time step can be varied to match that of the available data, a great economy of time in model use can be achieved.

While all of the models reviewed can accept a number of different time steps, usually ranging from hourly to daily, only two of the four models reviewed cannot vary their iteration time step; the HSPF and TOPMODEL. The modeling time step cannot be varied during a simulation run in the HSPF model (D. Beyerlein per. comm., 1997). Typically, this model uses time steps ranging from one minute up to 24 hours (K. Flynn per. comm., 1997). Simulation results can, however, be output at a time step greater than that of the input (iteration) time step. The most frequently used time step for the HSPF is one hour, which possibly reflects the sampling frequency of available data (K. Flynn per. comm., 1997). TOPMODEL also lacks the capability of varying the iteration time step during a simulation run. Typically, time steps of one to three hours are optimal for use in TOPMODEL (K. Beven per. comm., 1997).

The modeling time step can be varied during a simulation run in the UBCWM (M. Quick per. comm., 1997). However, past applications of the UBCWM have most frequently used a daily time step (M. Quick per. comm., 1997). The DHSVM also has the potential for modification of the time step during a simulation run. Version 1 of the DHSVM has a fixed time step that cannot be modified. However, other versions of the DHSVM at the University of Washington have incorporated a variable time step and it is likely that this attribute may be available in future versions of the model (M. Wigmosta per. comm., 1997). In past applications of the DHSVM, time steps have ranged from three to 24 hours. In other applications of the DHSVM, particularly those in small coastal watersheds with short channel lengths (e.g., Carnation Creek), time steps of 15 minutes have been deemed more appropriate because of the flashy hydrologic responses that are observed. Yet, data of this time step are not normally available in B.C. (M. Wigmosta per. comm., 1997).

3.6.5 Roads and Vegetation Modification

Roads and vegetation modification are treated very differently in the hydrologic models reviewed. Vegetation removal (e.g., logging) and roads are not specifically accounted for in the HSPF and any inclusion of these features in the model is relatively simplistic. Roads can be represented in the HSPF as impervious land segments whereas logged areas, depending upon their land characteristics, can be represented either as impervious or pervious land segments. The small size of these segments, especially in the case of roads and small cut-blocks, however, may not warrant their creation.

In TOPMODEL, roads are not explicitly modeled. Some versions of TOPMODEL, however, have incorporated roads and ditches into past simulations. For example, in the original application of TOPMODEL roads and field ditches were included in the calculation of the topographic index which subsequently, achieved improved results over the absence of their inclusion (K. Beven per. comm., 1997). It is unknown if or how TOPMODEL can represent a logged area or vegetation removal.

Roads and vegetation modification can be incorporated into the UBCWM. Roads are indicated in the UBCWM as extra fast runoff areas (M. Quick per. comm., 1997). Because the UBCWM models tree cover and the subsequent influence on interception and snow-melt, the influences of logging and possible wildfire can also be incorporated in the UBCWM (M. Quick per. comm., 1997).

Of all the models reviewed, the DHSVM is the only model that normally represents and models the influence of roads and vegetation removal in a watershed. A newly added road component to Version 1 of the DHSVM allows the modeling of the interception of subsurface flow and precipitation from road surfaces. The results produced by this module, however, are currently undergoing further testing and verification. The inclusion of logged areas and vegetation removal can be incorporated into the DHSVM via the modification of vegetation and soil parameters. Of the four models, the DHSVM is also unique in that it has the ability to model the effects of understory vegetation removal via the modification of understory vegetation parameters.

3.6.6 Parameter Modification

Parameter modification during a simulation run is another valuable model feature that can allow model users to investigate a wide range of hydrologic scenarios that may include: wildfire simulation, climate change, soil disturbance, timber harvesting impacts and vegetation re-growth to name a few. Each of the four models reviewed differ in their capabilities for parameter modification. In TOPMODEL, no parameter modification is possible as the number of parameters to be fitted becomes great and is counter to the purpose of TOPMODEL possessing as few parameters as possible (K. Beven per. comm., 1997).

Parameter modification can occur in the remaining three models although the method by which parameters are modified differs between them. Parameters can be modified in the HSPF model during a simulation run using the special actions section (block) of the model (K. Flynn per. comm., 1997). Parameter modification has been used in the HSPF in the past to investigate crop re-growth. It is possible that logged areas in B.C. could be treated and modeled in a similar manner. However, the HSPF's simplistic representation of forest vegetation cover may not lend itself to accurate simulations of vegetation modification.

Parameter modification can be performed in the UBCWM. However, such changes cannot occur automatically during a simulation run. UBCWM users can only incorporate parameter change (i.e., vegetation, soil, etc.) manually in the UBCWM by stopping a model run, changing the pertinent parameters and then re-starting the model (M. Quick per. comm., 1997). Climate and vegetation cover change can be incorporated into the UBCWM using this process (M. Quick per. comm., 1997).

The standard version of the DHSVM cannot be easily modified with respect to incorporating change (i.e., climate, vegetation re-growth, etc.) within a simulation run. However, parameter modification is possible to achieve by reading new parameters into the model at prescribed intervals. This process has been performed by DHSVM users in the past and researchers are currently examining the possible inclusion of this feature into future versions of the model.

3.6.7 Computer Programming Requirements

When selecting a hydrologic model, it is important to know if computer programming is a requirement for model use. Models that require users to have a competent grounding in computer programming may not be suitable for individuals who do not have time to learn a new computer programming language in addition to their everyday operational duties. The models reviewed here vary in their computer programming requirements. Normally, the HSPF model and the UBCWM are not modified by the user so knowledge of computer programming is not required for model use. Depending upon the version of TOPMODEL selected, some computer programming may be required (K. Beven per. comm., 1997). The DHSVM requires the model user to have competent knowledge of computer programming using the programming languages C and FORTRAN. The DHSVM is extremely difficult to use without this knowledge.

3.6.8 Unsuitable Landscape Types

Each of the models reviewed possesses different capabilities in the modeling of the hydrologic regime of an area. These models further differ in the regions and landscape types to which they can successfully be applied and in the subsequent results produced. The best place to apply each model is in climate and landscape types for which the model was developed. Yet, hydrologic models are frequently applied outside of these origins, often with great success. There are, however, a few landscape types for which application of each model under review may be problematic.

Many applications of the HSPF to wetlands in the past have proven to be less than satisfactory (K. Flynn per. comm., 1997). However, the USGS in Washington has been able to obtain acceptable results from the HSPF for these types of landscapes (K. Flynn per. comm., 1997). The HSPF can also have difficulty producing acceptable results in very arid climates (D. Beyerlein per. comm., 1997). The UBCWM too can have difficulty in extremely arid areas where evaporation is the most important controlling factor (M. Quick per. comm., 1997), as does the DHSVM (M. Wigmosta per. comm., 1997). The DHSVM calculates crude soil temperatures in these arid environments and model researchers are striving to improve the DHSVM in this respect. It is unknown whether or not TOPMODEL too has difficulty in arid areas. TOPMODEL can have difficulty though in landscapes that characteristically wet up after dry periods or in "climates where catchments are always wetting up" (K. Beven per. comm., 1997).

3.7 Benefits and Drawbacks for Operational Forestry Use in B.C.

Overall, each of the models reviewed possesses advantages and disadvantages for operational use in B.C. (Table 3.7-1). Hydrologic models can be very useful tools that can aid in assessing possible changes that might arise as a result of logging practices or wildfire; for example, changes in peak flow magnitude and timing. However, a comparison of the ability of each of the four models to predict such changes cannot be fully assessed as the predictive precision of each model has not been evaluated. The predictive power of each model is best determined by calibrating and validating each model to a series of different landscape types typical of those found in B.C. Once completed, a comparative discussion on model performance could then be adequately performed. Unfortunately, such a project was too large for this thesis.

Table 3.7-1 Advantages and Disadvantages of HSPF, TOPMODEL, UBCWM and DHSVM

	HSPF	TOPMODEL	UBCWM	DHSVM
Disadvantages	• very complex • user unfriendly • not created mountainous B.C. terrain • limited ability to represent greater than one forest cover type	• no standard version available • not yet applied in B.C. • no training available	• semi-distributed nature may limit application • author experienced moderately slow responses for technical support	• user unfriendly • data intensive • no user's manual • poor technical support • difficult to use initially without guidance • requires computer programming to use • no training available
Advantages	• proven reliable water quality and erosion simulator • ample documentation and user's manual • training available from agencies located close to B.C.	• distributed model with a small number of parameters • not data intensive • abundant literature available • successfully applied in a variety of climates worldwide	• specifically created for B.C. terrain. • used by government agencies and researchers at UBC • not data intensive • local training and technical support available • suitable for personal computers • can directly convert B.C. data formats into UBCWM formats	• model complexity well suited to investigate a wide range of forestry issues • model created for mountainous terrain • spatially distributed model well suited for assessing forest disturbances of a variety of magnitudes

The following is a discussion of some of the benefits and drawbacks of each model for operational use in forested areas in B.C.

3.7.1 HSPF

The primary drawback of using the HSPF model for operational forestry purposes in B.C. is that the model is complex. This complexity is compounded by moderate user-unfriendliness which makes it difficult to use the HSPF without direct guidance from an experienced HSPF model user. Another drawback of the HSPF is that it has no ability to flag errors during a model run and, therefore, any mistakes that are made during use are often difficult, frustrating and time consuming to solve (D. Beyerlein per. comm., 1997). The HSPF is also limited in that it originated in the U.S. and was created for terrain quite different from the mountainous terrain of B.C. Additionally, forest cover in the HSPF is represented as a single index making the representation of differing forest cover types very limited in the model (E. Hetherington per. comm., 1997). Proven success of applying the HSPF to sites in B.C. has also been limited to few applications.

There are many features of the HSPF model, however, that make it suitable for application in B.C. One of the biggest advantages of the HSPF model over the other models reviewed is that it has proven to be a reliable water quality and erosion simulator. Although not thoroughly tested in B.C., the HSPF's ability to examine a variety of water quality issues far exceeds that of any of the other three models reviewed. Additional benefits of the HSPF model include: ample documentation, a comprehensive user's manual and training available from a variety of agencies located close to B.C. Agencies responsible for providing HSPF information and correspondence were found to be informative and prompt in replying to inquiries submitted by the author. Turnaround time for model information usually ranged between same day replies up to one week.

3.7.2 TOPMODEL

The primary drawback of using TOPMODEL operationally in B.C. is the lack of a standard version of the model. TOPMODEL's creators state that it is not a modeling package; therefore, an "out of the box" version is not readily available for application in B.C. Furthermore, TOPMODEL has never been applied to any forested area in B.C. Hence, the initial application of TOPMODEL in B.C. should be left to those model users who are familiar with TOPMODEL and modeling limitations in general. This initial application should be approached with caution as the modeling of snow processes are included in only a select few versions of TOPMODEL. An extensive review of the theoretical base of the model would also be advisable before TOPMODEL is applied in B.C. Yet, TOPMODEL should be applicable to terrain types characteristic of British Columbia (K. Beven per. comm., 1997). Another drawback of using TOPMODEL in B.C. is a lack of available training in TOPMODEL use in North America. Additionally, the source for further information and correspondence on TOPMODEL is in the U.K. However, the turnaround times for inquires submitted by email, on average, ranged between one to two weeks.

The main benefit of using TOPMODEL operationally in B.C. is that it is a distributed model with a small number of parameters and, therefore, it is not as data intensive as other distributed models. TOPMODEL does not require extensive data to run and can provide semi-distributed to distributed results using a minimum of four parameters. These characteristics make TOPMODEL one of the more inexpensive and time saving distributed models available. Another advantage of TOPMODEL is the abundance of literature available that include a user's manual and references to many different applications for a wide variety of landscape types.

3.7.3 UBCWM

There are a few drawbacks to using the UBCWM operationally in B.C. Primarily, the UBCWM is not a pixel-based model and, therefore, some lumping of watershed characteristics and watershed processes have to be carried out in simulations. This reduces the applicability of the UBCWM in simulations that require highly detailed, pixel by pixel simulation results. Also, because the UBCWM is not a distributed model, the scope of hydrologic issues that may be addressed are narrower than those that can be covered by the DHSVM, TOPMODEL and HSPF models. Finally, the turnaround times for model support and inquiries were found to be slow, taking on average four to six weeks.

The main benefits of the UBCWM for operational forestry purposes in B.C. are that it is specifically created for B.C. terrain, it is not a data intensive model and it is quick and relatively simple to run. Additionally, the UBCWM has a local contact address and training available upon request. The UBCWM is well suited for use on personal computers and incorporates a variable time step which can lead to computational and data preparation economy. Unique to this model is the ability to transform BC Hydro, AES and Water Survey of Canada data formats into a format recognized by the model. This gives the UBCWM an advantage over the other four models reviewed as the time required to use the model will be shortened by these unique features.

3.7.4 DHSVM

The primary drawbacks of using the DHSVM operationally in B.C. are that it is a highly complex, user unfriendly, data intensive simulation model. The DHSVM requires ample data formatting that can consume a extremely large portion of time for model calibration and verification. Another drawback to using the DHSVM operationally is that it is difficult to use without extensive guidance from an experienced model user. Unfortunately, the DHSVM has sparse documentation, no user's manual, no user interface and requires computer programming to use. These characteristics make it extremely difficult to use without training, which also is not available. Contact and correspondence with those responsible for providing information and model support was found to be slow to extremely slow. Turnaround times for inquiries submitted by email took two to three months on average. The data intensive, distributed nature of the model makes it best suited to UNIX based, micro computer systems which also may not be available to all who wish to use the model.

The major benefit of the DHSVM is that its complexity is well suited to answer a wide range of forestry issues. The model was specifically created for mountainous terrain similar to that found in B.C. Additionally, the DHSVM is a spatially distributed model that can provide a point by point simulation of hydrologic processes in a watershed. The capabilities of the DHSVM in addressing forestry issues are well suited for operational use, but not yet geared towards it due to the esoteric nature of the model.

3.8 Summary and Conclusions

Each hydrologic model has its own advantages and disadvantages for suitability in operational forestry use in B.C. The strengths of the HSPF model lie in its ability to investigate water quality and erosion analysis issues. However, the HSPF is a complex model that can be difficult to use in the absence of more experienced model users. The HSPF has a simplistic representation of vegetation which may not adequately represent the differing forest types that are found in B.C. Thus, the scope of forestry issues that can be investigated with the model may be limited.

TOPMODEL's strengths lie in its flexible model structure and minimal parameter and data requirements. Drawbacks for forested applications, however, include a lack of previous application to terrain types of B.C., particularly those in mountainous, snow dominated regions.

The strengths of the UBCWM lie in its local development, simplistic data requirements and documentation. The UBCWM's time saving ability to reformat commonly available B.C. data types also make the model desirable for operational use. Its drawbacks lie in its simplicity and partial lumping of watershed processes that could make it unsuitable for problems requiring distributed results. Unfortunately, although a locally developed model, the contact for the UBCWM support can be slow.

The distributed, locally developed nature of the DHSVM make it well suited to investigate a wide variety of forestry modeling objectives in B.C. Unfortunately, because the DHSVM is a very complex, user unfriendly, data intensive model, it is difficult to use without the assistance of experienced DHSVM users. These features make it unsuitable for operational applications where liberal modeling time is not available. Problems with model contact and support also limit the DHSVM's suitability for operational use in B.C.

The purpose of the chapter was to highlight the strengths and weaknesses of each hydrologic model in terms of suitability for operational use in B.C. As demonstrated, each model possesses different qualities that make each model suitable for differing applications. Therefore, the results of the model review indicate that no single hydrologic model is optimally suited for widespread use in B.C. forest management due to the variability of modeling goals and model capabilities. While the knowledge gained in the preceding comparative review can be used to evaluate model suitability in addressing various hydrologic modeling objectives, the actual selection of an appropriate hydrologic model is often not determined solely by model suitability. Model selection can also be influenced by model user experience, model user creativity, modeling objectives, model funding and data resource availability.

CHAPTER 4
AVAILABILITY AND LIMITATIONS OF BRITISH COLUMBIA DATA RESOURCES

4.1 Introduction

A wide variety of data resources are available in British Columbia. The collection and distribution of these data resources are largely the responsibility of many different provincial government agencies and crown corporations. Yet, recent budget cuts to many of these government agencies have resulted in the down-sizing and restructuring of data collection programs. As a result, many agencies have been forced to decrease the services they can provide to the public. These factors combined have lead to situations where some data types are either unavailable, poorly maintained and/or costly. Knowledge of these data limitations are important to consider as insufficient data resources can feasibly limit the use of some hydrologic models.

This chapter examines the current state of the data resources in British Columbia by reviewing the availability of groundwater, streamflow, vegetation, soil, topographic, remotely sensed, snow and meteorological data resources. For each data type, a description of the data network (type), data cost, waiting period and contact address for further information is provided. General limitations of these data resources in relation to use in hydrologic modeling are also discussed.

4.2 Subsurface Hydrologic Data Resources

4.2.1 Groundwater Data Resources

The Ministry of Environment, Lands and Parks (MOELP) operates a network of 150 active water wells situated primarily in urban areas throughout British Columbia. Wells in this network record water level and water quality data. Of the 150 active wells, 90 are automated, collecting data continuously, while the remaining 60 wells are manually measured. The automated wells in the network use F68 Stevens water level recorders. Groundwater data are generally expressed in meters below the ground surface. The MOELP also operates a groundwater website (http://www.env.

gov.bc.ca/wat/gws) where information on groundwater links, groundwater reports, a water well record database and maps of well locations can be obtained.

Fees for groundwater data are based upon a cost-recovery system that varies depending upon the amount of time required to recover the data. On average, fees for data recovery can range in price from $7.50 to $30.00 plus tax. Depending upon the amount of data requested, the waiting period for groundwater data is usually between one day to one week. For further information, contact Rod Zimmermin or Carl Lee, Ministry of Environment, Lands and Parks (Appendix A).

4.2.2 Soils And Terrain Data Resources

Digital distributed soils data are currently one of the most difficult data types to obtain in B.C. However, this situation is expected to change shortly as two programs within the provincial government to produce digital soils and terrain data for both government and private use are in progress. Historically, the majority of soils information available in B.C. were paper soils maps produced by the federal and provincial governments. These maps varied in the information they contained as some maps also served as terrain and/or landform maps. A majority of the paper soils maps were at a 1:50,000 scale, although a few areas in the province had 1:20,000 scale map coverage. Currently, these older paper soils maps can be difficult to locate as recent budget cutbacks have reduced map availability and the number of distribution outlets. For further information on obtaining paper soils maps, contact Geodata B.C. or Rob McClenehan (Appendix A).

The distribution of digital soils and terrain data is slowly becoming available through two provincial government agencies that include the Ministry of Employment and Investment (B.C. Geologic Survey) and the Ministry of Agriculture, Fish and Foods. The Ministry of Employment and Investment (B.C. Geologic Survey) is in the process of compiling digital terrain map library. Once complete, a majority of the digital terrain maps available for B.C. will be at a 1:50,000 scale. Other map scales such as 1:15,000 and 1:20,000 will also be available for certain areas of the province. Information contained on the digital terrain maps pertains mainly to surficial geology, although some maps do contain specific soils information. A website to distribute digital terrain map data is still under development by the Ministry of Employment and Investment. Digital maps are expected to be distributed free of charge on this website. Further information on terrain map coverage and terrain mapping may be obtained from the website “http://www.ei.gov.ca/geosmin/minpot/mapguide.htm” or through Ward Kilby (Appendix A).

The Ministry of Agriculture, Fish and Foods is in the process of completing a digital soils map library of B.C. A majority of the soils maps in this library will either be at 1:50,000 or 1:20,000 scale. The digital soils information available will vary by map but, in general, will most often include information on soil type, parent material, soil chemical properties, soil texture and coarse fragment content (H. Hofmeyr per. comm., 1997). A website to distribute these digital soils maps is currently under development. Digital soils maps are expected to be distributed free of charge on this website. The 1:20,000 scale digital soils map series is expected to be complete and available to the public by the middle of 1998. The 1:50,000 scale soils map series is expected to be complete and available to the public by the end of 1998. Current soils map coverage of B.C. and further information on digital soils maps can be obtained from Hally Hofmeyr (Appendix A) or from the website “http://www.agf.gov.bc.ca/ agric/resplan /bcsoils.soil.htm”. Further soils information by regional area can also be obtained by contacting any one the six Ministry of Forests regional soil scientists as listed in Appendix A.

4.3 Streamflow Data Resources

The primary source of regional streamflow data in B.C. is from the Water Survey of Canada, Environment Canada. Other agencies, such as the Ministry of Environment, Lands and Parks, Ministry of Forests (MOF) and MacMillan Bloedel also operate local hydrometric networks in B.C. Environment Canada operates a network of approximately 600 surface water data collection stations in B.C. These stations vary in the types of information collected, but most often gather stage height and discharge data. Stations in the network range from fully automated, continuous trace stations to seasonal, manually read stations. Sampling frequency of the stations depends upon whether the station is seasonal or continuous. Continuous recording stations have the ability to produce data output in 15 minute, hourly and daily intervals. Many of the manually read, seasonal stations (30) output daily to weekly interval data. Overall, depending upon the station, Water Survey of Canada (WSC) has the ability to provide hourly, daily, monthly and annual data. Stage height data collected by the network are usually expressed in meters and where discharge are calculated, converted into cubic metres per second. Most of the recording stations in the network use Stevens Type A recorders that are either float-activated, servomanometer or gas purge. Environment Canada is currently in the process of slowly upgrading streamflow recorders with data loggers.

The cost of streamflow data from WSC varies with the amount of data requested, the data interval required and data format. Environment Canada has produced a CD that contains daily, weekly and monthly historical streamflow data up to 1995 for all streamflow stations in Canada. Data from the CD can be output in three formats that include: ASCII, lotus or binary. The cost of the CD is $750.00 plus tax, with yearly updates costing $250.00 plus tax (L. Campo per. comm., 1997). Individual data stations can be extracted by WSC from the CD at a cost of $60 plus tax (L. Campo per. comm., 1997). WSC also provides e-mail, photocopying and FAX services (L. Campo per. comm., 1997). Hourly data are available upon request using a cost recovery scheme. Costs for hourly data average $87.00 an hour labor for data extraction (L. Campo per. comm., 1997). WSC does offer a 25% discount for university students. The waiting period for data requests depends upon WSC's workload, but usually takes between two to five work days. For further information on WSC streamflow data contact Lynne Campo, Environment Canada (Appendix A) or visit the website: http://www.pwc.bc.doe.ca/buildings/water/index.html.

As mentioned, other agencies such as the Ministry of Environment, Lands and Parks, Ministry of Forests and MacMillan Bloedel also operate local hydrometric network in B.C. The hydrometric networks operated by these agencies are largely site specific as the data are generally collected for either research or operational purposes.

As such, the hydrometric stations in each network are usually in operation for only a short period of time and/or are sparse in numbers. For example, on Vancouver Island, MacMillan Bloedel currently operates four hydrometric stations while the Ministry of Forests operates three hydrometric stations in the region (Klohn-Crippen, 1997).

Historically, the Ministry of Environment, Lands and Park operated a network of 57 hydrometric stations in the Vancouver Island region. These stations recorded data during low streamflow conditions in the years 1977 and 1985 (Klohn-Crippen, 1997). The MOELP operated these stations during these periods to aid in the management of issuing water licenses on low summer flow streams. Currently, the MOELP operates one hydrometric station in the Vancouver Island region. For further information on MOELP historical hydrometric data contact Larry Barr, Ministry of Environment, Lands and Parks (Appendix A).

A description of these three networks and other hydrometric networks for the Vancouver Island region can be found in a report prepared by Klohn-Crippen (1997) for the Ministry of Environment, Lands and Parks. Unfortunately, up-to-date information on other site specific hydrometric stations in the other regions of the province could not be obtained. However, this information is expected to soon be available as inventories of the hydrometric / climate network resources are currently being undertaken in the Kamloops, Cariboo and Southern Interior regions of the province (E. Dawson per. comm., 1997).

4.4 Vegetation Data Resources

There are three main sources of vegetation data in B.C.: Biogeoclimatic Zone maps, Ecoregion maps and MOF Forest Cover maps.

4.4.1 Biogeoclimatic Zone Ecosystem Classification System (BGCZ) Data Resources

The Biogeoclimatic Zone Ecosystem Classification System (BGCZ) utilizes plant associations to define large geographic zones of similar climate, as reflected by vegetation, in B.C. This classification system can be useful for determining general climate and vegetation patterns as well as soil nutrient and moisture regimes. The BGCZ classification system has four main levels of detail. In B.C., there are 14 zones, 103 subzones, 170 variants and greater than 600 different site associations.

BGCZ information can be obtained from a variety of sources in B.C. that include both provincial government and private agencies. Paper BGCZ maps are available in scales of 1:2,000,000; 1:500,000; 1:250,000 and 1:100,000. Further information on these maps can be obtained from Map Sales, Victoria B.C. (Appendix A). BGCZ information is also available on the website "http://www.res.for.gov.bc.ca /projects/bec_doc.html# Products".

Hugh Hamilton Ltd., a private contractor, supplies colour BGCZ maps of the Vancouver forest region at 1:250,000 scale. There are a total of six maps in this series that cost $30.00 each plus tax. Interpretive guides to the BGCZ system by region can be obtained through the Research Branch of the Ministry of Forests or through any regional MOF office (Appendix A).

4.4.2 Ecoregion Classification System

The Ecoregion Classification System (ECS) is a much broader based classification system than the BGCZ classification system. The ECS is based upon macroclimatic processes and landforms that combine to produce distinct ecosystems. The ECS system is used primarily for habitat and wildlife management. The ECS has five levels of detail. In B.C. there are four ecodomains, seven ecodivisions, 10 ecoprovinces, 43 ecoregions and 116 ecosections (D. Demarchi per. comm., 1997). The ECS system and the BGCZ system are each unique and can be used together to derive information about watershed characteristics in B.C. ECS maps are available in scales of 1:2,000,000 and 1:250,000. At present, costs for ECS data have not been formally established. Contact Dennis Demarchi, Ministry of Environment, Lands and Parks, Wildlife Inventory Section (Appendix A) for further information or visit the website: http://www.env.gov.bc.ca/wld/his/ecosys.html.

4.4.3 Forest Cover Data Resources

The Ministry of Forests (MOF), Resource Inventory Branch is the primary source of forest cover data for B.C. Forest cover data are produced by the MOF in both paper and digital map format. On these maps, forest cover polygons contain information on tree species type, stand composition, age class, height class, site class, stocking class, crown closure, disturbance history as well as many other secondary elements. Forest cover polygons have been created from the interpretation of 1:15,000 air orthophotos. The accuracy of these interpretations are verified using a ground sampling program (A. Tolman per. comm., 1997). Forest cover data are available from the MOF for most of the forested areas in the province, with the exception of tree farm licenses (TFLs), provincial and national parks. Because MOF Forest Cover data is unavailable in TFLs, licensees must produce their own forest cover maps. The content and detail of these maps will vary between licensees. Therefore, individuals interested in forest cover data from these organizations should contact the pertinent licensee.

As mentioned, forest cover data are available in two formats: hard copy paper maps and digital data files. Paper copies of the forest cover maps can be obtained from the Ministry of Forests, Map Sales, Victoria, B.C. (Appendix A). 1:15,000 to 1:20,000 scale paper map copies from Map Sales cost $4.00 each plus tax. Digital data can be obtained from Anja Tolman, Ministry of Forests, Resource Inventory Branch (Appendix A). The price for digital data varies with the number of maps purchased. One map costs $250.00, two to nine maps cost $200.00 each, 10 to 19 maps cost $175.00 each and greater than 20 maps cost $150.00 each plus tax (A. Tolman per. comm., 1997). An additional charge of $650.00 is assessed if TRIM data have not previously purchased from the MOELP (A. Tolman per. comm., 1997). This fee is waived if proof of purchase can be provided at the time of sale. Further information on forest cover data can be obtained from Anja Tolman or from the website: http://www.for.gov.bc.ca/resinv/homepage.html

4.5 Topographic Data Resources

Topographic data are available for most of B.C. in both paper and digital format. The federal government has produced topographic maps at scales of 1:50,000 and 1:200,000. The provincial government has produced topographic maps at scales of 1:100,000. The province has also produced higher detail, 1:20,000 scale Terrain Resource Information Management (TRIM) maps. These maps are available in both digital and hard copy paper formats. A total of 7,027, 1:20,000 scale TRIM maps are available for B.C. (R. Balser per. comm., 1997). Other scales of TRIM maps are available that include: 1:2,000,000, 1:250,000, 1:120,000 and 1:5,000 in selected areas. In general, TRIM data have been captured from 1:70,000 air photographs (R. Balser per. comm., 1997). Approximately 90 percent of the points in the TRIM data sets are assumed to have an accuracy of plus or minus ten metres from both the true horizontal and vertical elevation positions (R. Balser per. comm., 1997).

Digital TRIM data can be supplied in two formats: MOEP Binary Compressed and SAIF-Zip format. Five files are provided with each MOEP format map that include information on DEM (digital elevation model), raw contours, planimetrics, non-positional and toponomy. One file is provided with each SAIF-Zip format map. A map detailing TRIM coverage in B.C. is available from the website: http://www.env. gov.bc.ca:80/gdbc/trim.htm. Paper copies of the 1:50,000 and 1:200,000 scale maps are available from Crown Publications, Victoria, B.C. (Appendix A). Paper and digital 1:20,000 and 1:100,000 can be obtained from Geographic Data B.C., Ministry of Environment, Lands and Parks (Appendix A).

The fees for paper hard copies of the topographic maps vary by type and dealer. Crown Publications sells hard copy, federal and provincial topographic maps for $8.45 and $5.15 (plus tax), respectively. Digital TRIM data cost approximately $600.00 per map and can be ordered through Geographic Data B.C. No discount for volume, student or organization is available. In the past, however, digital data have been donated by the provincial government for university research purposes. For further information on digital TRIM data contact Geographic Data B.C. (Appendix A) or visit the website: http://www.env.gov.bc.ca:80/gdbc/trim.htm.

4.6 Remotely Sensed Data Resources

4.6.1 Air Photograph Data Resources

Air photographs are a valuable source of information for hydrologic modeling. A variety of aerial photographs for B.C. can be purchased by individuals with accounts at Geographic Data BC* (formerly Maps B.C.) in Victoria, B.C. Individuals without accounts at Geographic Data B.C. can order air photographs through Crown Publications Inc. (Appendix A) or other designated dealers. Information on air photograph dealers can be obtained from Geographic Data B.C. (Appendix A). Air photographs can be viewed free of charge at the Geographic Data B.C. office. Available air photographs of forested areas in B.C. can range in scale from 1:1,000 up to 1:60,000, with 1:15,000 typifying the most common scale. The cost of air photographs varies depending upon dealer, photograph type and scale.

*Note as of June 30, 1997 Geographic Data B.C. will have undergone major program revisions that may result in reduced customer services. Individuals interested in air photographs should contact Geographic Data B.C. for more information.

4.6.2 Satellite Data Resources

Radarsat International Inc. can supply digital and hard copy optical and radar imagery for Canada. Radarsat International Inc. can provide images from Landsat, Radarsat and Spot satellites for all of B.C. The image types available vary by geographic area and image resolution, but images such as geologic structures, harvested areas, land cover classes, snow aerial extent and soil moisture differences can be supplied. At present, images denoting snow water equivalent and snow-depth are largely unavailable as deriving estimates for these features is still complex and experimental (K. Stevens per. comm., 1997). The image resolution of the various satellite images can range in pixel size from eight meters up to 100 meters, covering areas from 50 square kilometers up to 500 square kilometers, respectively.

Prices for satellite data vary by data and image type. A price list can be obtained from the contact listed below. Imagery that is available, on average, ranges in price from $4000.00 to $6000.00 plus tax, per scene. Additional charges for rush deliveries can range from an additional 30 to 200 percent. High priority, real time data acquisition can be delivered to customers as quickly as two hours after acquisition (at an additional cost). Images of normal priority generally take one week to deliver. For general information on Radarsat products contact Kate Stevens, Client Services Representative, RADARSAT International Inc. (Appendix A) or visit the website: http://www.rsi.ca/.

4.7 Snow Survey Data Resources

The Ministry of Environment, Lands and Parks is responsible for operating the B.C. Provincial Snow Survey Network in which there are currently 218 active snow courses and 47 automated snow pillows (J. Matthews per. comm., 1997). Data that are collected in the snow survey network vary by station type. On average, manual snow survey data collected will include snow-depth and snow water equivalent while automated snow pillow data include precipitation, temperature and snow water equivalent with some stations recording snow-depth. The sampling frequency of snow survey data varies with the station type and locale. Snow pillows record hourly values. Manual snow course measurements begin in January and end in June with monthly sampling occurring until May and bi-weekly sampling until June 15. Snow-depth is measured in centimeters and snow water equivalent is expressed in millimeters. Snow density estimates are expressed as a percent.

Historical snow survey data are available through the MOELP Resource Inventory Branch on 3.5 inch diskettes. These diskettes contain all active and inactive stations that have been part of the snow survey network. Programs to expand the compressed data and a map of station locations are included. The disk costs $10.00 plus tax and no discounts are offered for university research purposes (J. Matthews per. comm., 1997). Data are available in ASCII and Binary format only. A small amount of snow survey data are also available from the website: http://wtrwww.env.gov.bc.ca/ wat/snow_bulletin /current /snoinf.html. To obtain snow survey data contact Cindy Frampton, Water Inventory Section, Ministry of Environment, Lands and Parks (Appendix A). To obtain general information about snow survey data contact Jan Matthews, Snow Survey Technician, Ministry of Environment, Lands and Parks (Appendix A).

4.8 Meteorological Data Resources

There are a total of 31 meteorological networks operated by the regional, provincial and federal governments as well as crown agencies in B.C. (Resources Inventory Committee, 1996). Each network differs in the types of meteorological data collected as each network serves a distinct purpose for the agency involved. A detailed description of these networks can be found in a document sponsored by the Resources Inventory Committee entitled "Description of British Columbia Meteorological Networks" (Resources Inventory Committee, 1996). This document provides a comprehensive description of the meteorological networks, research programs, data contacts, data types, element descriptions, sensor descriptions, routine reports, data formats, sampling software, operation periods, data standards and quality assurance programs. Another report, prepared by Klohn-Crippen (1997) for the MOELP provides a comprehensive description of all active and inactive hydrometric and climate stations for the Vancouver Island region. This report provides a detailed description of the recording history, latitude, longitude, elevation and data elements collected for each station in each network. As such, this thesis will only present a summary of the networks and refers the reader to these two documents for a more detailed description of the stations in each network. These two documents are limited, however, in that they do not contain any information on data costs. In addition, the RIC document is out-of-date in terms of current contacts and data types collected within each network. The following is an up-to-date review of the various meteorological networks in B.C. including a cost summary for obtaining such data types (1997 prices).

The agencies involved with monitoring meteorological conditions on a provincial basis in B.C. include: Atmospheric Environment Service, B.C. Hydro, Ministry of Environment Lands and Parks, Ministry of Transportation and Highways and the Ministry of Forests. Other agencies such as Parks Canada, MacMillan Bloedel, the Ministry of Forests and the Greater Vancouver Regional District also operate their own site specific meteorological networks in B.C.

4.8.1 Atmospheric Environment Service (AES)

The Atmospheric Environment Service (AES) operates five meteorological networks that include: AES Automated Systems, AES Buoy Network, AES Climate Network, AES First Order Network and AES Upper Air Network (Resources Inventory Committee, 1996). There are roughly 35 to 40 automated stations, 12 buoy stations, 400 climate stations, 100 first order stations and four upper air stations (G. Myers per. comm., 1997). Data from the automated stations, first order stations and climate network are available on CD. Data from the remaining two networks can be purchased separately from Gary Myers, Environment Canada (Appendix A).

Environment Canada collects meteorological data for B.C. on an hourly, daily and monthly basis. There are three CD's available for purchase from Environment Canada that can provide monthly, daily and hourly data, respectively. Meteorological variables available vary per CD, but usually include: maximum temperature, minimum temperature, mean temperature, rain, snow and total precipitation. Solar radiation data are available on the monthly CD only. Single data stations can be extracted from the CD’s by the AES. The waiting period for data is approximately one week, although large data requests (except CD requests) can take up to two weeks for delivery (G. Myers per. comm., 1997).

The three CD's available from Environment Canada increase in price, as the data sampling frequency becomes shorter. The monthly CD costs $200.00, the daily CD $2000 and the hourly CD costs approximately $8000 plus tax (G. Myers per. comm., 1997). University students are offered a 25% discount on all data purchases from Environment Canada. For more information on AES meteorological data contact

Gary Myers, Environment Canada (Appendix A).

4.8.2 BC Hydro

Historically, BC Hydro operated three meteorological networks that included: an Autographic Station network, a DCP (Data Collection Platform) Network and a Snow Course Network (Resources Inventory Committee, 1996). At present, the only network B.C. Hydro actively collects data from is the DCP network. Stations in the other two networks are now contracted out to other agencies or are closed. Many of the stations in these two networks in the past were cooperatively operated by BC Hydro and the Ministry of Environment, Lands and Parks and/or Environment Canada. At present, BC Hydro obtains most of its snow information from the MOELP who have incorporated many of BC Hydro's sites into their snow survey network. However, some localized snow sample sites and autographic stations may still be in operation at this time.

The primary meteorological network run by BC Hydro is the DCP Network. There are approximately 100 stations in the DCP network that are located mostly in dammed drainage basins across the province (B. Fast per. comm., 1997). In general, stations in this network operate year round and collect hourly data that include air temperature, precipitation, wind and relative humidity. Data from the network are usually provided free of charge to the public, although a cost recovery fee for data requests may apply in the near future (B. Fast per. comm., 1997). For more information on B.C. Hydro Meteorological data contact Brian Fast or Wayne Johnson, BC Hydro (Appendix A).

4.8.3 Ministry of Environment, Lands and Parks (MOELP)

Historical and current meteorological data are available from the Air Resources Branch of the Ministry of Environment, Lands and Parks. Historically, the MOELP operated two climatic networks that included the BC MOE ARB Climate Data Capture (CDC) network and the BC MOE ARB Meteorological Information System. Currently, the CDC network is inactive, although archived data are available for approximately 600 stations. In general, data that were collected in the CDC network included: daily precipitation, daily temperature, hourly wind speed, hourly wind direction and total solar radiation.

Currently, there are 37 active stations in the Meteorological Information System scattered throughout the province, in or close to urban centers. Stations in the Meteorological Information System network collect hourly temperature, wind speed and wind direction. The MOELP may charge a cost recovery fee for some data requests. The MOELP is currently working on a website to distribute meteorological data. For more information on MOELP meteorological data contact Sharon Gunter, Air Resources Branch, Ministry of Environment, Lands and Parks (Appendix A).

4.8.4 Ministry of Transportation and Highways (MOTH)

The MOTH operates two meteorological networks in British Columbia; a manual recording station network and a remote automated network. Currently, the MOTH is in the process of replacing the old manual network with an up-to-date automatic network (T. Weick per. comm., 1997). Therefore, station locations seem to be dynamic at present. Historical climate data from the MOTH, however, will still be useful for hydrologic modeling purposes as station locations in the past were fairly static. The MOTH operates both meteorological networks on a seasonal basis, primarily confined to the winter and spring months. In general, stations in the networks operate either from November 1 to April 30 or October 1 to May 15 (Resources Inventory Committee, 1996).

The MOTH operates a network of 128 manual meteorological stations across B.C. A majority of the stations in this network are located in easily accessible areas such as maintenance yards or avalanche prone areas along road sides. Manual observations are generally performed twice daily (Resources Inventory Committee, 1996). Data collected at the manual stations include: current temperature, maximum temperature, minimum temperature, precipitation, precipitation type, sky conditions and wind speed.

The MOTH also operates a network of 39 remote automatic weather stations

(RAWS) that record hourly data that generally include: precipitation, wind, temperature, snow-depth, snow-pack temperature and relative humidity (Resources Inventory Committee, 1996). The stations in this network are located in high elevation and remote avalanche prone areas. There are three types of meteorological stations in this network: namely, high elevation wind sites, precipitation sites and combined sites (Resources Inventory Committee, 1996).

Historical meteorological data are available from the MOTH by request. Real-time data collected by the MOTH are only released to agencies involved with public safety (T. Weick per. comm., 1997). The waiting period for data requests depends upon the amount of data requested but usually ranges from one day up to one month. Meteorological data are maintained in a FOXPRO database system and subsets of data can be provided in ASCII or DBF format. Data costs have not been formally established by the MOTH, however, a cost recovery fee may apply for large data requests (T. Weick per. comm., 1997). For further information on MOTH meteorological data contact Ted Weick, Avalanche Systems Technician, Ministry of Transportation and Highways (Appendix A).

4.8.5 Ministry of Forests (MOF)

The Ministry of Forests operates six different meteorological networks in B.C.: the BC Forest Service Daily Fire Weather Stations, BC Forest Service Hourly Fire Weather Stations, BC Forestry Research Branch FRDA Climate Network, BC Forestry Nelson-West Arm Demonstration Forest Network, BC Forestry-Penticton Creek Experimental Watershed Network and the BC Forestry Silviculture Seed Orchard Climate Network (Resources Inventory Committee, 1996). The Penticton Creek Experimental Watershed, Nelson-West Arm Demonstration Forest and the Silviculture Seed Orchard Networks are local networks, whereas the remaining three networks have stations distributed throughout the province.

BC Forest Service Daily Fire Weather and BC Forest Service Hourly Fire Weather Networks

The stations in the two fire weather networks form the bulk of the meteorological stations operated by the Ministry of Forests. While some stations in the fire weather networks are operated year round, most stations are in operation during the fire season which extends from April to November. Stations in the daily fire weather network acts as a supplement to the hourly network stations. Daily fire weather stations are largely the responsibility of each MOF district office and data from these stations are either collected manually or remotely using VHF communication (Resources Inventory Committee, 1996). In general, daily fire weather stations collect temperature, relative humidity, wind and precipitation. The hourly fire weather network consists of 240 automated hourly reporting climate stations that collect data that include: precipitation, temperature, relative humidity and wind (Resources Inventory Committee, 1996). These stations are located in remote areas of the province. Contact Eric Meyer, Fire Weather Specialist, Ministry of Forests (Appendix A) for more information.

BC Forestry Research Branch FRDA Climate Network

Historically, the MOF operated a network of climate stations across B.C. that formed the BC Forestry Research Branch FRDA Climate Network. Data from these stations were collected during the growing season, as the focus of the research program was to investigate improved seedling regeneration after forest harvesting. At present, all stations in this network are inactive (D. Spittlehouse per. comm., 1997). Unfortunately, there was no central organization of data in this network as storage and quality control was largely the responsibility of each individual researcher. Hence, historical data can only be obtained from the individual researcher responsible for the station in question. A majority of the data collected in this network may not be wholly suited for hydrologic modeling due to the variable quality and discontinuous characteristics of the data recording regime. Data from this network may, however, be useful in verifying or correcting other meteorological records. Contact Dave Spittlehouse, Research Branch, Ministry of Forests (Appendix A) for more information.

BC Forestry Nelson - West Arm Demonstration Forest Network

The MOF operates a network of eight meteorological stations in the Nelson forest region in the West Arm Demonstration Forest (D. Gluns per. comm., 1997). A majority of stations in this network record hourly temperature, relative humidity, precipitation, wind speed, wind direction, snow temperature and soil temperature (Resources Inventory Committee, 1996). Manual measurements of snow-depth are available at two of the eight stations (D. Gluns per. comm., 1997). Contact Dave Gluns, Hydrologist, Nelson Ministry of Forests (Appendix A) for more information.

BC Forestry - Penticton Creek Experimental Watershed Network

The MOF currently operates four climate stations located in the Penticton Creek Experimental Watershed. The number and location of meteorological stations as well as the types of data collected at these stations have varied over the data recording history. Overall, data available from this network include: precipitation, temperature, wind speed, solar radiation, relative humidity and snow-depth that vary in sampling frequencies and record length. Contact Rita Winkler, Research Hydrologist, Kamloops Forest Region, Ministry of Forests (Appendix A) for more information.

BC Forestry Silviculture Seed Orchard Climate Network

The MOF operates a network of climate stations in the Silviculture Seed Orchard Climate Network. Four of the five silviculture orchards in B.C. have climate monitoring programs (Resources Inventory Committee, 1996). These orchards include Saanich, Cobble Hill, Campbell River and Bowser (Resources Inventory Committee, 1996). Surrey is the only silviculture orchard without a climate program (Resources Inventory Committee, 1996). In general, data that are collected year round from these stations include manual measurements of temperature, precipitation, relative humidity, wind speed and wind direction (Resources Inventory Committee, 1996). Hourly wind data are available on a seasonal basis from February to April (G.

Reynolds per. comm., 1997). For more information on these climate stations contact George Reynolds, Virga Consultants (Appendix A).

4.8.6 Site Specific Meteorological Networks

There are also many site specific meteorological networks operated in B.C. Many of these regional meteorological networks have been established for operational and/or research purposes. For example, Parks Canada operates three weather networks in Mt. Revelstoke & Glacier, Kootenay and Yoho National Parks (Resources Inventory Committee, 1996). As mentioned above, the Ministry of Forests operates site specific networks in Nelson, Penticton and in silviculture orchards across the province. The Greater Vancouver Regional District operates several meteorological networks in their region. Contacts for these organization are provided in Appendix A.

One of the biggest site specific research networks on Vancouver Island is at Carnation Creek. The Carnation Creek Experimental watershed is a small coastal catchment located on the west coast of southern Vancouver Island. A network of hydrometric and climate stations were established in the Carnation Creek Experimental watershed in 1971. This network was established as the result of a project initiated by the Department of Fisheries and Oceans to study the effects of timber harvesting and silviculture on the watershed (Resources Inventory Committee, 1996). Historically, data were collected at five weir stations, a main climate station, 10 precipitation stations (that over lapped with some weir sites) and four hygrothermographs in the watershed. Currently, hydrometric and climate data are collected year round at four weir stations, one main climate station, five total precipitation gauges and five tipping bucket gauges. The half-hour data elements collected vary by station type (i.e., weir, climate, precipitation) but may include: precipitation, temperature, relative humidity, wind speed, wind direction, solar radiation, water depth and water temperature. For more information on the historical and current data collection regime of this network, refer to Resources Inventory Committee document (1996) or contact George Reynolds, Virga Consultants (Appendix A).

There may also be other agencies in B.C. that operate meteorological networks on a local basis. Information on these regional networks, if they exist, should be available in the near future as many forest regions are currently undergoing hydrometric and climate network inventories. In the mean time, other agencies that may possibly operate meteorological networks in B.C. may include: local municipal watersheds, forest companies, mining companies, municipal governments and ski hills.

4.9 B.C. Data Resource Limitations

Several limitations exist that can affect the suitability of B.C. data resources for use in hydrologic modeling. These limitations can be divided into two categories: namely, general and inherent data limitations. General data limitations are created primarily by inadequate data collection funding that can result in one or more of the following: substandard data quality, limited quantity, poor accessibility and/or high cost. When present in a data type, general data limitations usually affect every station in the data network. An example of a general data limitation would be the limited availability of groundwater data in upland forested areas in B.C.

Inherent data limitations are specific to each data recording station for each data type and may include limitations such as erroneous measurements, substandard data quality, dynamic station locations and incomplete data records. Unlike general data limitations, inherent data limitations are not present in every station record for every data type. Furthermore, the detection of inherent data limitations in a data record can be difficult at first, as many of these limitations are not readily apparent until the data are thoroughly examined. This point is illustrated in chapter 5 - Attempt to Apply the DHSVM to the Upper Penticton Creek Watersheds which provides a specific account of some inherent data limitations encountered in the original thesis research.

The severity of the limitations that B.C. data resources exhibit for use in hydrologic modeling varies depending upon hydrologic model used and simulation objectives. For example, data requirements for partial or event based models that are used for operational flood forecasting will differ from the data requirements of distributed or semi-distributed models used for predicting wildfire impacts on water yield. Many partial and/or event based models do not require yearly data and, therefore, may avoid portions of the year when data are problematic or unavailable. Furthermore, data limitations that may be problematic to a distributed model can feasibly be absent in a partial model as that limiting data type may not be required. The perception of data limitations can also vary with hydrologic modeler experience and problem solving skills. For example, a hydrologic modeler may incorporate an alternative algorithm within a hydrologic model to overcome a particular data limitation thereby bypassing the need for that limiting data type.

The remainder of the chapter discusses the general limitations of B.C. data resources for hydrologic modeling purposes from the perspective of using such data in any one of the four models reviewed in Chapter 3. It should be noted that the limitations presented here are based upon the perspectives of the author, a first time hydrologic modeler. Therefore, it is possible that other data limitations that can only be learned through experience may be unknowingly omitted. To minimize potential omissions, this thesis project interviewed current hydrologic model users to supplement the author's views.

4.9.1 Subsurface Hydrologic Data Limitations

Together, groundwater and soils data are used in the simulation of subsurface hydrologic processes within many hydrologic models. Soils properties such as texture, depth, bulk density, coarse fragment content, rooting depth, etc are frequently used to characterize subsurface hydrologic characteristics in the soil mantle. A distinction can be made between deep and shallow groundwater which is sometimes incorporated into hydrologic models (e.g., UBCWM). Shallow groundwater is associated with saturated conditions in the soil mantle (unconfined aquifer) which often occur when a saturated zone forms above an impermeable barrier (e.g., bedrock or compact glacial till). This situation is sometimes referred to as a perched watertable. Water in this zone (shallow) either flows along this impermeable boundary or percolates into a deeper aquifer through cracks and fissures in the confining layer (aquiclude). Hence, deep groundwater is usually defined as a confined aquifer.

Currently, shallow and deep groundwater monitoring is sparse in forested watersheds in B.C. because a majority of the stations in the groundwater network are located in domestic areas. The overall availability of groundwater data for hydrologic modeling purposes is therefore quite rare in forested watersheds. Because of this, most hydrologic modelers are forced to either collect their own groundwater data and/or use estimates of groundwater parameters. As such, any expansion of the current groundwater data collection network in forested watersheds would be a valuable asset to hydrologic modelers in B.C. However, it is unlikely that such an expansion will occur anytime in the near future given the current funding situation of the provincial and federal governments.

Currently, the digital soils data that are available for B.C. are also sparse. This situation is expected to change, however, within the next two to three years as programs that are to provide digital soils and terrain data come to fruition. At present, a limited number of digital soils maps are available that are suitable for use in hydrologic modeling. Unfortunately, the incomplete status of the digital soils and terrain map libraries makes it impossible to comment further on the limitations of these data types.

Recommending the creation of a general set of regional subsurface hydrologic parameters for B.C. by soil type and/or regional area (deep groundwater) was contemplated. Such a set of parameters would be extremely beneficial to hydrologic modelers during model calibration. These parameters could be adjusted on the basis of a pre-defined range of values, instead of arbitrary modification guided largely by the objective of improving simulation results. Arbitrary modification of model parameters can create situations whereby parameters are modified to the point of becoming unrealistic. However, recommending the creation of such a range of regional groundwater and soil parameters was unrealistic for two reasons. First, in light of the current funding situation, such an endeavor would be costly and time consuming. Second, the direct measurement of parameters such as hydraulic conductivity or infiltration capacity would be virtually impossible to summarize on a site or regional scale due to the inherently variable spatial and temporal nature of these parameters.

Overall, while current funding is prohibitive to the expansion of the subsurface hydrologic data collection programs, it should be recognized that improving the quantity and quality of subsurface hydrologic data are vitally important, not only for the creation of better modeling data but also to further our understanding of subsurface hydrologic processes. Therefore, at present, the most cost efficient and reliable method to obtain accurate subsurface hydrologic data for hydrologic modeling purposes in B.C. appears to be through collecting one's own groundwater and soils data.

4.9.2 Vegetation Data Limitations

B.C. vegetation data have several limitations for use in hydrologic modeling. The digital overstory vegetation data inventory for B.C., as contained in MOF forest cover maps, is fairly comprehensive and available in a format that is well suited for use in distributed and semi-distributed hydrologic models. However, there are some limitations of this data type that, depending upon hydrologic modeling objectives, may make it unsuitable for use. Some inherent limitations of the MOF forest cover data are also given in Chapter 5.

The main limitation of the digital overstory forest cover data arises as a result of the way in which data are represented in the MOF forest cover map files. Because forest cover data are continuously changing, all MOF inventory data are projected to an arbitrary year in the future (year x) for each polygon on a map. Hence, the actual vegetation characteristics on the ground, in the present, may differ slightly to significantly from year x, depending upon the accuracy of original projection and the projection date. Further differences between the actual and projected vegetation data may also appear as a result of varying site conditions, species composition and stand age. In general, young stands will possess more vigor and, hence, more potential to invalidate projections than mature stands that are less vigorous and, hence, less dynamic. The use of projected overstory forest cover data could be problematic in hydrologic modeling applications that attempt to simulate the recovery of vegetation. For example, simulating the effects of vegetation removal on hydrologic recovery on a site or watershed scale. In these cases, vegetation parameters will be highly dynamic and most often not well represented by the projected data, if a projection for the young stand even exists. Yet, the use of forest cover data for modeling mature stands may not be problematic as vegetation characteristics are generally less dynamic in these older stands.

While overstory vegetation data are comprehensive for the province, specific understory vegetation data are poorly inventoried and largely unavailable in either paper or digital format. Province wide, only general understory vegetation information can be obtained from BGCZ and Ecoregion maps. Understory vegetation data are important for use in hydrologic models that simulate two vegetation canopy layers (e.g., DHSVM). Accurate understory vegetation data are also important for modeling applications that wish to simulate the effects of the removal or recovery of the understory vegetation layer. Currently, the MOF are in the process of conducting and compiling an understory vegetation inventory to be included with the overstory vegetation inventory of B.C. This project is expected to be completed in the next five to ten years (R. Woods per. comm., 1997).

Two other types of vegetation data are currently unavailable on a provincial scale that can be required by hydrologic modelers. These data types include leaf area index (LAI) and rooting depth values per vegetation species. Depending upon region and vegetation species, both data types can be highly variable in both space and time and, thus, could feasibly be difficult to derive as regional parameters. LAI is an important vegetation parameter that is used by some hydrologic models in the simulation of evapotranspiration and interception processes. LAI can be modified during forest disturbances such as wildfire, wind-throw and forest harvesting. As such, the ability to accurately account for and modify LAI in a hydrologic model is essential in simulations that attempt to assess the possible impacts from these disturbances. However, not all hydrologic models require estimates of LAI; for example, the UBCWM does not.

Information on rooting depth by vegetation species is also largely unavailable for B.C. Rooting depth can be important in the modeling of transpiration and subsurface hydrologic processes. As vegetation matures, rooting depth and biomass will increase. The zones in the soil from which vegetation can extract water will therefore also increase in depth as the vegetation grows. Knowledge of the approximate rooting depth by vegetation canopy layer (stand) are important for hydrologic models such as the DHSVM which use estimates of these parameters in the simulation of unsaturated soil moisture movement. As with LAI, deriving values for rooting depth is subjective, difficult and often rudimentary.

4.9.3 Topographic Data Limitations

The topographic data available for hydrologic modeling in B.C. are comprehensive and readily available in two formats. The primary limitation of the topographic data is cost. Digital TRIM data can be expensive, costing approximately $600.00 plus tax per map. Some inherent limitations of digital TRIM data are given in Chapter 5.

4.9.4 Remotely Sensed Data Limitations

As with digital TRIM data, the cost of satellite data is a major limitation for hydrologic modeling use. Costs for satellite data are expensive, averaging $4000.00 to $6000.00 per scene and, thus, limited to high budget modeling applications.

4.9.5 Snow Survey Data Limitations

General limitations of manual snow survey data arise as a result of sparse monitoring sites in B.C. and an unsuitable sampling regime for use in hydrologic models. Although there are 218 snow courses in operation across the province, most watersheds in B.C. do not have snow survey courses located within their boundaries. Of those watersheds that are monitored, there is usually only one snow course available within the catchment boundaries that can be used to determine snow accumulation and ablation processes for the entire watershed. The limitation of using single point measurements can prove to be problematic when processes such as snow redistribution, aspect influences and elevation differences are present in a watershed and must, therefore, be accurately accounted for from single point data. In these cases, use of point snow data may feasibly lead to the inadequate estimation of distributed snow data, which will in turn result in erroneous simulation results.

While the quality of manual snow survey data is good, the data sampling regime of bi-weekly to monthly also can be problematic for some hydrologic modeling applications, especially those where daily to hourly time steps are desired. In these situations, modelers must often fabricate hourly to daily data from the available bi-weekly to monthly observations. Unfortunately, data fabrication can lead to questionable significance of simulation results during these time periods. However, this limitation is not perceived to be significant by some current hydrologic modelers in B.C. For example, the MOELP does not view the current sampling regime of the snow survey data to be problematic for use in operational flood forecasting on the Fraser River (R. Wyman per. comm., 1997; R. McNeil per. comm., 1997). The MOELP's main concern is to obtain an accurate estimate of the snow water equivalent of the snow-pack before melt conditions occur. Hence, most of the daily and weekly totals throughout the snow accumulation period are inconsequential for operational flood forecasting use. Robert Hudson, regional hydrologist for the MOF in Nanaimo, also does not view the current sampling regime of the manual snow survey data to be limiting. Hudson does not recommend that manual snow survey data be used as a direct input for hydrologic modeling (R. Hudson per. comm., 1997). Rather, the available manual snow survey data is best used to verify snow mass balance model simulation results (R. Hudson per. comm., 1997).

A limited amount of snow pillow data are available for use in hydrologic modeling applications in B.C. Snow pillow data can be advantageous over manual snow course data for use in hydrologic modeling in that snow pillows can be installed in remote areas and measure the accumulation and ablation of snow on an hourly basis. However, the availability of snow pillow data are even sparser than manual snow survey data. Currently, there are only 47 snow pillows in operation across the province (J. Matthews per. comm., 1997). Snow pillow data can be further limited for use in hydrologic modeling in that the accuracy of data can be affected in two ways. First, temperature variations at the recording site can alter the density of liquid in the instrument thereby leading to erroneous measurements. Second, the formation of ice layers within the snow-pack that support a portion of the weight overlying the snow pillow can also lead to erroneous measurements. Overall, while snow pillow data may be more suitable than manual snow survey data for use in hydrologic modeling, the sparse availability of this data type make its use limited.

Other, more expensive, methods of monitoring seasonal snow conditions are also available, but not widely used in B.C. As mentioned, satellite data can be used to measure the aerial extent of snow cover during the accumulation and ablation periods. The cost of obtaining satellite snow data is expensive, however, as one satellite scene costs between $4000.00 to $6000.00. Radioactive gauges can be used to measure the water equivalent of a snow-pack (Dingman, 1994). Radioactive gauges measure gamma radiation emitted from the soil surface by either sensors fixed above the snow-pack or from aircraft (Dingman, 1994). The operational use of radioactive gauges to monitor snow-pack conditions, however, has not occurred in B.C.

In all, the severity of the above mentioned limitations of B.C. snow survey data will vary depending upon the size of the watershed modeled, modeling objectives and hydrologic model capabilities. Yet, all hydrologic models will encounter some degree of limitation in the currently available B.C. snow data resources. From a research and hydrologic modeling perspective, expanding the snow survey program to collect data on a smaller time step (i.e., hourly to daily) would provide data of a fine enough resolution to allow for further research on winter snow accumulation and ablation processes in mountainous terrain. Such an expansion would also allow for more confident hydrologic modeling of winter hydrologic processes to occur.

4.9.6 Streamflow Data Limitations

General limitations of B.C. streamflow data arise as a result of sparse monitoring sites, an unsuitable sampling regime for hydrologic modeling and data cost. Some inherent limitations of the currently available streamflow data are given in Chapter 5. As with snow survey data, a majority of watersheds in B.C. do not possess streamflow monitoring equipment. In some instances, the absence of streamflow data in a locale can be limiting to hydrologic modeling applications that examine the accuracy of absolute changes (vs. relative changes) that could occur after forest disturbance. The availability of streamflow data in these instances can ultimately define where hydrologic modeling *calibration* can occur in B.C. The calibration process is an important step for obtaining significant simulation results. As well, calibration is important in validating hydrologic models that are to be applied to other watersheds in the same locale where streamflow data are unavailable. As such, the sparseness of streamflow data in B.C. watersheds can create instances where the significance of simulation results cannot be determined. Hence, the inability to verify the significance of simulation results can be limiting in the calibration and application of hydrologic models in many watersheds where these objectives are desired.

Another limitation of B.C. streamflow data is the limited availability of year round, hourly data. Since many distributed models are most efficiently run using one to three hour time steps, short frequency streamflow data (e.g., hourly) are often required. Yet, daily streamflow measurements are the shortest time interval of data currently available from the CD produced by Environment Canada. Unfortunately, hourly streamflow data can only be obtained through manual extraction from storage by WSC workers. In addition, some stations in the B.C. streamflow network are incapable of providing streamflow measurements shorter than 24 hours. Manual data extraction is limited in that it can be costly and labour intensive to obtain because most hourly data must be transposed from analogue recording charts. The scarcity of hourly streamflow data is expected to change in the future as many of the manual and analogue chart recording streamflow stations are upgraded to a digital recording format. At present, however, obtaining hourly streamflow data is still possible if gauges are present in a watershed but costly, as a fee of $87.00 per hour for data extraction is charged.

4.9.7 Meteorological Data Limitations

Limitations in B.C. meteorological data resources arise primarily due to a sparseness of stations that collect a complete set of meteorological variables required by many hydrologic models. In B.C., only a handful of meteorological stations record a complete set of variables that are suitable for hydrologic modeling on a year round basis. Most of these year round meteorological stations are located either in research watersheds such as Carnation Creek and Penticton Creek or in suburban areas and valley bottoms that are usually not of great interest to hydrologic modelers. Yet, as illustrated in Chapter 5, even intensively monitored watersheds such as Penticton Creek can possess inherent limitations in meteorological data records that can be prohibitive to modeling attempts.

At present, many meteorological stations record only a few meteorological variables because the purpose of the particular station is to provide the operating agency with a specific type of information. Therefore, in order to minimize costs, many of the current meteorological stations do not operate year round. For example, the MOF fire weather networks are only in operation during the fire season and the MOTH networks are only in operation during the winter months. Overall in B.C., there is a shortage of meteorological stations in the middle to high elevations that collect a complete set of meteorological variables required by many hydrologic models.

The second limitation of B.C. meteorological data resources is the sparseness of meteorological data available across the province. Although there appears to be an abundance of meteorological stations available, a majority of watersheds in B.C. do not possess meteorological data recording equipment. In addition, many of the stations that can provide year round, hourly data (e.g., AES network) are usually located in valley bottoms or near urban centers. The data that are available can thus be inappropriate for use in modeling middle to high elevation watersheds where a majority of operational forestry modeling is expected to occur. For example, while adjusting low elevation data to high elevation sites is feasible, it can also prove to be problematic in areas where topography exerts a large control on meteorological variables; e.g., orographic effect on precipitation amounts, intensity and distribution. Thus, the use of such meteorological data can be limited in that localized meteorological storms and phenomena such as temperature inversions can complicate hydrologic simulations if their presence is not adequately accounted for (or removed) in a data record.

Improving the current meteorological data resources available would benefit not only hydrologic modelers but all who use the meteorological data. It would be a valuable asset for hydrologic modelers in B.C. if many of the meteorological stations were to collect a complete set of hourly variables that include: precipitation, temperature, relative humidity, wind and solar radiation on a year round basis; especially in the middle to upper elevations. As with all the other data types reviewed in this chapter, funding limitations most likely will prohibit any realistic expansion of the various meteorological data collection networks. However, many of the changes that would be required to improve the current meteorological data networks are minor; for example, adding equipment to an established recording site (e.g., winter precipitation recording device) or upgrading equipment (i.e., data loggers to allow for shorter sample regimes and/or extending the recording period). The cost of these upgrades could be partially offset through cost-sharing of network stations among the agencies currently operating networks and/or those who use the data. In this manner, agencies could increase the number of stations they have access to, streamline redundant stations and improve the overall quality of data that are collected.

4.9.8 Conclusions

While hydrologic modeling data needs are model specific, most hydrologic models require accurate meteorological, snow and streamflow data on a spatially distributed basis. For all hydrologic models, the most limiting factor of B.C. data resources appears to be the sparseness of these three data types. It is stressed that the limitations presented in this chapter are based upon the experiences of a first time hydrologic modeler. As such, it would be valuable for a similar and perhaps more intensive review to be conducted by more experienced hydrologic modelers who can possibly construct more realistic solutions to ameliorate the data limitations.

Overall, the current limitations in B.C. data resources are created largely by funding restrictions and the outlook for any expansion of the various data collection programs in B.C. appear to be remote. It is important to recognize, however, that adequate data collection programs are essential not only for proper resource management and hydrologic modeling but also for public safety (e.g., flood forecasting). For hydrologic modeling, it is also the quality of input data that ultimately dictates the quality of simulation results that can be obtained. As such, the use of substandard data in a hydrologic model can be ineffectual. B.C. data resources will likely never be fully adequate for use in widespread operational hydrologic modeling in B.C. However, with minor improvements to many of the current data types, many areas of the province could possess data that would be suitable for use in hydrologic modeling. It is also possible that these minor improvements could lead to a decrease in the level of inherent limitations of B.C. data resources.

CHAPTER 5

ATTEMPT TO APPLY THE DHSVM TO THE UPPER PENTICTON CREEK EXPERIMENTAL WATERSHEDS

5.1 Introduction

This chapter describes the many inherent limitations encountered during the preliminary thesis research. The research focused on using data from the Upper Penticton Creek (UPC) Experimental Watersheds to calibrate the Distributed Hydrology-Soils-Vegetation Model (DHSVM). Unfortunately, the preliminary research was unsuccessful due to numerous limitations encountered in the input data, hydrologic model, project logistics and thesis research design. The lessons learned from this experience illustrate a variety of difficulties that one might typically encounter when attempting to use a hydrologic model in British Columbia. The following is a detailed description of the inherent data, research design, DHSVM and logistic limitations encountered.

5.2 Initial Project Description

The original thesis was entitled: "Exploring the Simulation of Wildfire Impacts on the Hydrologic Regime of the Upper Penticton Creek Experimental Watersheds using the Distributed Hydrology-Soils-Vegetation Model (DHSVM)." The objective of this project was to apply the DHSVM to two small sub-basins in the Upper Penticton Creek Experimental Watershed to explore the feasibility of using the DHSVM to simulate hydrologic-wildfire impacts. The project was divided into two stages: Stage-1, calibration and validation of the DHSVM to the study area and Stage-2, exploration of the feasibility of hydrologic-wildfire simulation using the DHSVM.

5.2.1 Site Description

The UPC Experimental watersheds are located 26 kilometers northeast of the city of Penticton in the upper reaches of the Penticton creek watershed at a latitude of 49° 39' 01" and longitude of 119° 23' 50" (Figure 5.2-1). The research site consists of two small, 500 hectare areas drained by 240 creek and 241 creek (Figure 5.2-1). These sub-basins can be classified as belonging to the ESSF dc1-Okanagan dry cold, Engelmann Spruce-Subalpine Fir Biogeoclimatic Zone. The sub-basins are forested primarily by mature lodgepole pine (*Pinus contorta* var. *latifolia*) with lesser amounts of Engelmann spruce (*Picea englemannii*) and subalpine fir (*Abies lasiocarpa*). The soils of the research site are ortho humo-ferric podzols underlain by rocks of the Monashee group; consisting of granitic gneisses, quartizites and marbles (Butt, 1994). The surficial geology of the sub-basins is comprised of morainal blankets, colluvial blankets and fluvio-glacial terraces with areas of exposed bedrock in the upper elevations of each sub-basin.

In general, 240 Creek and 241 Creek sub-basins receive 700 to 900 millimeters of precipitation annually (Butt, 1994; Hudson, 1995), with between 50% (Hudson, 1995) to 70% (Butt, 1994) falling as snow. Snow-packs in the sub-basins generally persist until the middle of May, with maximum depths averaging 79-85 cm. occurring at the end of March to the beginning of April.

5.2.2 Rationale for Research Site and Model Selection

The DHSVM was selected as being a suitable hydrologic model for the initial thesis project for two reasons. First, the DHSVM incorporates many of the hydrologic parameters that are affected by wildfire which could be altered in the simulation of hydrologic-wildfire impacts. Second, the DHSVM was developed in Washington state for topographic and climatic conditions similar to those found in British Columbia. As such, minimal modification of the hydrologic equations in the DHSVM would be necessary in order for the model to be successfully applied to the study site as well as in the simulation of hydrologic-wildfire impacts.

The Upper Penticton Creek Experimental Watersheds study area was selected because of the abundance of data and support available. The UPC watersheds are a long term research site for the Ministry of Forests to investigate the effects of forest

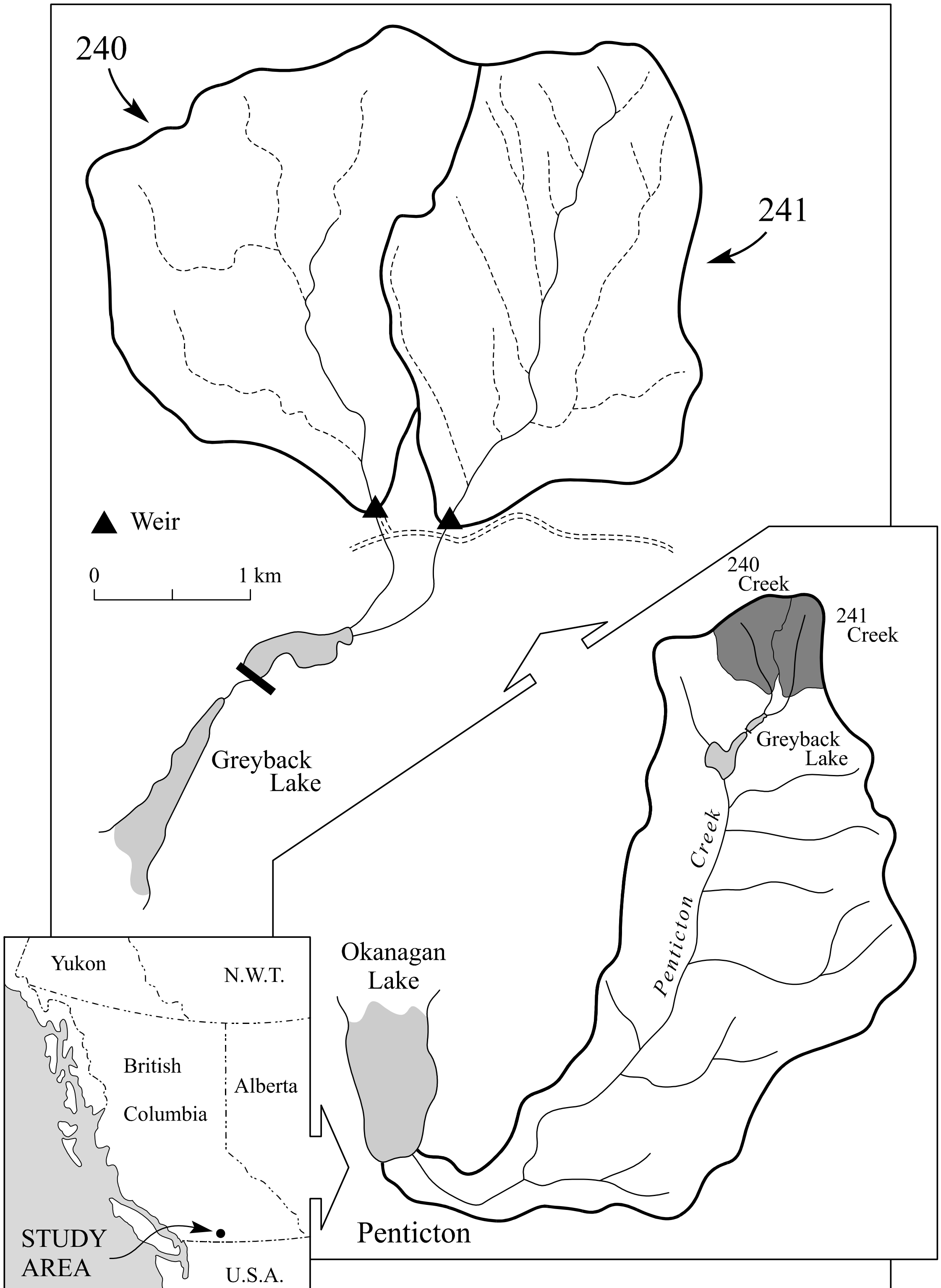

Figure 5.2-1 Upper Penticton Creek Experimental Watersheds

disturbance on streamflow and water quality. Therefore, due to the research status of this watershed, it was assumed that the available streamflow and meteorological data would be suitable for input into a hydrologic model. Overall, no major calibration or model verification problems were anticipated as the UBC watershed model had already been successfully applied to the Upper Penticton Creek Watersheds (Hudson, 1995). Unfortunately, the preceding assumptions were erroneous. Unforeseen problems emerged in both the data and the DHSVM that created barriers to the timely progression of the initial thesis project.

5.3 Inherent Data Limitations

When the initial research proposal was developed, it was assumed that the data available from Penticton Creek would be suitable for investigating hydrologic modeling objectives. This assumption was justified as the UPC area was an established research watershed and the available data had previously been used to calibrate and validate the UBCWM to the research site (Hudson, 1995). As such, only minor data problems were anticipated and minimal time was allotted in the research design for dealing with such problems. However, as the study proceeded and the data were collected and examined, severe limitations in many of the data types became evident. As will be discussed, the precision of the data was found to be inappropriate for use in the DHSVM and subsequently, in investigating the preliminary research topic. Unfortunately, the additional time that would have been required to create suitable input data was beyond what could reasonably be expected for the thesis.

This section will detail the data limitations encountered in the preliminary thesis research. The purpose of this review is not to be hypercritical of the Penticton Creek data but rather, to use these limitations to highlight areas where data problems could emerge in any hydrologic modeling project. Data limitations are important to confront at the beginning of a modeling project as they ultimately define the maximum level of precision that can be obtained from a simulation. The following sections discuss the inherent meteorological, streamflow and forest cover data limitations encountered.

5.3.1 Meteorological Data Limitations

For this thesis project, 10 years of meteorological data were obtained that included: maximum and minimum temperature, precipitation, wind and solar radiation. After the meteorological data were examined, it became apparent that two problematic areas in the data existed: namely, shifting data recording locations and unreliable meteorological values. First, the locations of the meteorological data recording sites in the experimental watershed shifted over the data recording history. Several times during the 10-year data recording period, meteorological stations were either relocated or shut-down. The disruption of recording sites was viewed to be problematic as the data recording regime of the stations would change and, therefore, would need to be adjusted to create a consistent data record for input into the DHSVM.

Second, measurements of wind speed, solar radiation, temperature and precipitation were found to be unreliable. Wind speed measurements were deemed to be unreliable as the calibration coefficients used in the wind monitoring instrumentation were unknown. As a result, the data provider advised that wind values in the data records obtained not be used in hydrologic modeling. Solar radiation values too were problematic as they were found to be exceedingly discontinuous and sporadic. The sporadic nature of the solar radiation data made the creation of a continuous data record from the obtained data impossible. The solar radiation data thus had to be discarded.

Temperature measurements in portions of the data record were also found to be problematic. For example, the meteorological station in the 240 Creek sub-basin was located under a forest canopy, in close proximity to the streamflow recording station. Temperature measurements from this station would therefore need to be adjusted to remove the influence of both the water body and the forest canopy on temperature values as well as on the wind, precipitation and solar radiation values.

Finally, winter precipitation measurements were also unreliable as the gauges that were used to collect precipitation data were designed primarily for liquid precipitation measurement. This proved to be problematic because between 50% to

70% of the annual precipitation in the research area falls as snow. Therefore, obtaining accurate winter precipitation measurements from the meteorological stations in the research area was not possible.

Subsequently, it was decided that the most efficient way to handle the limitations in the meteorological data was to exclude those portions of the data record that required extensive correction. Unfortunately, due to the unsatisfactory condition of the obtained data, this action resulted in a reduction of the data record length to three years. The number of available meteorological variables were also reduced from five to three; namely precipitation, maximum temperature and minimum temperature.

To remedy the unsatisfactory winter precipitation record, shortened meteorological record, missing observations and reduced number of meteorological variables, data from five additional sources were collected that included: Mission Creek snow pillow data, Idabelle Lake fire weather data, McCuloch Weather Station data, Greyback Lake snow survey data and Big White historical snow fall data (Table 5.3-1). However, at the time of obtaining this supplemental data other inherent limitations in the forest cover data and the DHSVM were being encountered. Subsequently, the data correction process was halted and project viability was re-examined.

The time required to correct the meteorological data was estimated and the suitability of the shortened data record in investigating the thesis objectives was determined. It was concluded that the estimated time to create a suitable meteorological data record for input into the DHSVM was unreasonably long for the thesis project. It was also concluded that the data, even when corrected, would not be suitable for use in investigating the thesis project objectives for two reasons. First, the reduction of meteorological variables to three would necessitate the creation of the missing variable types from the remaining problematic variables. Any errors present in the remaining variables would then be transferred to the newly created variables and, therefore, errors would cascade through the modeling procedure.

Second, by reducing the data record length to three years, the corresponding streamflow data record was also reduced. Unfortunately, the three years of hydrometric data that were available did not possess as much variation as the original

Table 5.3-1 Hydrometric and Climate Data Obtained for Hydrologic Modeling

Station	Elevation	Latitude	Longitude	Data Source	Climatic Data Collected	Record Length	Data Frequency
240 Creek	1600 m.	49°39'01"	119°23'50"	MOF[1]	Precipitation, Maximum and Minimum Temperature, Solar Radiation	1983-94	Daily
Idabelle Lake	1250 m.	49°42.2'	119°10.6'	MOF	Precipitation, Maximum and Minimum Temperature, Relative Humidity and Wind Speed	1983-94	Daily: April - October only
Greyback Reservoir	1550 m.	49°37'	119°25'	MOELP[2]	Average Snow Depth, Snow Water Equivalent and Snow Density	1953-95	Monthly, Jan-April. Bi-weekly May - until snow-pack gone
Mission Creek - Snow Pillow	1780 m.	49°57'	118°57'	MOELP	Maximum and Minimum Temperature, Daily Precipitation, Accumulated Precipitation, Snow Water Equivalent	1985-95	Daily
McCulloch	1220 m.	49°46'06"	119°06'48"	MOTH[3]	Sky Condition, Precipitation Type, Precipitation, Maximum and Minimum Temperature, Snow Pack Depth, Wind Direction and Wind Speed	1985-95	Daily winter values November to April only
Big White Ski Resort	2210 m.	49°43'30"	118°55'33"	Big White Ski Resort	Snowfall Accumulation	1981-95	Monthly winter values November to April only
08NM240, 08NM241	1600 m.	49°39'01" 49°39'05"	119°23'50" 119°23'30"	Water Survey Canada	Streamflow	1983-94	Daily values

[1]MOF Ministry of Forests, [2]MOELP -Ministry of Environment, Lands and Parks, [3]MOTH - Ministry of Transportation and Highways

10-year data record. Under these circumstances, the calibration of the DHSVM would not be as significant as if the original 10-year data record were available for model use. Overall, the meteorological data obtained was unexpectedly in a condition that was not satisfactory for use in investigating this thesis modeling objectives. The time estimated to remedy the unsatisfactory winter precipitation record, shortened meteorological record, missing data observations and reduced number of meteorological variables was seriously underestimated in the research design.

5.3.2 Streamflow Data Limitations

As mentioned, inherent limitations in the streamflow data also became apparent during the initial thesis research. At the beginning of the thesis project, the streamflow data obtained from Water Survey of Canada was assumed to be error free and appropriate for use in the DHSVM. Field personnel at the Penticton field office of the Water Survey of Canada maintained that no anomalies or errors in the obtained streamflow data existed as the data had already been processed by WSC. A more extensive review of the streamflow data collection regime, however, revealed issues that possibly could have lead to unsatisfactory hydrologic simulation results.

The primary limitation of the streamflow data resulted from an infrequent sampling and maintenance schedule of the recording stations. To better understand these limitations, the following is a summary of the current (1997) sampling and maintenance regime of streamflow recording stations 08NM240 (240 creek) and 08NM241 (241 creek) as denoted by Bud Skinner (per. comm., 1997), Penticton Field Office, Water Survey of Canada.

Both streamflow recording stations in the research area use LAS-A71 float recorders to measure continuous stage height. Each streamflow recording station uses a four foot, wooden rectangular weir than allows a V-notch insert to be installed during low flow periods. V-notch inserts are usually installed during July or August and removed during the spring thaw maintenance visit. Streamflow overflows each weir at values greater than 0.315 m^3/s (Figure 5.3-1 and 5.3-2). For each station, streamflow is rated to discharge vs. stage depending upon the size and shape of the weir opening. Thus, separate rating curves are used for each weir type; one for the V-notch and one for the four foot opening. Overall, the derived rating curves are estimated to be within +/- 5% of the actual flow rates (R. Winkler per. comm., 1995; B. Skinner per. comm., 1997). Each recording station is visited 10-12 times per year for maintenance, at which time the station recorder is checked and the water level in the weir pond noted. Manual streamflow measurements are collected during site visits only if the weir is over-topped. During the spring maintenance visit, the recording well is steamed out, any ice present in the weir pond is removed and snow is cleared back from the pond edges.

In considering the preceding maintenance and data sampling schedule, the primary limitation of the streamflow data is the low number of sample points that were used to create portions of the rating curves. For each station, the lower portion of the rating curve is based upon weir table data while the upper portion (streamflow values greater than 0.315 m^3/s) is based entirely upon manual streamflow measurements. In general, the overflow portion of the rating curve is based upon only one to three measurements per year (B. Skinner per. comm., 1997) and, therefore, the confidence interval of this portion of the rating curve will differ from the lower portion. The lower portion of the rating curve, thus, has an approximate +/- 5% error while error estimates of the upper portion of the curve may actually be up to 10% in some years (B. Skinner per. comm., 1997). In addition to variable rating curve precision, erroneous streamflow measurements could also occur as a result of high approach velocities (momentum spill-over), shifting rating curves due to weir pond infilling and stream channel changes (B. Skinner per. comm., 1997).

Major concerns of the preliminary research project were the accuracy of the timing of peak flows, peak flow magnitude and the correlation of daily flow to simulation results. The author felt uncomfortable with the precision of the rating curve estimates as a majority of the peak flows and daily flow estimates in the spring are above 0.315 m^3/s (Figure 5.3-1 and 5.3-2) and, thus, lie in the less confident portion of

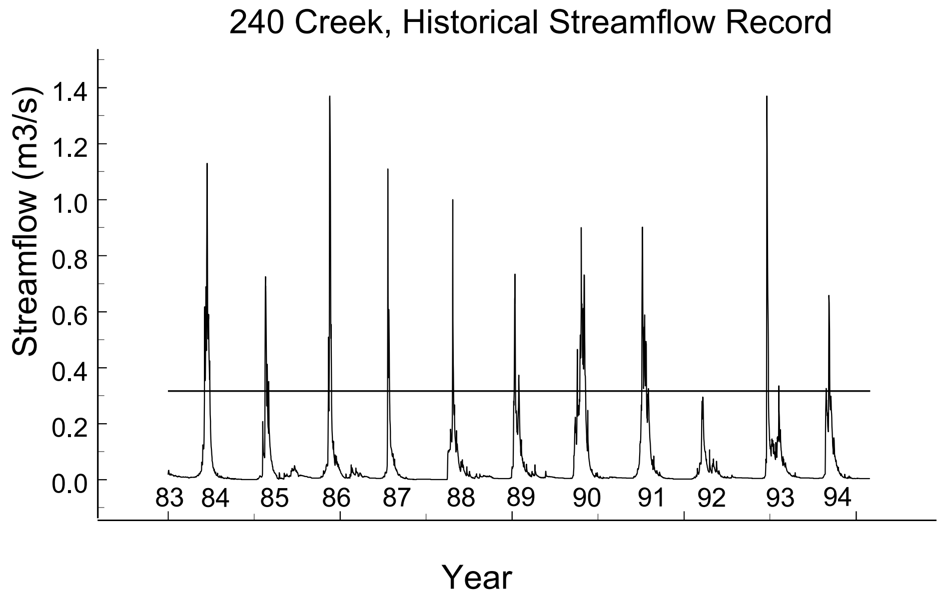

Figure 5.3-1 Historical Streamflow Record, 240 Creek.

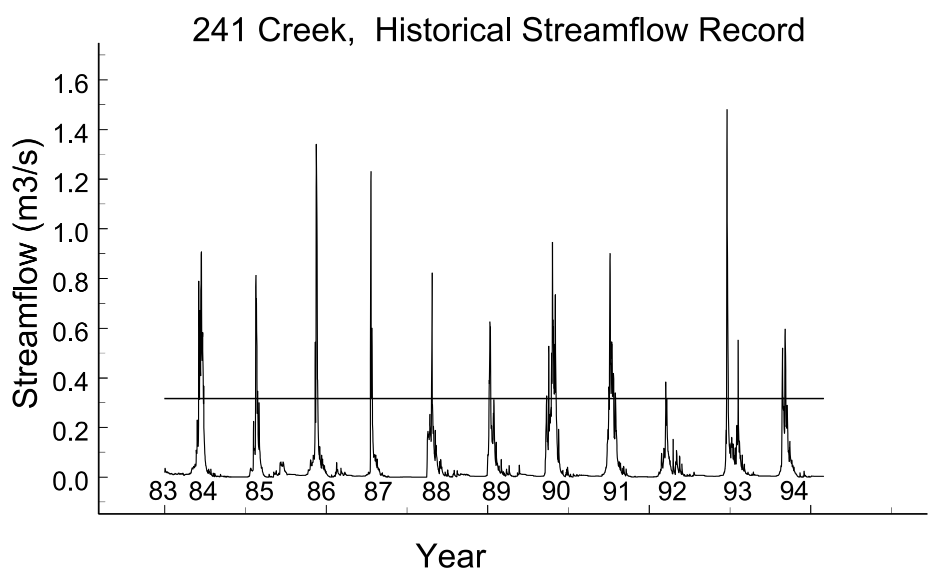

Figure 5.3-2 Historical Streamflow Record, 241 Creek.

the rating curve. Therefore, it was concluded that hydrologic simulation results could not be consistently validated if the precision of the rating curve varied and/or was feasibly imprecise during high flow situations because of infrequent calibration. It is unknown, however, at what level these errors would begin to significantly affect the reliability of simulation results. Therefore, the streamflow data warrants further investigation to substantiate or dissolve this noted limitation.

In summary, while the streamflow data were appropriate for Water Survey of Canada purposes, the current streamflow sampling regime may not have been suitable for the investigation of the preliminary thesis topic, especially in those cases where high streamflow values are simulated. This project erred by assuming that streamflow data would be appropriate for use in hydrologic-wildfire impact modeling without first examining the data collection regime of the streamflow stations. The exact influence these limitations would have on model calibration results are unknown as the current streamflow data regime may well lead to satisfactory model calibration.

5.3.3 Forest Cover Data Limitations

Inherent limitations in the digital forest cover data obtained from the Ministry of Forests were also encountered in the preliminary thesis research. The primary limitation of the digital MOF forest cover data is that the supplied data format is not compatible with many current GIS systems. Therefore, forest cover data must first be translated into a standard format before it can be used by a GIS package. This project encountered further project delays as a result of difficulties with the forest cover data translation process.

The translation of MOF forest cover data into a standard format can be a difficult and time consuming procedure without the aid of a translator program. To aid in the translation of forest cover data, the government of B.C. has created the Feature Manipulation Engine BC (FMEBC) translator program that is freely distributed on the internet. FMEBC is a bi-directional translator which supports translations to SAIF (Spatial Archive and Interchange Format), a vendor-neutral format for Geographic Information System (GIS) data. FMEBC software and support can be obtained from the website: http://www.env.gov.bc.ca/gdbc/fmebc/.

This project used the FMEBC program to translate the forest cover data into a standard format that could be recognized by ARC/INFO, a GIS software package. The following is a brief summary of the three step translation process performed (Figure 5.3-3). In the first step of the translation, the original MOF forest cover files (FIP and FC1) were translated into SAIF format with the use of FMEBC. The FC1 file is a Microstation design file that contains information about the geometry of the map.

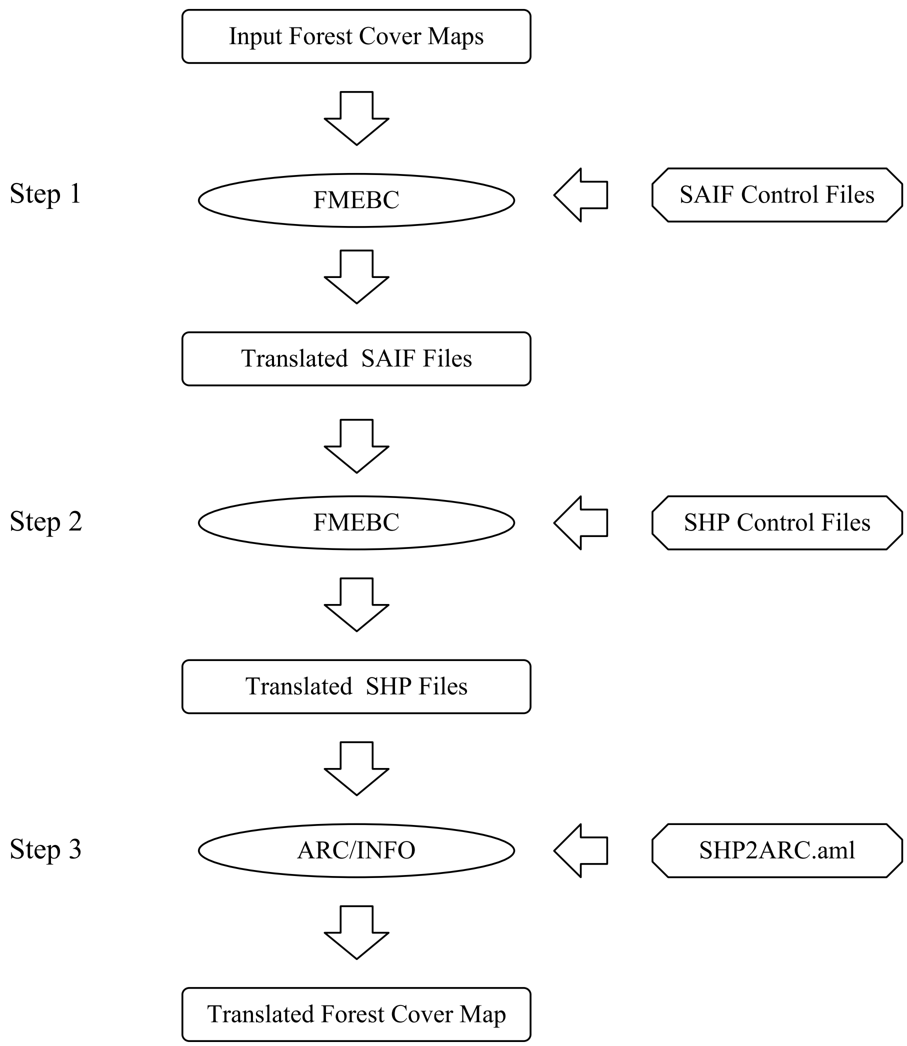

Figure 5.3-3 Forest Cover Map Translation Process

The FIP file contains information about the attribute data in a flat file format. In step two, the output SAIF files were translated into ESRI Shapefile Format (SHP) again with the use of FMEBC. In step three of the translation process, the SHP format files were input into ARC/INFO and converted into ARC/INFO coverages by using the ARC/INFO Macro Language (AML) - SHP2ARC.aml. This AML was obtained from the website: http://www.env.gov.bc.ca/gdbc/ArcAML/amlintro.htm. While other methods of translating forest cover data are available, this translation method ensures that all attributes remain linked as they are translated from the MOF format into ARC/INFO coverages.

Two problems were encountered in the data translation process that further delayed project progression. First, the AMLs available on the MOELP website are generic and, therefore, must be modified to work with the specific version of ARC/INFO used. In this case study, the AML obtained had to be modified to suit an older version of ARC/INFO. Again, this resulted in additional time required for data processing in the research project.

Second, forest cover maps themselves can be problematic due to the differing storage formats used by the MOF. In this case study, map sheet 82E063 was problematic because the map attributes were stored in string form by the MOF. While this does not pose a problem for MOF users on Microstation systems, the attempted translation failed due to an unrecognizable string file structure when input into FMEBC. Subsequently, upon request, a special modification of FMEBC and the control files were developed for map 82E063 by Peter Friessen at the Ministry of Environment. However, once the translation process was successful, each attribute had to be manually converted in ARC/INFO from string to integer format.

Hydrologic modelers should be aware that the forest cover data translation process can take much longer than one would normally expect, especially if problematic maps are encountered. Ideally, forest cover maps can be translated within one to two hours depending upon computer capabilities. Longer translation times could be expected for problematic maps. At the time of writing this chapter though, a professional version of FMEBC, called FME recently became available. This translation program may reduce forest cover map translation time down to five to ten minutes per map.

Overall, the inherent limitations in the meteorological, streamflow and forest cover data all lead to additional time being required for data processing. Unfortunately, the time that was required to ameliorate all of these inherent data limitations was beyond what could be reasonably expected for this thesis project. The inherent limitations encountered in the data, however, were not the only reason why the thesis project was reformulated. Limitations in the research design, DHSVM and project logistics also created problems within the original thesis research.

5.4 Inherent Research Design Limitations

Limitations in the research design were also a contributing factor in the re-formation of the original thesis topic. It is valuable to illustrate these limitations as they can potentially affect the success of any hydrologic modeling project. In retrospect, two errors were made in designing the original research project; 1) an unsuitable modeling time step was selected for investigating the thesis objectives and, 2) insufficient time was budgeted for model calibration.

First, a daily (24 hour) hydrologic modeling time step was selected for model calibration. At the time of designing the research project, this time step appeared reasonable and matched the sampling frequency of the available hydrometric and meteorological data. However, because of the relatively small size of the sub-basins, a modeling iteration time step of three hours was determined to be more appropriate. A shorter time step would be more suitable for the simulation of snow-melt conditions on days when the temperature hovers around the melting point as the DHSVM may not exhibit significant melt using a daily time step (T. Kenward per. comm., 1997). In reality, snow-melt would occur in the daytime during such days. It was possible for the daily meteorological observations to be decomposed to a three hour time step for the thesis project. However, due to the unsatisfactory condition of the meteorological data, decomposing the observations was viewed to be non-productive. Overall, the research design erred in not matching the objectives of the hydrologic simulation to that of the available data frequency.

Second, the time allotted in the research design for dealing with possible inherent meteorological, streamflow and forest cover data limitations was grossly underestimated. Together, these limitations created project delays that eventually prompted the re-evaluation of thesis project viability. In retrospect, the necessity of being over generous in allotting time for data processing and dealing with unforeseen problems is a critical component of every modeling project. Unfortunately, this thesis project erred in that time budgeted for data preparation and problem solving was too conservative.

5.5 Inherent DHSVM Limitations

Five inherent limitations in the DHSVM were also uncovered that can be categorized as either model limitations or operational limitations. The following two model limitations are currently being or have been resolved by DHSVM modelers in Washington state. These limitations were prominent at the time of using the DHSVM in this thesis project. First, the DHSVM does not impose an explicit channel routing scheme on the DEM data during a simulation and, therefore, inefficiencies in simulation results can be produced (T. Kenward per. comm., 1997). These inefficiencies occur in situations where the simulated water table rises to the surface and water is assumed to flow over the surface at a rate greater than that of the subsurface flow. In the DHSVM, this quantity of water is assumed to continue to flow to the basin outlet at the surface rate, whereas in reality, the flow would most likely be reabsorbed down slope (T. Kenward per. comm., 1997). Second, the DHSVM does not explicitly model the influence of roads on the hydrologic regime of a watershed. Roads are important to account for as they can feasibly channel water down a road grade via intercepting subsurface flow and/or precipitation as a result of soil compaction and, subsequently, reduced infiltration rates. As mentioned in Chapter 3, the DHSVM now has the capability to represent roads in a watershed and, therefore, this limitation should not be significant at present.

Three operational difficulties with the DHSVM were also encountered. First, at the time of performing the initial thesis research, the DHSVM was still under development and there was no standard version of the model available. As a result, many different versions of the DHSVM were in existence as historically, each DHSVM user modified the computer code to suit their research needs. As such, prospective DHSVM users had to be aware that the version of the model obtained might contain unnoticeable modifications that could feasibly lead to unsatisfactory simulation results. A standard version of the DHSVM is now available and, therefore, this limitation should not be significant at present.

Second, in an operational sense, the DHSVM is extremely difficult to learn how to use as the model has no user's manual and is highly user unfriendly. Furthermore, use of the DHSVM is limited largely to modelers who are proficient with the following software: GIS, UNIX, S-plus and the C computer programming language. This software are essential in DHSVM calibration and verification. The DHSVM can also be operationally limited in that access to a high end UNIX based computer is essential in order to decrease computer file transfer time and data processing when using the model remotely.

Finally, the DHSVM is oriented towards United States format data and, hence, model applications outside of the U.S. will require more time to convert data formats into suitable input formats for the DHSVM. In all, these limitations can result in additional time being required for DHSVM calibration and verification in Canadian locations.

5.6 Inherent Logistic Limitations

Two logistic limitations in the original thesis research were also encountered that lead to delays in research project progression. First, the most optimal way to currently use the DHSVM is within the modeling environment at the University of Washington. At this location, a model user is immersed in an environment where many people have experience in DHSVM use and calibration. Unfortunately, modelers in areas outside of Washington state may not have the time or funding to travel to the university to learn how to use the DHSVM. As this project experienced, working in isolation is the most difficult and inefficient way to use the DHSVM due to the lack of a user's manual, model training and off-site model support.

Second, a reluctance of the modelers at the University of Washington to release the DHSVM off-site was also encountered. It was thus necessary to perform all data formatting and file transfer remotely through telnet connections. As mentioned, this is a extremely difficult and inefficient way to use the DHSVM. Therefore, although well suited for application in B.C., the use of the DHSVM is limited in operational applicability due to the reluctance of the modelers at the University of Washington to release the DHSVM off-site and the lack of model support available outside the University of Washington.

5.7 Recommendations

Many valuable lessons can be drawn from this case study. As such, several remarks can be made about the development of hydrologic modeling projects in general. These comments are directed at and will be most useful to, first time hydrologic modelers.

1) When obtaining data for a hydrologic modeling project, it is essential that modelers never assume that the recording history of a data station has been static. Modelers need to investigate the data recording history of the station to verify that observations have been recorded consistently. If inherent limitations are detected, an assessment of the data's suitability for modeling use should be performed. As illustrated in this case study, changes such as equipment upgrades, shifting station locations and site modification are important limitations to seek out in data.

2) It is essential that modelers never assume that data are reliable and appropriate for use in hydrologic modeling, no matter what the data supplier claims the data are suited for. Furthermore, the objectives of the data collectors should be kept in perspective when using data as these objectives may not be compatible with the modeling project objectives. For example, while appropriate for WSC purposes, the streamflow data obtained for this project may not have been suitable for investigating hydrologic-

wildfire impacts.

3) It is essential that modelers review the types of data recording equipment used in data collection to ensure that these instruments are appropriate in providing the desired data variables. For example, gauges that were used to collect year round precipitation were found to be inappropriate for providing accurate winter precipitation data.

4) It is essential that modelers ensure that the data sampling frequency (i.e., hourly, daily, etc.) is suitable for both the hydrologic model used and in investigating the objectives of the modeling project. For example, this project was unable to obtain meteorological data of an interval smaller than 24 hours that would be suitable for DHSVM calibration and hydrologic-wildfire simulation.

5) It is essential that modelers ensure that hydrologic model support is available from more than one source. Sources of hydrologic model support could include: user's manuals, on-line documentation, on-line user groups or personal contacts. Having access to more than one source of model support is important because, in the event one source fails, another is still available for consultation. In this case study, only one source of model support was available for the DHSVM. During the creation of the original research design, the support of DHSVM modelers was secured at meetings at the University of Washington. However, during the thesis research, model support never materialized and in the absence of a user's manual and on-line documentation, problem solving and model calibration was found to be difficult.

6) It is essential that modelers budget a generous amount of time for data processing in the research design, especially when modeling for the first time and/or using an unfamiliar hydrologic model. Modelers should budget approximately 70-80% of their project time for data collection and preparation. As illustrated by this case study, it is inevitable that inherent limitations of some form will emerge during a modeling

project that could possibly lead to project delays.

5.8 Conclusions

This case study illustrated a variety of limitations encountered in an attempt at applying the DHSVM to the Upper Penticton Creek Watershed. Data, model, logistic and research design limitations ultimately lead to project delays and a realization of an underestimation of time required for project completion. All of these limitations combined prompted the re-evaluation of the initial thesis project viability which, subsequently, lead to the re-formulation of the thesis topic. The attempt to apply the DHSVM to a B.C. interior watershed illustrates the importance of being prudent in matching hydrologic data and the hydrologic model to modeling goals. This chapter also highlights the necessity of allowing ample time for data preparation and model calibration when using a hydrologic model for the first time.

CHAPTER 6
HYDROLOGIC-WILDFIRE IMPACTS AND SIMULATION

6.1 Introduction

The original thesis topic proposed to investigate whether or not the DHSVM could be used successfully as a tool to predict hydrologic-wildfire impacts. While this objective could not be assessed due to the aforementioned problems and limitations, the author felt it was important to continue with the original theme of the research. This was because of a personal interest in the topic and, more importantly, because of the noticeable absence of literature on the subject of hydrologic-wildfire impact modeling. Subsequently, in place of evaluating the use of the DHSVM as a hydrologic-wildfire simulator, this thesis discusses hydrologic-wildfire impacts and simulation.

This chapter reviews the possible affects wildfire can have on the hydrologic regime of a forested catchment. This discussion forms the initial step necessary for the development of a conceptual hydrologic-wildfire model. The focus will be on the potential physical effects of wildfire on the quantity and timing of water storage in a watershed. A discussion of potential hydrologic-wildfire impacts, current limitations of hydrologic models in simulating wildfire and criteria for the selection of a candidate model for hydrologic-wildfire impact simulation are provided.

6.2 Wildfire Background

Background information on four topics are presented to introduce the discussion of hydrologic-wildfire impacts. The topics include: the importance of wildfire, similarities and differences between wildfire and forest harvesting, variability of wildfire impacts and limitations of current hydrologic-wildfire literature.

6.2.1 Importance of Wildfire

Wildfire is an important disturbance process in the forests of British Columbia. In many ecosystems, wildfire plays an important role in the formation, maintenance and evolution of forest stands. Past forest management policies, however, have viewed wildfire as an unnatural and destructive agent that must be vigorously suppressed. At present, this historically negative view of wildfire is changing. In some areas of the province, particularly in provincial and national parks, fire suppression has been reduced allowing for the re-introduction of wildfire to occur. Over the last 75-100 years, however, the suppression of wildfire has lead to a build-up of forest fuels in many areas. This fuel build-up can create conditions whereby wildfires have the potential to burn with greater intensity and, thus, more destructive power than normal.

In forest management, knowledge of the effects of wildfire on the quality, quantity and timing of water (hydrologic regime) are important to consider because wildfire has the potential to affect large areas of a watershed in a short period of time. The ability to investigate and quantify such impacts, however, is largely not possible in B.C. due to an absence of an appropriate tool. While a hydrologic model could be used to quantify wildfire impacts, the current operational use of hydrologic computer models to gauge forest disturbance impacts is still largely experimental.

6.2.2 Similarities and Differences Between Wildfire and Forest Harvesting

The literature available on quantifying hydrologic-wildfire impacts is sparse. While timber harvesting case studies can be used to strengthen hypotheses on hydrologic-wildfire impacts, it is important to understand the differences between these disturbance agents. Eight major differences and similarities between wildfire and timber harvesting are listed below. In these points, timber harvesting is considered to be synonymous with the clear-cut silviculture system and wildfire is considered to be synonymous with a severe forest fire that consumes both overstory and understory vegetation layers (conflagration).

- Wildfire is unpredictable and, therefore, has the potential to affect large portions of a watershed in a short period of time. Conversely, timber harvesting is predictable and, therefore, can be planned in both time and space to minimize adverse impacts to the hydrologic regime of a watershed.

- Wildfire is indiscriminate of the areas of a watershed that are affected and may burn through riparian and sensitive areas. Conversely, timber harvesting activities can be regulated and planned to minimize impacts in riparian and sensitive areas of a watershed.

- Timber harvesting often creates varying degrees of soil compaction and soil disturbance in a watershed. Conversely, wildfire does not directly create soil compaction. However, wildfire can lead to the formation of hydrophobic conditions in coarse textured soils (McNabb and Swanson, 1990) which may reduce infiltration rates or generate localized surface runoff.

- Wildfire can consume the overstory vegetation, understory vegetation and forest floor (LFH) in a forest stand. Conversely, timber harvesting removes only the overstory vegetation layer in a forest stand.

- Both wildfire and timber harvesting will change the albedo of an area. The magnitude of albedo change is usually greatest for wildfire due to a blackening of vegetation and soil surfaces.

- Forest disturbance by wildfire is seasonal, as wildfire only occurs when fuels are dry enough to support ignition and sustained burning. Conversely, timber harvesting can occur year round. The resulting hydrologic impacts can therefore vary between wildfire and timber harvesting. For example, wildfires that burn in the summer may create different hydrologic impacts from timber harvesting activities that occur during heavy precipitation events.

- Both wildfire and forest harvesting will alter the wind regime of an area.

- Both wildfire and timber harvesting can result in altered site microclimate.

In considering the previous points, the hydrologic impacts created by wildfire and timber harvesting can be both similar and dissimilar depending upon the hydrologic process examined. Hydrologic processes that are affected differently between the two disturbance types are those that are integrally linked to the soil component in the hydrologic cycle. These hydrologic processes include: infiltration, subsurface flow and surface runoff. These processes are affected differently because wildfire and timber harvesting do not affect the soil component of a watershed in a similar manner. For example, timber harvesting can disturb the soils in a watershed through compaction and/or through the construction of roads, skid trails and landings. This soil disturbance may lead to reduced infiltration rates, localized surface runoff and the channeling of water down a road grade. Conversely, wildfire does not directly create soil compaction, but may induce water repellent conditions in certain soil types. As such, the effects created by each disturbance type in regards to runoff and other hydrologic processes influenced by soil disturbance will be dissimilar.

Timber harvesting and wildfire do, however, share similarities in the effects they can create on surface hydrologic processes that are influenced by vegetation defoliation; the action common to both disturbance types. Surface hydrologic processes such as evapotranspiration, precipitation, solar radiation, interception and snow-pack accumulation and melt can therefore be affected in a similar manner, potentially creating similar impacts. Although runoff produced from a watershed will also be affected by vegetation cover removal, the impacts created by wildfire and timber harvesting may differ.

Therefore, timber harvesting studies that examine hydrologic processes and components affected by vegetation removal (i.e., evapotranspiration, precipitation, solar radiation, fog drip, interception, snow-pack accumulation and melt) can be used to support hydrologic-wildfire impacts. Timber harvesting studies that examine hydrologic processes and components affected by soil disturbance (i.e., surface runoff, infiltration, subsurface flow, and runoff) are not necessarily appropriate for supporting hydrologic-wildfire impacts.

6.2.3 Variability of Wildfire Impacts

The variability of wildfire impacts are important to illustrate as varying degrees of wildfire severity can cause varying degrees of hydrologic impacts. The primary wildfire factors that determine the nature of the hydrologic-wildfire impacts in a watershed are intensity and spatial extent. Wildfire severity (intensity) is temporally site specific and varies regionally depending upon past fire disturbance, fire suppression history, antecedent moisture conditions, climate, topography, vegetation, hydrology, soil and human modifications to a watershed. Typically, the higher the wildfire severity and/or the greater the spatial extent of the burn, the greater the effect a wildfire will have on altering the normal hydrologic regime of a watershed. Beschta (1990: 220) listed five main factors that influence the hydrologic response of a prescribed fire that include:

- "The severity of a burn.
- The proportion of the watershed burned.
- The relative proximity of the burned area to the stream channel.
- General slope of the watershed.
- Soil type."

The duration of hydrologic response that a wildfire may create will be influenced by site conditions. It could be expected that watersheds with more favorable growing conditions will recover (re-vegetate) faster after a wildfire than where re-vegetation and soil recovery is slower. As such, the duration of hydrologic be shorter in those watersheds that re-vegetate rapidly after a wildfire.

6.2.4 Limitations of Current Hydrologic-Wildfire Literature

Research on hydrologic-wildfire impacts in B.C. has been sparse. There are three main limitations of the currently available literature in relation to suitability for use in generalizing hydrologic-wildfire impacts in B.C. First, a majority of wildfire studies are limited in applicability to B.C. forests, as many have occurred in ecosystem types considerably different to those found in B.C. Second, some wildfire studies are limited in significance in that the authors have not acknowledged the variability of wildfire behavior in both time and space (Pyne et al., 1996). Failing to adequately measure or estimate wildfire severity and duration can detract from the significance of a study that attempts to link wildfire impacts to the hydrologic changes observed. Lastly, some wildfire studies are limited in methodology; particularly in cases where burned areas are compared with unburned controls. This type of methodology is problematic as it makes an important assumption that the control and treatment areas under review are ecologically identical, when rarely they are (Pyne et al., 1996). Because of these limitations, the applicability of many hydrologic-wildfire studies to B.C. forests is limited. However, despite the above limitations, some of the wildfire studies that are available can be useful in supporting potential hydrologic-wildfire impacts in B.C.

6.3 Hydrologic-Wildfire Impacts

The impacts that wildfire can have on hydrologic processes operating in a watershed can be complex. As with any disturbance type, the modification of one process or component in the hydrologic cycle will ultimately influence other hydrologic processes and components (Figure 6.2-1). Wildfire physically affects the vegetation and soil components in the hydrologic cycle through the direct combustion of organic material, killing of vegetation and blackening of soil and vegetation surfaces. In turn, these modifications can result in a wide array of changes in the hydrologic processes and components of which soil and vegetation are integral (Figure 6.2-1). The processes and components of the hydrologic cycle that are altered by wildfire include: solar radiation, precipitation, evapotranspiration, interception, fog drip, snow accumulation and melt, infiltration, subsurface flow and soil water content. Overall, the changes in the above mentioned processes by wildfire will affect the streamflow produced by a watershed.

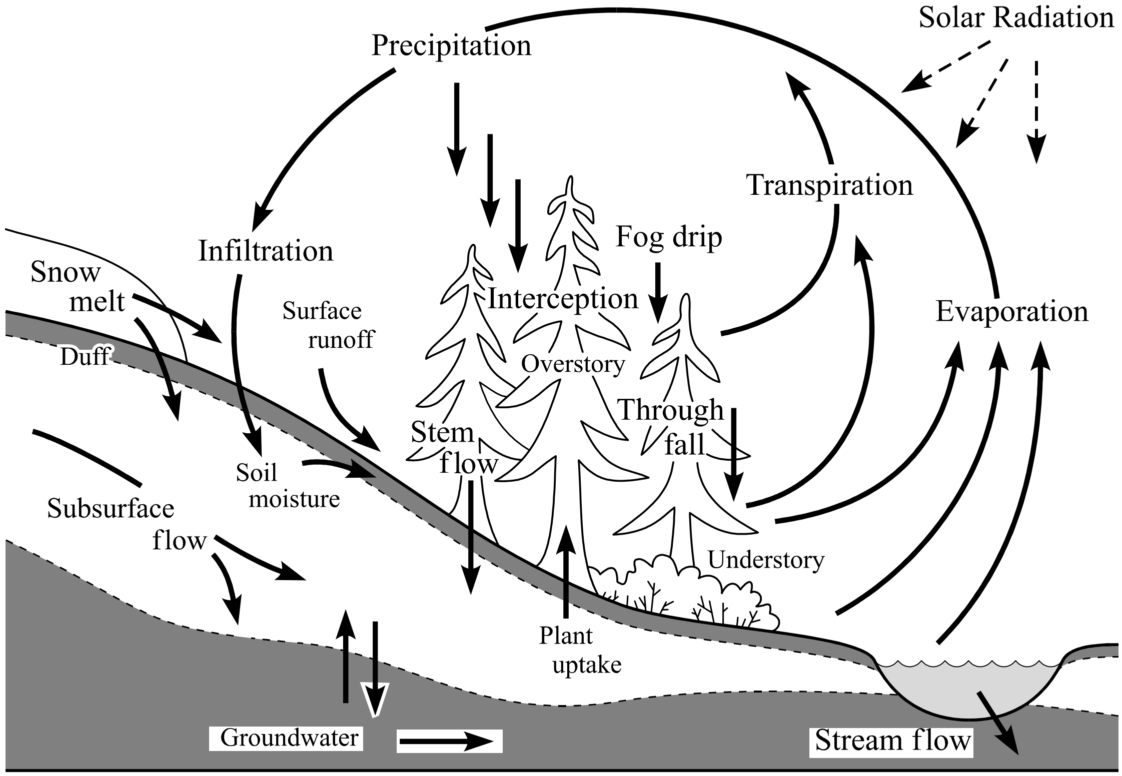

Figure 6.2-1 Forest Hydrologic Cycle

6.3.1 Solar Radiation Energy Balances

Although the amount of solar radiation emitted by the sun is constant, wildfire can change the distribution of solar radiation in a watershed. Wildfire can alter the short and long wave radiation energy balances in a watershed by reducing vegetation cover and changing the albedo of an area. The density of vegetation cover (foliar surface area) in a forest is an important factor in determining long and short wave radiation energy balances. A reduction of vegetation cover in a watershed will lead to changes in the fraction of short wave radiation transmitted, reflected and absorbed by the overstory vegetation, understory vegetation and soil surface. Defoliation will lead to increased amounts of short wave radiation being able to reach the understory vegetation and ground surfaces. This increase will lead to changes in evaporation, transpiration, microclimate, snow-pack melt, soil water content and vegetation growth. A blackening of the vegetation and soil surfaces by wildfire (changed albedo) will result in more short wave solar radiation being absorbed by these surfaces, and hence, warmer microclimatic conditions. The warmer temperatures of these surfaces will then affect the long wave energy balance of an area as well as evapotranspiration rates, snow-melt and soil moisture.

In support, Megahan (1983) observed short wave solar radiation increases at the snow surface ranging from 100 to 375 percent after clear-cutting, in a study of wildfire and timber harvesting impacts in Idaho. Megahan (1983) suggested that these large increases in solar radiation could result in increased snow-melt rates in the affected areas. Overall, wildfire can alter the short and long wave radiation energy balances in a watershed by reducing vegetation cover and changing the albedo. Subsequently, the altered solar radiation balances will then lead to changes in the microclimate, evapotranspiration, soil moisture, snow-melt and vegetation growth of an area.

6.3.2 Precipitation

The next process in the hydrologic cycle (Figure 6.2-1) that can be affected by wildfire is precipitation (rain). The influence of wildfire on occult precipitation (i.e., fog drip) and snow accumulation and melt processes will be discussed later in this chapter. Wildfire can change the precipitation regime in a watershed on a *local* scale as a result of altering microclimate via a blackening of vegetation and soil surfaces and altering wind patterns through a reduction of forest vegetation cover. The influence of wildfire on the precipitation regime of a watershed, however, will depend upon the scale and, hence, form of precipitation. Two precipitation types that could be influenced by wildfire are orographic and convective precipitation.

Orographic precipitation results when an air mass encounters a topographic barrier, usually a mountain range, and is forced to rise and cool thereby triggering precipitation. The influence of wildfire on this precipitation type should be minimal due to wildfire's inability in affecting the triggering mechanism, topography. However, wildfire can change the friction of a forest canopy by reducing vegetation cover, thus possibly leading to altered air mass movement. The absolute effect of this change in friction on orographic precipitation, however, is unknown.

Convection precipitation occurs when hot air, created by the heating of the earth's surface, rises and cools at the adiabatic lapse rate. The blackened surfaces caused by wildfire (if large enough) could influence convective precipitation events by increasing the intensity of air updrafts in burned areas as these areas will be warmer than normal. This could result in more frequent and/or more intense convective precipitation events.

Wildfire can also influence the wind regime of an area that could possibly lead to localized changes in the amount and distribution of precipitation in a watershed. Defoliation by wildfire will reduce the friction of the forest surface thereby altering wind velocity and turbulence patterns. After a wildfire, wind velocities will typically increase at the ground surface; feasibly altering raindrop trajectories and, hence, distribution. The increased winds may result in less precipitation recorded by a rain gauge situated in a burned area due to wind acceleration over the instrument and altered trajectories in relation to the catchment surface. The disruption of normal wind patterns over a forest stand can also be influential on snow accumulation patterns and evapotranspiration as discussed later in this chapter.

6.3.3 Evapotranspiration

Wildfire can also directly and indirectly affect the processes of evaporation and transpiration (evapotranspiration) in a watershed (Figure 6.2-1). As discussed, vegetation defoliation and albedo changes created by wildfire will influence the wind, solar radiation and microclimate of an area, which in turn will indirectly affect evapotranspiration rates. Wildfire can also directly affect the evapotranspiration regime of an area by reducing or eliminating vegetation surfaces from which evapotranspiration occurs. More specifically, overstory and understory vegetation killed by wildfire will no longer transpire and, subsequently, will no longer act as a pathway for water transport from the soil. Wildfire, therefore, has the potential to reduce transpiration losses in a watershed by causing vegetation mortality. The reduction of vegetation cover by wildfire will also reduce the surface area upon which water is intercepted. Therefore, wildfire also has the potential to reduce evaporation losses from forest vegetation through defoliation. However, the reduced evapotranspiration losses created by wildfire may be offset by increased evaporation from the soil as defoliation will leave the soil surface more exposed to wind and solar radiation inputs.

Overall, the removal of vegetation by wildfire can significantly affect the evapotranspiration regime of a watershed, most often leading to decreased losses of incoming precipitation to evapotranspiration. For example, in a study of wildfire and timber harvesting impacts in Idaho, Megahan (1983) calculated that wildfire reduced annual evapotranspiration amounts by 79 millimeters. Therefore, it could be expected that decreased evapotranspiration losses as a result of wildfire may result in increased soil moisture storage in a watershed (Berndt, 1971; Helvey, 1980).

6.3.4 Interception

Interception in hydrology can be viewed both as a process and as an amount. As a process, wildfire can affect the normal downward movement of precipitation through defoliation. As an amount, wildfire has the potential to reduce the depth of water lost through interception and, hence, evaporation by reducing vegetation cover. Vegetation modification by wildfire can also affect the related processes of stemflow and throughfall in a watershed (Figure 6.2-1).

In a forested watershed, although some interception of precipitation occurs by the forest floor layer (duff), interception is primarily a function of the composition of the vegetation cover. In a typical forest, the maze of vegetation surfaces that precipitation must negotiate include a main canopy, secondary canopy, ground shrubs, small herbs and finally the forest floor. In general, the denser the vegetation cover and/or the greater the number of vegetation canopy layers, the greater the interception will be. The removal of this maze of vegetation, or portion thereof, by wildfire will therefore result in reduced interception losses. Thus, reduced interception losses mean that more precipitation is available to enter other storage reservoirs within the hydrologic cycle, possibly resulting in an increased potential for runoff (Tiedemann et al., 1979).

As mentioned, although the process and amount of interception that occurs in a watershed is primarily a function of vegetation, the interception regime of the duff layer can also be influenced by wildfire. A reduction in duff depth by wildfire will lower the ability of this layer to attenuate and store precipitation inputs before entering the soil mantle. As with defoliation, the reduction of duff depth by wildfire will lead to reduced interception losses and more precipitation available to enter other storage reservoirs in the hydrologic cycle.

Wildfire also has the ability to modify the interception storage capacities of a forest canopy that in turn will affect throughfall and stemflow processes. The maximum interception storage capacity of a forest canopy can be defined as the maximum amount of precipitation that can be stored on the leaf and branch surfaces. Once the interception storage capacity is filled, additional precipitation will either fall through the forest canopy (throughfall), or flow down the tree bole (stemflow). A reduction in the foliar surface area by wildfire will thereby lead to less precipitation inputs required before maximum interception storage capacities are reached. As such, the processes of throughfall and stemflow (Figure 6.2-1) will be initiated at lower storage capacities with more precipitation available to enter other storage reservoirs more quickly within the hydrologic cycle. Yet, in areas completely defoliated by wildfire, stemflow may be decreased due to the reduced ability of the vegetation surfaces to collect and funnel water. However, the process of throughfall will be increased in these circumstances as there is less foliage and small branches to intercept precipitation.

In summary, the amount of interception that occurs in a watershed is a function of the density and layering of forest vegetation. The magnitude of changes in interception produced by wildfire are therefore primarily dependent upon the level of vegetation and forest floor removal (Tiedemann et al., 1979). Overall, reduced vegetation cover as created by wildfire will result in reduced interception losses and, thus, more water available for entering other storage reservoirs in the hydrologic cycle.

6.3.5 Fog Drip

Fog drip (horizontal interception of fog or cloud water) is another process in the hydrologic cycle that can be affected by wildfire (Figure 6.2-1). Wildfire can modify the fog drip regime of a watershed primarily by reducing or eliminating the vegetation surfaces on which fog drip occurs.

Fog drip can be important source of additional moisture in forest stands. This is particularly the case in coastal areas where fog is prevalent or in areas where low cloud is common. For example, in the western Cascade mountains of Oregon, Harr (1982) demonstrated that differences in precipitation measurements between a clear-cut and a forested area suggested that fog drip contributed a considerable amount of water to the yearly precipitation total. After adjusting rainfall data for interception losses and expressed the data on full water year basis, Harr (1982) concluded that up to 882 mm of water could have been added to the yearly precipitation total (2160 mm) of the clear-cut area. Similarly, a reduction of the foliar surface area in a forest stand by wildfire could also lead to decreased fog interception. Simply stated, the lower the foliar surface area, the lower the ability of the forest stand to harvest fog or cloud water. Therefore, a wildfire that reduces the foliar surface area in a stand prone to fog drip may eliminate a significant source of water throughout the year.

The hydrologic response that a reduction in fog interception can cause is spatially variable. A reduction in the foliar surface area by wildfire will result in reduced evapotranspiration and interception losses, thereby resulting in increased water yield. However, a reduction in fog interception and drip could offset the expected increase in water yield (Ingwersen, 1985). It is also possible that the absolute effect of reduced fog interception in a watershed may not be significant if only a portion of the watershed is affected. For example, fog interception may be redistributed to areas downwind of the burned area likely causing increased levels of localized runoff to occur.

6.3.6 Snow-pack Accumulation and Melt

Wildfire can have a complex influence on modifying snow processes in a watershed (Figure 6.2-1). Wildfire can affect snow accumulation and melt regimes by reducing vegetation cover and blackening vegetation and soil surfaces. These modifications create changes in forest microclimate, solar radiation balances, interception, evapotranspiration and the wind regimes of an area that in turn affect snow accumulation and melt. The following is a simplified discussion of wildfire impacts on snow accumulation and snow-melt processes in a watershed.

In general, wildfires that reduce the vegetation cover in an area will result in snow-packs that will be deeper and melt faster than normal (Pyne et al., 1996). Wildfires that reduce vegetation cover will eliminate or decrease interception losses in a watershed and, hence, allow for more snow to be available to accumulate on the forest floor. Snow-packs will also be deeper than normal due to the alteration of wind velocity and turbulence patterns via forest canopy friction changes and forest edge creation by wildfire. Typically, reduced vegetation cover will allow wind to blow closer to the ground, at higher velocities than normal. This may result in snow redistribution and altered snow accumulation in an area. The formation of a forest opening could enhance snow deposition in cases where wind traveling over a forest canopy encounters an opening and forms an eddy, thereby depositing snow on the leeward side of the forest edge.

The overall impact that wildfire can have on snow accumulation is variable. The size, shape and orientation of the forest opening all have an important influence on snow accumulation (Golding, 1981; Troendle and Leaf, 1981). In general, snow accumulation will increase with decreasing forest density (Golding, 1982). Furthermore, snow accumulation is generally less in an uncut forest vs. a small opening but may be more than a large clearing (Golding, 1982). For example, in a clear-cut harvesting study in Alberta, Golding (1981) documented deeper snow accumulations in openings two to three tree heights in diameter, in comparison to an adjacent uncut forest and larger openings three to six tree heights in diameter. The delineation, however, of the optimal opening size for maximum snow accumulation varies in the literature. Golding (1982) reported optimal opening sizes of five tree heights or less. However, he also noted other studies where optimal opening sizes varied from one to three tree heights (Golding, 1982). Larger forest openings can have lower snow depth totals in the late snow accumulation period due to a greater exposure to evaporation and wind erosion. On the other hand, larger openings could also have deeper snow accumulation totals than adjacent forest stands if the adjacent forest canopy enhances snow-melt. Wildfire may also exhibit a similar variable effect on creating deeper snow-packs as a result of vegetation cover reduction and wind regime alteration. In support, Helvey (1980) in north-central Washington observed deeper snow-packs and streamflow rates three times greater than maximum calibration period values after a wildfire.

Snow-packs in areas affected by wildfire would melt more quickly than normal because of more direct exposure to solar radiation, blackened vegetation surfaces and wind. Increased exposure to solar radiation, in combination with blackened tree boles, would lead to increased amounts of long wave energy available to melt the snow-pack. For example, in a study of wildfire and timber harvesting impacts in Idaho, Megahan (1983) determined that a 100 to 375 percent increase in solar radiation resulted in a 30 percent increase in the ablation rate of a snow-pack in a clear-cut. Unfortunately, in his study Megahan (1983) was unable to evaluate the effect of wildfire on enhancing snow accumulation and melt due to a lack of an adequate statistical control. Increasing the exposure of a snow-pack to wind should also accelerate snow-melt due to the reduced ability of the forest canopy in sheltering the snow-pack from heat transported by wind (Hetherington, 1987).

In summary, wildfire has the potential to increase snow accumulation and melt regimes in a watershed by reducing vegetation cover and blackening vegetation and soil surfaces. Deeper snow accumulations could be attributed to redistribution of snow and/or reduced interception losses. Earlier melting snow-packs could result due to greater exposure to evaporative forces of increased wind and solar radiation input into the snow-pack.

6.3.7 Infiltration

Wildfire can modify the infiltration regime of a watershed in two ways; 1) through the consumption of the organic forest floor layer (duff) and, 2) through the creation of hydrophobic conditions in the soil. First, the forest floor or duff layer acts as an important interface between interception and infiltration processes (Figure 6.2-1). The duff layer shields the underlying soil layers from the erosive power of precipitation as well as attenuating precipitation inputs into the soil mantle. Wildfire has the potential to alter these properties. For example, the attenuation of incoming precipitation can be eliminated and the erosive potential of precipitation and throughfall increased if the duff layer is completely consumed by wildfire. The hydrologic significance of the loss of the duff layer by wildfire, however, will vary depending upon the importance of the duff layer in the local hydrologic regime. In B.C., the consumption of the entire duff layer by wildfire over a large spatial area is rare, even during severe wildfires (S. Taylor per. comm., 1997).

Second, wildfire can also modify the infiltration regime of a watershed by creating and/or enhancing the formation of hydrophobic (non-wettable) soil conditions. Wildfire can create hydrophobic conditions in the soil by partially volatilizing organic compounds in the duff layer. These volatilized compounds move down through the soil profile by convection where condensation onto cooler soil surfaces occurs (McNabb and Swanson, 1990; Debano, 1981; Pyne et al., 1996). Hydrophobic organic compounds are a product of biological decomposition that, in the absence of wildfire, can naturally create non-wettable conditions in the duff layer (Pyne et al., 1996). Wildfire speeds up the decomposition process and relocates the non-wettable layer further down into the soil profile (Pyne et al., 1996). The formation of hydrophobic conditions by wildfire is most prevalent in coarse textured soils. These soils have a smaller internal surface area and frequently greater temperature gradients than finer textured soils (McNabb and Swanson, 1990). The thickness and water repellency of a hydrophobic layer varies depending upon soil type, vegetation type and fire intensity (Boyer and Dell, 1980). In areas where hydrophobic conditions form in the Pacific Northwest, Beschta (1990) noted that these layers are usually destroyed within the first few rainfalls following a wildfire.

The presence of a hydrophobic layer in the soil profile can create water repellent conditions that may lead to reduced infiltration capacities and an increased potential for overland flow. In turn, this may increase the susceptibility of an area to erosion as well as alter streamflow yield and timing through increased surface runoff. Hydrophobic conditions may also lead to a decrease in soil evaporation levels "as [the] capillary forces necessary to move water to the soil surface are lessened" (Debano, 1981:10).

Geographically, hydrophobicity can occur anywhere soil, vegetation and wildfire conditions are appropriate. However, within the literature it can be observed that the formation of water repellent conditions is most prevalent in areas like the chaparral watersheds of southern California (Debano, 1981; Pyne et al., 1996). Dryness (1976) noted that the formation of non-wettable soils in these areas is due largely in part to the organic substances produced by the local vegetation. In these areas, organic litter in the absence of burning can naturally cause mild non-wettable soil conditions. Hydrophobic organic substances can also be found naturally in forest ecosystems further north that include stands of ponderosa pine, lodgepole pine and Douglas fir (Wright and Bailey, 1982).

The documentation of hydrophobic soils in the Pacific Northwest has not been prolific. Dryness (1976) studied soil wettability and re-vegetation trends for six years following a large 7,700 acre wildfire in a lodgepole pine forest in the high Cascade mountains of Oregon. Dryness observed that burning increased the water repellency of the soil at depths of 2.5 to 27 centimeters which persisted for five years after the wildfire (Dyrness, 1976). He found that soils not burned in the study absorbed water approximately three times faster than burned soils. In the sixth year of study, soil wettability levels in the burned soils began to approach pre-fire values.

In a ponderosa pine ecosystem in north-central Arizona, Campbell et al. (1977) documented the formation of water repellent conditions that lasted four years after a wildfire. They observed that infiltration rates one day after a wildfire on severely burned soils were 2.6 centimeters per hour vs. 6.8 centimeters per hour on unburned soils.

In a Coastal Western Hemlock Biogeoclimatic ecosystem in B.C., Henderson and Golding (1982) compared the water repellency of ten slash burned and three clear-cut areas to an uncut mature forest. They found no difference in water repellency between the unburned clear-cuts and the uncut control. Henderson and Golding (1982) observed that water repellent conditions were more frequent in the burned clear-cut samples (35% of samples) than in the uncut control (21% of samples). However, these differences were observed to be significant for only two years following the burn. They found that the water repellency in the burned samples was most frequent at 0-4 cm. below the humus layer. At depths of 8-10 cm. and greater than 15 cm., no significant differences were observed in comparison to the control.

6.3.8 Subsurface Hydrologic Processes

The direct influence of wildfire on subsurface hydrologic processes (i.e., deep and shallow groundwater) is minor in comparison to the surface processes previously covered (Figure 6.2-1). Yet, the cumulative effects of wildfire on surface hydrologic processes can have an indirect influence on the amount of soil water and, subsequently, the amount of water available to enter groundwater storage in a watershed. For simplicity, the distinction between deep and shallow groundwater, as covered in Chapter 4, has not been illustrated in Figure 6.2-1. For the purposes of this discussion, wildfire's effect on groundwater depends largely upon the magnitude of change to the soil water content in a watershed. Therefore, depending upon hydrologic regime, wildfire has the potential to either increase or decrease the soil water content in a watershed which in turn will alter groundwater storage.

In some hydrologic regimes, cumulative wildfire impacts on surface hydrologic processes can result in higher soil water levels. Vegetation removal by wildfire will result in lower evapotranspiration and interception losses which in turn will result in more water available to enter other storage reservoirs in the hydrologic cycle (i.e., soil mantle, deep groundwater). The removal of vegetation cover could therefore, lead to longer periods of higher soil water content in a watershed and, consequently, increased water yield. In support, Tiedemann et al. (1979) noted that the removal of vegetation by fire generally creates higher soil water conditions than normal at the end of the growing season due to a decrease in evapotranspiration.

In other hydrologic regimes, cumulative wildfire impacts on surface hydrologic processes can result in lower soil water levels. Vegetation destruction and a blackening of forest surfaces by wildfire will leave the soil more exposed to the drying effects of wind and solar radiation. In support, Campbell et al. (1977) observed lower soil moisture levels in the soil of a severely burned ponderosa pine ecosystem in Arizona vs. an unburned control. The lower soil moisture levels observed were attributed to greater runoff levels (decreased infiltration rates) and greater drying due to a blackened surface. Wildfire may also indirectly lower soil moisture levels as a result of lowering fog interception rates, creating hydrophobic soil conditions and/or increasing evapotranspiration in vegetation not consumed by wildfire. Evapotranspiration levels in vegetation not consumed by wildfire may be increased due to a greater exposure to wind and solar radiation and, hence, higher photosynthetic rates than normal.

In summary, wildfire has an indirect affect on the subsurface hydrologic regime of a watershed, as most of the processes affected by wildfire are surface hydrologic processes. As discussed, the cumulative impacts of wildfire on surface hydrologic processes can therefore either increase or decrease the amount of water stored in the soil at a given time during the summer. Higher and longer periods of soil water will ultimately lead to altered subsurface flow and groundwater storage regimes.

6.3.9 Impacts of Wildfire on Streamflow

Wildfire can have a complex influence on streamflow in a watershed. As with subsurface hydrologic processes, wildfire affects streamflow indirectly as the result of the cumulative impacts on surface hydrologic processes. As such, it is difficult to generalize the overall effect that wildfire can have on streamflow due to the variable nature of hydrologic-wildfire impacts. Unfortunately, available literature is sparse relating the sole influence of wildfire on streamflow. Some wildfire studies are confounded because wildfire impacts are often combined with other disturbance types such as forest harvesting. As mentioned, wildfire studies may also be limited in that they fail to discuss the effect of spatial-temporal variability of wildfire behavior in relation to hydrologic-wildfire impacts observed. Some hydrologic-wildfire studies are also confounded due to abnormally high precipitation regimes following a wildfire (Helvey, 1973) that mask the influence wildfire has on altering streamflow. Despite these limitations, a few studies have been able to examine the sole influence of vegetation and soil modification by wildfire on streamflow at the watershed scale.

Wildfire can potentially increase the water yield, summer flow and peak flow magnitudes in a watershed. The proportion of increase in water yield as a result of wildfire, however, will be proportional to the amount of watershed burned, annual precipitation (Beschta, 1990), ecosystem type and fire intensity. The following case studies illustrate the variable hydrologic impacts wildfire can create on streamflow in a watershed.

Cheng (1980) studied a severe wildfire that burned a number of watersheds near Salmon Arm, British Columbia. Using streamflow data from two watersheds, one 60% burned and one unburned, Cheng determined that the wildfire resulted in "higher and earlier annual peak flows, the advancement in time of the major snow-melt runoff volume, increases in total April-August runoff volume and in monthly water yields during the August-November period" (Cheng, 1980: 251). Over the four year study period (post-burn), Cheng observed an average seasonal water yield increase of 24%, most likely the result of increased soil moisture levels via reduced evapotranspiration losses. The peak flow increases observed were attributed to increased snow-melt rates and reduced evapotranspiration losses (Cheng, 1980).

In a ponderosa pine ecosystem in north-central Arizona, Campbell et al. (1977) observed that runoff during heavy autumn rains from a severely burned area was approximately eight times greater than runoff from an unburned control. Campbell et al. (1977) also observed that water yield in the first year following the wildfire was 3.1 and 3.8 times greater on moderately and severely burned areas vs. the unburned control in their study.

Berndt (1971) observed three main impacts of wildfire on streamflow during the first week after a wildfire in a north-central Washington watershed. First a reduction in streamflow occurred during the wildfire, presumable caused by the vaporization of water. Second, a change in the diurnal streamflow pattern occurred, as daily oscillations were greatly reduced in magnitude. This dampening was the result of the reduction in vegetation transpiration withdrawals (Berndt, 1971). Finally, streamflow one week after the forest fire was "generally above protracted depletion curves" (Berndt, 1971 :4). In a follow-up study one year after the wildfire, Helvey (1972) observed a higher and earlier than normal peak flow from the burned area. In addition, Helvey (1973) noted that water yield from the watershed was approximately 50% greater than predicted values based on pre-fire watershed conditions.

In a study of bark beetle infestation in Colorado, Bethlahmy (1974) documented an increase in water yield as a result of the defoliating action of bark beetles. Bethlahmy explained the increased water yield as a result of decreased evapotranspiration losses from the dead, defoliated trees. Wildfire could also have a similar influence on influencing water yield in this area due to the similar defoliating action of both disturbance types.

In summary, the hydrologic response that a wildfire can create in a watershed will vary by ecosystem type, amount of watershed burned, annual precipitation regime and fire intensity. Wildfire physically affects the vegetation and soil components in the hydrologic cycle through the direct combustion of organic material, killing of vegetation and blackening of forest surfaces. In turn, these modifications can result in a wide array of changes in the hydrologic processes and components of which soil and vegetation are integral. In considering the preceding case studies, the influence of wildfire on streamflow is indirect and depends upon the impacts that wildfire creates on the surface hydrologic processes in a watershed. In general, most wildfire case studies report an increase in streamflow after a wildfire. Increases in streamflow are most often explained by reduced evapotranspiration and interception losses that in turn result in higher soil moisture contents, thereby leading to higher streamflow outputs.

6.4 Hydrologic Model Limitations in Modeling Forest Disturbance

As documented above, the hydrologic-wildfire impacts that may exist in a watershed are complex due to the variable spatial-temporal nature of watershed and wildfire behavior characteristics. Therefore, the simulation of hydrologic-wildfire impacts would be most accurately achieved by a hydrologic model that attempts to represent the complexity of the hydrologic cycle. Yet, depending upon modeling goals, even complex hydrologic models can be limited in gauging the effects of forest disturbance as many of these models have been designed around the assumption that vegetation and ecosystems in a watershed are static. This creates difficulties in using these models because they generally lack the ability to modify vegetation and soil parameters during a simulation. For example, in cases where precise, long term (25-50 year) simulation of vegetation recovery is a modeling objective, the inability to modify watershed parameters throughout a simulation is an important barrier to hydrologic-wildfire and timber harvesting impact modeling. However, in cases where the short term (e.g., first year after wildfire) simulation of defoliation impacts is a modeling objective, the inability to modify parameters in a hydrologic model will not be limiting, as parameter modification throughout the simulation would not be required. Therefore, the successful creation of a hydrologic-wildfire model depends upon the hydrologic-wildfire modeling goals. Some examples of potential hydrologic-wildfire modeling goals may include:

- to assess the first year changes in water yield after a wildfire;
- to determine the long term effects of wildfire on water yield, peak flow magnitude and peak flow timing;
- to determine the percentage of a watershed that must be burned before its hydrologic regime is changed;
- to assess a variety of long and short term disturbance (wildfire and/or logging) scenarios that could affect peak flows, water yield, snow accumulation and melt, timing of runoff and soil water levels in a watershed and;
- to determine the precise impacts of wildfire on water yield at a variety of spatial scales and intensities in a community watershed.

The above goals illustrate some of the modeling objectives that could be of interest to hydrologic-wildfire modelers. As mentioned in Chapter 2, the differences between each of these goals will result in different expectations from a hydrologic model and, hence, different model requirements for parameters, parameter change and data inputs. Therefore, the suitability of a hydrologic model for hydrologic-wildfire simulation will vary depending upon hydrologic-wildfire modeling goals.

A further barrier to the development of a calibrated hydrologic-wildfire model in B.C. is related to the absence of theoretical support in the literature. In North America, relatively few case studies have been performed on linking fire intensity with fire impacts. In B.C., such studies are extremely sparse and more information is available on wildfire effects on water quality than water quantity. Therefore, more research is needed in B.C. to allow for a ground truthing of the impacts (i.e., hydrophobicity, fog precipitation, etc...) presented above. Further research is important as it can aid in the determination of which wildfire impacts are of hydrologic concern in B.C. and, subsequently, which effects are important to include in a model. As well, further research may also reveal other wildfire impacts not covered in this thesis.

6.5 Criteria for the Selection of a Candidate Hydrologic Model

In order to adequately represent and simulate hydrologic-wildfire impacts, the following criteria for the selection of a candidate hydrologic model were defined. These criteria focus on developing a model for long term hydrologic-wildfire impact simulation on a spatially distributed basis. This focus was selected because a model developed for long term modeling objectives could also be used for short term hydrologic-wildfire impact simulation. However, the reverse may not be true as a short term hydrologic-wildfire model would most likely not possess the ability to modify parameters during a simulation and, therefore, would be unsuitable for long term modeling applications. Therefore, the candidate hydrologic model should:

- be distributed and developed specifically for the topography and ecosystem type being modeled;
- be physically-based (a theoretical model vs. an empirical model);

- use parameters that represent vegetation, soil and albedo characteristics and;
- possess the ability to modify watershed characteristics (i.e., vegetation, albedo and soil) during a simulation.

A distributed hydrologic model would be an efficient choice for use in long and short term hydrologic-wildfire simulation. Distributed hydrologic models can represent the complex characteristics of a watershed and wildfire on a spatial-temporal basis. The ability to model on a spatial-temporal basis is important as the spatial distribution of wildfire in a watershed is unique. Unlike a clear-cut area, the portion of a watershed affected by wildfire will not be contiguous and/or evenly affected within the wildfire boundaries. Therefore, the spatial representation of wildfire will be most efficiently achieved by using a pixel-based, distributed model. A more accurate representation of the extent of a wildfire by a small pixel model should provide better simulation results in comparison to lumped or larger pixel-based models that are unable to accurately capture discontinuous wildfire boundaries.

The candidate model should be a theoretical model (physically-based) as this model type should allow for the dynamic simulation of watershed and wildfire characteristics in both time and space. Empirically based models are not appropriate for use in long or short term hydrologic-wildfire simulation as this model type is solely a representation of data and, hence, temporally and spatially constrained. Empirical models will therefore only be valid when used under watershed conditions from which they were created.

The ability to modify watershed descriptive parameters is also critically important for hydrologic-wildfire simulation. However, this is only the case for long term hydrologic modeling objectives as short term modeling goals will not usually require parameters to be modified. To facilitate long term wildfire-hydrologic modeling, parameters must be abruptly changed in a simulation and then, depending upon parameter type, continuously modified until pre-fire parameters values are reached. Estimates of the model parameters could be obtained from forest growth models that have the ability to output forest cover, LAI and many other stand growth parameters on a spatially distributed basis. The three main parameter groups that must be altered to simulate long term wildfire impacts include: vegetation cover, soil characteristics and albedo. All three of these parameter groups will respond differently to the initial application of wildfire and, subsequently, in recovery to pre-fire values.

Vegetation parameters in a hydrologic-wildfire simulation must be modified to reflect an abrupt reduction in vegetation cover and then a recovery at a site specific rate. Soil parameters in a hydrologic-wildfire simulation must be modified to reflect a reduction and recovery of duff depth and/or the formation of non-wettable soil conditions. As reflected in the literature, the duration of change required by soil parameters could last anywhere between one or two precipitation events up to five or six years.

Albedo values also need to be modified in a hydrologic-wildfire simulation until recovery to pre-fire values are reached. In hydrologic-wildfire simulation, albedo change in a watershed can be complex and will vary depending upon wildfire behavior and season. For example, in the absence of snow, the albedo of a burned area will be a function of the vegetation cover, ground surface blackened plus the density of tree boles blackened. When a snow-pack is present, the albedo will be a function of the percentage of tree boles blackened and the snow surface. Therefore, during a hydrologic-wildfire simulation, albedo values must be modified not only on a recovery basis but also seasonally. Overall, because of the differing characteristics of parameter recovery, the hydrologic model selected must be designed so that parameter modification is not an arduous task.

In all, the preceding criteria are a starting point from which a hydrologic model can be selected and modified for use in hydrologic-wildfire impact simulation. Overall, it could be expected that some modification of modeling equations and/or structure of a candidate model may be necessary to allow for the dynamic incorporation of parameter change specific to wildfire. The use of a forest growth model that can output results on a spatially distributed basis, may ease the task of estimating the continuously changing parameters of a forest stand. In this respect, further research and ground truthing of the various hydrologic-wildfire impacts are necessary for the development of an accurate hydrologic-wildfire model for B.C. In summary, the best candidate model for use as a hydrologic-wildfire model is one that has the ability to capture the uniqueness of the spatial and temporal variability of watershed and wildfire behavior characteristics.

6.6 Chapter Summary and Conclusions

The ability of wildfire to affect large tracts of forest land is great and, therefore, knowledge of the subsequent effects wildfire can create on the hydrologic regime is important to obtain in forest management. Wildfire can directly affect the vegetation and soil components in a watershed as well as the hydrologic processes of which soil and vegetation are integral. Wildfire has the potential to enhance streamflow, create earlier and larger peakflows, deeper and earlier melting snow-packs and higher than average soil water contents. Within the literature, wildfire has been observed to create changes in the magnitudes of annual water yield, summer flow, peak flow and peak flow timing.

With the re-introduction of wildfire into the environment, concerns over past fire suppression effects on fuel build-up and, subsequently, increased fire intensity are high. However, tools to quantify such concerns are largely not available to forest managers in B.C. The development of a hydrologic-wildfire model is a tool that could be used by forest managers to supplement forest management decisions. However, the development and testing of such a model has yet to be achieved. A hydrologic model that is physical-based and distributed was determined to be the most optimal candidate for further research due to the ability of this model type in capturing the spatial-temporal variability in watershed characteristics on a small pixel basis. The use of a spatially distributed, forest growth model to provide values for parameters that are to be modified was also suggested. Overall, further research is required on the linking of wildfire impacts to observed changes in water quantity in B.C.

CHAPTER 7
THESIS SUMMARY AND CONCLUSIONS

7.1 Thesis Summary

This thesis was initiated with an attempt to apply the Distributed Hydrology-Soils-Vegetation Model (DHSVM) for complex terrain to a watershed located in the Interior of British Columbia. Unforeseen circumstances, limitations in the obtained modeling data and difficulties with the DHSVM resulted in the eventual termination of the modeling project. To augment this modeling attempt, the thesis topic was expanded to include a review of four popular hydrologic models in relation to their suitability for use in B.C. Also included is a review of data resource availability and limitations as well as some ideas on the development of a hydrologic-wildfire simulation model. A primary objective was to provide a basic understanding of the issues surrounding hydrologic modeling and to highlight the current problems and limitations of hydrologic modeling in B.C. with respect to operational forestry use and hydrologic-wildfire modeling.

Chapter 2 provides a discussion on what hydrologic models represent and why they are important in B.C. Also included is background information on four model classification categories based upon differing model, process, temporal and spatial characteristics.

Chapter 3 documents the background of the HSPF, TOPMODEL, UBCWM and DHSVM hydrologic simulation programs. These four models are also comparatively reviewed by documenting their strengths and weaknesses in relation to suitability for operational use in B.C. The results of the model review indicate that no single hydrologic model is optimally suited for widespread use in forest management due to the variability of modeling goals and model capabilities. Moreover, the selection of an appropriate hydrologic model is often not determined solely by model suitability. Model selection can also be influenced by model user experience, model user creativity, modeling objectives, model funding and data resource availability.

Chapter 4 examines the current state of data resources in British Columbia by reviewing the availability of groundwater, streamflow, vegetation, soil, topographic, remotely sensed, snow and meteorological data resources. General limitations of these data resources in terms of use in hydrologic modeling are discussed. Knowledge of these data limitations was deemed important as insufficient data resources could feasibly limit the use of some hydrologic models. It appears that the most limiting factor of B.C. data resources, for hydrologic modeling purposes, is the sparseness of meteorological, snow and streamflow data on a spatially distributed basis. Many of the current limitations in B.C. data resources result from funding restrictions and the outlook for any expansion of the various data collection programs appears to be remote. However, with minor improvements in B.C. data resources, many areas of the province could possess data that would be suitable for use in hydrologic modeling.

Chapter 5 presents a case study that provides a detailed description of the inherent data, research design, DHSVM and logistic limitations encountered during the preliminary thesis research. This chapter also gives details on the original thesis topic. The preliminary research topic was unsuccessful due to numerous limitations encountered in the input data, hydrologic model, project logistics and thesis research design. The lessons learned from this experience illustrate a variety of difficulties that one might typically encounter when attempting to use a hydrologic model in British Columbia. Highlighting these limitations was deemed to be valuable as this information should be useful for those who may wish to gauge the viability of hydrologic modeling projects.

Chapter 6 reviews the possible effects wildfire can have on the hydrologic regime of a forested catchment by examining hydrologic-wildfire impacts, current limitations of hydrologic models in simulating wildfire and criteria for the selection of a candidate model for hydrologic-wildfire impact simulation. The focus of the chapter is on the physical effects that wildfire can impose on the quantity and timing of water storage in a watershed.

Chapter 6 demonstrates that the ability of wildfire to affect large tracts of forest land is great and, therefore, knowledge of the subsequent impacts wildfire can create on the hydrologic regime can be important to obtain in forest management.

Wildfire can directly affect the vegetation and soil components in a watershed as well as the hydrologic processes of which soil and vegetation are integral. Wildfire has the potential to create earlier and larger peakflows, higher than average soil moisture conditions and deeper and earlier melting snow-packs. In the literature, wildfire has been observed to create changes in the magnitudes of annual water yield, summer flow, peak flow and peak flow timing. A hydrologic model that is physically-based and distributed was determined to be the most optimal candidate for development into a hydrologic-wildfire simulator due to the ability of this model type in capturing the spatial-temporal variability in watershed characteristics on a small pixel basis. It was also concluded that further research on the linking of wildfire impacts to observed changes in water quantity in B.C. is required.

7.2 Conclusion

The alteration of the normal hydrologic regime of a watershed by disturbances such as timber harvesting and wildfire is often at the forefront of forest management concerns in British Columbia. Forestry activities and disturbances that create changes in streamflow, water quality, water temperature and snow-pack accumulation and melt may have repercussions on features such as flooding, water supply, water quality, fish habitat and fish survival. Yet, due to the complexity of many hydrologic systems, accurately predicting the changes that may result from forest disturbance is a difficult task.

Many of the current limitations of hydrologic modeling in B.C. in relation to operational forestry use and hydrologic-wildfire modeling are discussed in this thesis. At present, the use of hydrologic simulation models to aid forest management in B.C. is not widespread. While the ability to simulate static hydrologic regimes in B.C. is feasible, the use of a hydrologic model to simulate dynamic hydrologic regimes as the result of forest disturbance (i.e., wildfire and timber harvesting) is not well developed.

The reasons why hydrologic simulation models have not gained popularity in forest management in B.C. may be due to excessive model complexity, a lack of suitable data, user unfriendliness and the esotericism of many hydrologic models. In addition, many current hydrologic models are limited in adaptability both internally, in addressing hydrologic issues, as well as externally, in application to sites beyond the locale for which the model was developed. As such, many hydrologic models are unable to provide answers to the questions that are of utmost concern to forest managers. The absence of a hydrologic model specifically designed for operational use in B.C. ultimately limits widespread hydrologic modeling in forest management. Yet, despite the above mentioned limitations, hydrologic simulation models have a great potential for use in forest management in B.C.

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APPENDIX A

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e-mail: mquick@civil.ubc.ca

Chapter 3.5 - DHSVM

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Chapter 4.2.1 - Groundwater Data Resources

Rod Zimmermin, Groundwater Section
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Water Management Branch, Ministry of Environment, Lands and Parks
3rd Floor, 2975 Jutland Rd.
Victoria, B.C., V8T 5J9
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Chapter 4.2.2 - Soils And Terrain Data Resources

For soil map information contact:

Geographic Data BC (formerly Maps B.C.)
Ministry of Environment, Lands and Parks
4th. Floor, 1802 Douglas St., Victoria, B.C.
V8V 1X4
Phone: (250) 387-1441 FAX: (250) 387-3022

or,

Rob McClenehan
Ministry of Environment, Lands and Parks
Environmental Remediation and Integrated Pest Management Section
Pollution Prevention and Remediation Branch
2175 Jutland Rd., Victoria B.C.
V8T 5J9
Phone: (250) 387-9974 FAX: (250) 387-9935

For BC Geologic Survey terrain mapping information contact:

Ward E. Kilby
Manger, Mineral Potential Program
British Columbia Geological Survey
Ministry of Employment and Investment
Victoria, B.C., V8W 9N3
Phone: (250) 952-0422 FAX: (250) 952-0381
email: WKILBY@Galaxy.gov.bc.ca

For digital B.C. Soils map information contact:

Hally Hofmeyr
Resource Information Specialist
Ministry of Agriculture, Fish and Foods
2nd Floor, 808 Douglas St., Victoria, B.C.
PO Box 9120
Phone: (250) 387-0242 FAX: (250) 356-0044
email: Hally.Hofmeyr@gems9.gov.bc.ca

Regional MOF soil researchers

Vancouver Forest Region (250 751-7001)
Paul Courtin, Ministry of Forests
2100 Labieux Rd., Nanaimo, B.C.
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Phone: (250) 751-7120 FAX: (250) 751-7198

Kamloops Forest Region (250 828-4131)
Graham Hope, Ministry of Forests
515 Columbia St., Kamloops, B.C.
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Cariboo Forest Region (250 398-4345)
Bill Chapman, Ministry of Forests
200-640 Borland St., Williams Lake, B.C.
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Phone: (250) 398-4718 FAX: (250) 398 4406

Nelson Forest Region (250 354-6200)
Mike Curran, Ministry of Forests
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Prince George Forest Region (250 565-6100)
Paul Sandborn, Ministry of Forests
1011 4th Avenue, Prince George, B.C., V2L 3H9
Phone: (250) 565-6226 FAX: (250) 565-6671

Prince Rupert Forest Region (250 847-7500)
Marty Kramabetter, Ministry of Forests, Bag 5000
Smithers, B.C., V0J 2N0
Phone: (250) 847-7435 FAX: (250) 847-7217

Chapter 4.3 - Streamflow Data Resources

For further information on WSC streamflow data contact:

Lynne Campo, Data Management & Applications
Pacific and Yukon Region, Water Survey of Canada
Environment Canada
Suite 120 - 1200 West 73rd Avenue, Vancouver, B.C.
V6P 6H9
Phone: (604) 664-9324 FAX: (604) 664-9066
e-mail: lynne.campo@ec.gc.ca

For further information on MOELP historical hydrometric data contact:

Larry Barr
Water Management Branch
Ministry of Environment, Lands and Parks
2080 Labieux Rd., Nanaimo, B.C.
V9T 6J9
Phone: (250) 751-3136 FAX: (250) 751-3103
email: lbarr@nanaimo.env.gov.bc.ca

Chapter 4.4.1 - BGCZ Ecosystem Classification System Data Resources

For further information on BGCZ maps contact:

Map Sales
Ministry of Forests
Lower Main, 1450 Government St., Victoria, B.C.
V8W 3E7
Phone: (250) 387-8688 FAX: (250) 387-8687

Research Branch, Ministry of Forests
31 Bastion Square, Victoria, B.C.
V8W 3E7
Phone: (250) 387-6721 FAX: (250) 387-0046
website: http://www.res.for.gov.bc.ca/projects/bec_doc.html#Products

Hugh Hamilton Ltd.
850 West 15th., North Vancouver
V7P 1M6
Phone: (604) 980-5061 FAX: (604) 986-0361
e-mail: info@hugh-hamilton.com website: http://www.hugh-hamilton.com

Regional MOF offices:

Vancouver Forest Region (250 751-7001)
Kamloops Forest Region (250 828-4131)
Cariboo Forest Region (250 398-4345)
Nelson Forest Region (250 354-6200)
Prince George Forest Region (250 565-6100)
Prince Rupert Forest Region (250 847-7500)

4.4.2 Ecoregion Classification System

Further information on the ECS contact:

Dennis Demarchi
Ministry of Environment, Lands and Parks
Wildlife Inventory Section
2nd Floor, 2975 Jutland Rd., Victoria, B.C.
V8T 9M1
Phone: (250) 387-9772 FAX: (250) 387-2733

Chapter 4.4.3 - Forest Cover Data Resources

For further information on digital forest cover data contact:

Anja Tolman
Ministry of Forests
Resource Inventory Branch
722 Johnson Street, Victoria, B.C.
V8W 9C2
Phone: (250) 387-3393 FAX: (250) 387-5999

For paper forest cover maps contact:

Map Sales
Ministry of Forests
Lower Main, 1450 Government St., Victoria, B.C.
V8W 3E7
Phone: (250) 387-8688 FAX: (250) 387-8687

Chapter 4.5 - Topographic Data Resources

For further information on TRIM maps contact:

Geographic Data BC (formerly Maps B.C.)
Ministry of Environment, Lands and Parks
4th. Floor, 1802 Douglas St., Victoria, B.C.

V8V 1X4
Phone: (250) 387-1441 FAX: (250) 387-3022

Roger Balser P.Eng., Manager Operations
Geographic Data BC (formerly Maps B.C.)
Ministry of Environment, Lands and Parks
1802 Douglas St., Victoria, B.C.
V8V 1X4
Phone: (250) 387-9321 FAX: (250) 356-7831

For information on obtaining paper topographic and TRIM maps contact:

Crown Publications Inc.
521 Fort St., Victoria, B.C.
V8W 1E7
Phone: (250) 386-4636 FAX: (250) 386-0221

Chapter 4.6.1 - Air Photograph Data Resources

For general information about air photographs and viewing contact:

Geographic Data BC (formerly Maps B.C.)
Ministry of Environment, Lands and Parks
4th. Floor, 1802 Douglas St., Victoria, B.C.
V8V 1X4
Phone: (250) 387-1441 FAX: (250) 387-3022

Jennifer Bulter, Air Photo Librarian
Geographic Data B.C.
4th. Floor, 1802 Douglas St., Victoria, B.C.
V8V 1X4
Phone: (250) 387-9317

Crown Publications Inc.
521 Fort St., Victoria, B.C.
V8W 1E7
Phone: (250) 386-4636 FAX: (250) 386-0221

Chapter 4.6.2 - Satellite Data Resources

For general information on Radarsat products contact:

Kate Stevens, Client Services Representative
Western North America
RADARSAT International Inc.
Phone: (604) 231-4973 email: kstevens@rsi.ca

or,

RADARSAT International Inc.
Suite 200, 3851 Shell Road, Richmond, B.C.
V6X 2W2
Phone: (604) 231-5000 FAX: (604) 231-4900

Chapter 4.7 - Snow Survey Data Resources

To obtain snow survey data contact :

Cindy Frampton, Water Inventory Section
Resources Inventory Branch, Ministry of Environment, Lands and Parks
2nd floor 2975 Jutland Rd., Victoria, B.C.
V8T 1M1
Phone: (250) 387-9483 FAX: (250) 356-5496

To obtain general information about snow survey data contact:

Jan Matthews, Snow Survey Technician
Water Inventory Section, Resources Inventory Branch
Ministry of Environment, Lands and Parks
2nd floor 2975 Jutland Rd., Victoria, B. C.
V8T 1M1
Phone: (250) 387-9485 FAX: (250) 356-5496
email: JMATTHEW@water.env.gov.bc.ca

Chapter 4.8.1 - Atmospheric Environment Service (AES)

For more information on AES meteorological data contact:

Gary Myers, Superintendent of Climate Services
Climate Services
Pacific & Yukon Region, Environment Canada
120-1200 West 73rd Ave., Vancouver, B.C.
V6P 6H9
Phone: (604) 664-9067 email: Gary.Myers@ec.gc.ca

Chapter 4.8.2 - BC Hydro

For more information on B.C. Hydro Meteorological data contact:

Brian Fast (604) 528-2242 or,
Wayne Johnson (604) 528-7775
BC Hydro
Power Supply Operation
6911 Southpoint Drive, Burnaby, B.C.
V3N 4X8

Chapter 4.8.3 - Ministry of Environment, Lands and Parks (MOELP)

For more information on MOELP meteorological data contact:

Sharon Gunter
Air Resources Branch, Ministry of Environment, Lands and Parks
3rd Floor 2975 Jutland Rd., Victoria, B.C.
V8T 5J9
Phone: (250) 387-9937 FAX: (250) 356-7197

Chapter 4.8.4 - Ministry of Transportation and Highways (MOTH)

For further information on MOTH meteorological data contact:

Ted Weick, Avalanche Systems Technician
Ministry of Transportation and Highways
940 Blanshard Street, Victoria, B.C.
V8W 2E6
Phone: (250) 387-7518 FAX: (250) 356-8143
email: tweick@vines.gems.gov.bc.ca

Chapter 4.8.5 - Ministry of Forests (MOF)

For information on Fire Weather Network data contact:

Eric Meyer, Fire Weather Specialist, Ministry of Forests
2nd floor 2957 Jutland Rd., Victoria, B.C.
V8W 3E7
Phone: (250) 387-8744 FAX: (250) 387-5685

For information on the BC Forestry Research Branch FRDA Climate Network contact:

Dave Spittlehouse
Research Branch, Ministry of Forests
31 Bastion Square, Victoria, B.C.
V8W 3E7

Phone: (250) 387-3453 FAX: (250) 387- 0046

For more information on the Nelson-West Arm Demonstration Forest Network contact:

Dave Gluns, Hydrologist
Forest Sciences Research-Nelson, Ministry of Forests
518 Lake St., Nelson, B.C.
V1L 4C6
Phone: (250) 354-6281 FAX: (250) 351-6250

For information on Penticton Creek Experimental Watershed climate data contact:

Rita Winkler, Research Hydrologist
Kamloops Forest Region, Ministry of Forests
515 Columbia St., Kamloops, B.C.
V2C 2T7
Phone: (250) 828-4169 FAX: (250) 828-4154

For information on Silviculture Seed Orchards Climate Data contact:

George Reynolds
Virga Consultants
1298 Holloway Street, Victoria, B.C.
V9P 1M7
Phone and FAX: (250) 382-1064

Chapter 4.8.6 - Site Specific Meteorological Networks

For information on the Carnation Creek Experimental Watershed Network:

George Reynolds
Virga Consultants
1298 Holloway Street, Victoria, B.C.
V9P 1M7
Phone and FAX: (250) 382-1064

For information on the Greater Vancouver Regional District networks contact:

Greater Vancouver Regional District
Air Quality and Source Control
Metrotower II,
4720 Kings, Burnaby, B.C.
V5H 4N2
Phone: (604) 436-6746

For information on available meteorological data in National Parks, contact Park Warden's Office.

Yoho National Park - (250) 343-6324
Revelstoke and Glacier National Park - (250) 837-6274
Kootenay National Park - (250) 347-9361

APPENDIX B

HSPF, TOPMODEL, UBCWM and DHSVM Websites

Selected HSPF Model Related Websites

ftp://ftp.epa.gov/epa_ceam/wwwhtml/hspf.htm
http://abete.eletpolimi.it/gaia/SECOND/modelli/hspf.ht
http://asae.org/mtgs/am95/events/abstract/245.html
http://dino.wiz.uni-kassel.de/model_db/mdb/hspf.html
http://h2o.usgs.gov/software/hspf.html
http://res.agr.ca/lond/pmrc/sweep/rep75.html
http://waisqvarsa.er.usgs.gov/software/hspf.html
http://www.cee.odu.edu/cee/model/hspf.html
http://www.epa.gov/epa_ceam/wwwhtml/hspf.htm#TOP
http://www.epa.gov/OWOW/watershed/tools/model.html#1
http://www.hydrocomp.com/HSPFinfo.html
http://www.hydrocomp.com/journal2.html
http://www.mde.state.md.us/tarsa/models/HSPFinfo.html
http://www.wcc.nrcs.usda.gov/water/matrix/info#14
http://www3.bae.ncsu.edu/info1/courses/bae573/models/hspf.txt
http://wwwnv.wr.usgs.gov/projects/tcp/fs_082_96/hspf_fs.html

Selected TOPMODEL Related Websites

http://www.es.lancs.ac.uk/es/Freeware/Freeware.html
http://dino.wiz.uni-kassel.de/model_db/mdb/topmodel.html
http://www.gsf.de/UFIS/ufis/modell40/modell.html
http://pasture.ecn.purdue.edu/~aggrass/models/topmodel/
http://wwwks.cr.usgs.gov/Kansas/pubs/abstracts/1995/WOLOCK1.TOPMODEL.html
http://www.mluri.sari.ac.uk/top.htm

Selected UBCWM Related Websites

http://www.civil.ubc.ca/home/ubcmodel/main.htm

Selected DHSVM Related Websites

http://maximus.ce.washington.edu/%7Enijssen/docs/DHSVM/
http://cdiac.esd.ornl.gov/newsletr/spring96/r_rs96.htm
http://maximus.ce.washington.edu/~hydro/Lettenmaier/Publications/Effect_of_DEM_Accuracy_and_Scale_on_Hydrological_Modeling/agu_fig1.htm
http://maximus.ce.washington.edu/~hydro/Lettenmaier/Publications/Effect_of

_DEM_Accuracy_and_Scale_on_Hydrological_Modeling/agu_post.htm#T3

http://maximus.ce.washington.edu/~hydro/Lettenmaier/Publications/small_watershed/poster.html

http://maximus.ce.washington.edu/~lxb/poster.html

http://maximus.ce.washington.edu/~hydro/Lettenmaier/CurrentResearch.html

APPENDIX C

Selected Hydrologic Model References

The following references are a listing of documents that together provide a comprehensive background to the HSPF, TOPMODEL, UBCWM and DHSVM hydrologic simulation models and related applications. Unfortunately not all of these references could be obtained by the author. References that were obtained by the author have been indicated with an asterisk (*).

<u>*Selected HSPF References*</u>

Barnwell, T.O. Jr. and R.C. Johnson. 1981. HSPF: A Comprehensive Package for the Simulation of Watershed Hydrology and Water Quality. In *Nonpoint Pollution Control: Tools and Techniques for the Future*. Interstate Commission on the Potomac River Basin. Rockville, MD.

* Bicknell, B.R., J.C. Imhoff, J.L. Kittle Jr., A.S. Donigian Jr. and R.C. Johanson. 1993. *Hydrological Simulation Program-FORTRAN. User's Manual for Release 10*. US EPA, Environmental Research Laboratory. Athens, GA.

* Donigian, A.S. Jr. and L.A. Mulkey. 1992. STREAM, An Exposure Assessment Methodology for Agricultural Pesticide Runoff. p.297-330. In *Fate of Pesticides and Chemicals in the Environment.* J. Schnoor (ed.) John Wiley & Sons. New York, New York.

Donigian, A.S. Jr., B.R. Bicknell and J.L. Kittle Jr. 1986. *Conversion of the Chesapeake Bay Basin Model to HSPF Operation.* Prepared by AQUATERRA Consultants and US EPA Chesapeake Bay Program. Annapolis, MD.

Donigian, A.S. Jr., B.R. Bicknell, A.S. Patwardhan, L.C. Linker, D.Y. Alegre, C.H. Chang and R. Reynolds. 1991. *Chesapeake Bay Program Watershed Model Application to Calculate Bay Nutrient Loadings*. Prepared by AQUATERRA Consultants for the U.S. EPA. Annapolis, MD.

* Donigian, A.S. Jr., B.R. Bicknell and J.C. Imhoff. 1995. Hydrological Simulation Program - FORTRAN (HSPF) - Chapter 12. p.395-442. In *Computer Models of Watershed Hydrology*. V.P. Singh (ed.) Water Resources Publications. Colorado.

* Donigian, A.S. Jr., J.C. Imhoff, B.R. Bicknell and J.L. Kittle Jr. 1984. *Application Guide for Hydrological Simulation Program-FORTRAN (HSPF).* US EPA Environmental Research Laboratory. Athens, GA. EPA-600/3-84-065/066.

* Donigian, A.S. Jr., J.C. Imhoff, B.R. Bicknell, J.L. Baker, D.A. Haith and M.F. Walter. 1983. *Application of Hydrologic Simulation Program-FORTRAN in Iowa Agricultural Watersheds.* US EPA Environmental Research Laboratory. Athens, GA. EPA-600/S3-83-069.

Donigian, A.S., Jr., B.R. Bicknell and J.L. Kittle, Jr. 1986 *Conversion of the Chesapeake Bay Basin Model to HSPF Operation.* Prepared by AQUATERRA Consultants for the Computer Science Corporation, Annapolis, MD. and U.S. EPA Chesapeake Bay Program. Annapolis, MD.

* Flynn, K.M., P.R. Hummel, A.M. Lumb and J.L. Kittle Jr. 1995. *User's Manual for ANNIE, Version 2: A Computer Program for Interactive Hydrologic Data Management*. U.S. Geological Survey. Water Resources Investigations Report 95-4085.

* Hetherington, E.D., B. Walsh and M. Leytham. 1995. Calibration of HSPF Hydrologic Simulation Model Using Carnation Creek Experimental Watershed Data. p.47-54. In *Mountain Hydrology; Peaks and Valleys in Research and Application.* Proceedings of a Conference May 16-19, 1995, Vancouver B.C. Guy, B.T. and J. Barnard (eds.) Canadian Water Resources Association. Ontario.

Imhoff, J.C., B.R. Bicknell and A.S. Donigian Jr. 1983. *Preliminary Application of the HSPF to the Iowa River Basin to Model Water Quality and the Effects of Agricultural Best Management Practices.* US EPA. Athens, GA.

Johanson, R.C., J.C. Imhoff, H.H. Davis, J.L. Kittle Jr. and A.S. Donigian Jr. 1981. *User's Manual for the Hydrologic Simulation Program-FORTRAN (HSPF): Version No. 7.0.* prepared by Anderson-Nichols & Co. Inc. for US EPA Environmental Research Laboratory. Athens, GA.

Johanson, R.C., J.C. Imhoff and H.H. Davis. 1980. *User's Manual for the Hydrologic Simulation Program-FORTRAN*. U.S. EPA Environmental Research Laboratory. Athens, GA. EPA-600/9-80-105.

Johanson, R.C., J.C. Imhoff, J.L. Kittle Jr. and A.S. Donigian Jr. 1984. *Hydrologic Simulation Program-FORTRAN (HSPF): User's Manual for Release 8.0.* US EPA Environmental Research Laboratory. Athens, GA. EPA-600/3-84-066.

Lumb, A.M. and J.L. Kittle Jr. 1990. *User's Manual for ANNIE, A Computer Program for Interactive Analysis and Data Management.* U.S. Geologic Survey. Reston, VA. U.S. Geological Survey Water Resources Investigations Report 89-4080.

* Northwest Hydraulic Consultants ltd. 1993. *Calibration of the HSPF Hydrologic Simulation Model Using Carnation Creek Data-Final Report*. Prepared for Forestry Canada. (unpublished report).

U.S. EPA. 1994. *Upper Grande Ronde River Riparian Characterization and Temperature Modeling Projects: Project Summary, January 1994*. U.S. EPA. Washington, DC.

<u>Selected TOPMODEL References</u>

Ambroise, B., J. Freer and K. Beven. 1996. Application of a Generalized TOPMODEL to the Small Ringelbach Catchment, Vosges, France. *Water Resources Research*. 32(7): 2147-2159.

Ambroise, B., K.J. Beven and J. Freer. 1996. Towards a Generalization of the TOPMODEL Concepts: Topographic Indices of Hydrological Similarity. *Water Resources Research.* 32(7): 2135-2145.

Beven, K.J. (ed.) 1997. *Distributed Modelling in Hydrology: Application of the TOPMODEL concepts*. Wiley, Chichester. ISBN: 0-417-97724-1.

* Beven, K.J. and M.J. Kirkby. 1979. A Physically Based, Variable Contributing Area Model of Basin Hydrology. *Hydrological Sciences Bulletin*. 24 (1):43-69.

* Beven, K.J., M.J. Kirkby, N. Schoffield and A. Tagg. 1984. Testing a Physically-Based Flood Forecasting Model (TOPMODEL) for Three UK Catchments. *Journal of Hydrology*. 69:119-143.

* Beven, K.J., R. Lamb, P.F. Quinn, R. Romanowicz and J. Freer. 1995. Chapter 18 - TOPMODEL. p.627-668. In *Computer Models of Watershed Hydrology*. V.P. Singh (ed.) Water Resources Publications.

* Chairat, S. and J.W. Delleur. 1993. Integrating a Physically Based Hydrological Model in GRASS. p.143-150. In *HydroGIS 93: Application of Geographical Information Systems in Hydrology and Water Resources*. Proceedings of the Vienna Conference, April 1993. Kovar, K and H.P. Nachtnebel (eds.) IAHS Pubn. No. 211.

* Durand, P., A. Robson and C. Neal. 1992. Modeling the Hydrology of Sub-Mediterranean Montane Catchments (Mont Lozère, France), Using TOPMODEL: Initial Results. *Journal of Hydrology*. 139:1-14.

* Famiglietti, J.S., E.F. Wood, M. Sivapalan and D.J. Thongs. 1992. A Catchment Scale Water Balance Model for FIFE. *J. Geophys. Res*. 97: 18997-19007.

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Franchini, M., J. Wendling, C. Obled and E. Todini. 1996. Physical Interpretation and Sensitivity Analysis of the TOPMODEL. *Journal of Hydrology*. 175: 293-338.

* Hornberger, G.M., K. Beven, B.J. Cosby and D.E. Sappington. 1985. Shenandoah Watershed Study: Calibration of a Topography-Based, Variable Contributing Area Hydrological Model to a Small Forested Catchment. *Water Resources Research*. 21(12): 1841-1850.

Iorgulescu, I. and J.P. Jordan. 1994. Validation of TOPMODEL on a Small Swiss Catchment. *Journal of Hydrology*. 159: 255-273.

Lamb, R. 1996. *Distributed Hydrological Prediction Using Generalized TOPMODEL Concepts*. Ph.D. Thesis. Lancaster University, U.K.

Lepisto, A. 1994. Areas Contributing to Generation of Runoff and Nitrate Leaching as Estimated by Empirical Isotope Methods and TOPMODEL. *Aqua Fennica*. 24: 2:1-18.

Moore, R.D. and J.C. Thompson. 1996. Are Water Table Variations in a Shallow Forest Soil Consistent with the TOPMODEL Concept. *Water Resources Research*. 32(3): 663-670.

Quinn, P.F., K. Beven and R. Lamb. 1995. The ln(a/tan) Index: How to Calculate it and How to use it in the TOPMODEL Framework. *Hydrological Processes*. 9: 161-182.

* Robson, A.J., P.G. Whitehead and R.C. Johnson. 1993. An Application of a Physically Based, Semi-Distributed Model to the Balquhidder Catchments. *Journal of Hydrology*. 145:357-370.

* Romanowicz, R., K.J. Beven and R.V. Moore. 1993. TOPMODEL as an Application module within WIS. p.197-205. In *HydroGIS 93: Application of Geographical Information Systems in Hydrology and Water Resources*. Proceedings of the Vienna Conference, April 1993. Kovar, K. and H.P. Nachtnebel (eds.) IAHS Pubn. No. 211.

Wolock, D.M. 1993. *Simulating the Variable Source Area Concept of Streamflow Generation with the Watershed Model TOPMODEL.* U.S. Geological Survey, Water-Resources Investigations Report 93-4124.

Wolock, D.M. and G.J. McCabe. 1995. Comparison of Single and Multiple Flow Direction Algorithms for Computing Topographic Parameters in TOPMODEL. *Water Resources Research.* 31 (5) :1315-1324.

Selected UBCWM References

* Hudson, R.O. 1995. *The Response of Water Chemistry to Hydrological Conditions and Flow Paths Under Different Forest Cover Types in Small Subalpine Catchments.* Ph.D. Thesis. Faculty of Forestry, University of British Columbia, Vancouver.

* Hudson, R.O. and M.C. Quick. 1997. A Component Based Water Chemistry Simulator for Small Subalpine Watersheds. *Canadian Water Resources Journal*. 22(3) 299-235.

* Quick, M.C. 1995. Chapter 8 - The UBC Watershed Model. p.233-280. In *Computer Models of Watershed Hydrology.* V.P. Singh (ed.) Water Resource Publications. Colorado.

Quick, M.C., A. Loukas, R.G. Millar, D. Nixon and E. Yu. 1993. *Application of the UBC Watershed Model to Two Climatically Different Watersheds*. UBC Mountain Hydrology Group. 27th Annual Canadian Meteorological and Oceanographic Society Congress. Fredericton, New Brunswick.

* Quick, M.C., A. Pipes, D. Nixon, E. Yu, A. Loukas, R.G. Millar, H. Assaf and B. Start 1995. *UBC Watershed Model Manual, Version 4.* Mountain Hydrology Group. Department of Civil Engineering, University of British Columbia. Vancouver, B.C.

* Quick, M.C. and A. Pipes. 1977. UBC Watershed Model. *Hydrological Sciences Bulletin*. 21(3): 285-295.

* Weiss, E. 1995. Using the UBC Watershed Model to Calculate Operational Critical Levels for Strathcona Reservoir. p.183-190. In *Mountain Hydrology; Peaks and Valleys in Research and Application. Proceedings of a Conference May 16-19, 1995, Vancouver B.C.* Guy, B.T. and J. Barnard (eds.) Canadian Water Resources Association. Ontario.

<u>*Selected DHSVM References*</u>

* Arola, A. and D.P. Lettenmaier. 1996. Effects of Subgrid Spatial Heterogeneity on GCM- Scale Land Surface Energy and Moisture Fluxes. *Journal of Climate*. (9): 1339-1349.

Bowling, L.C., D.P. Lettenmaier, M.S. Wigmosta and W.A. Perkins. 1996. Predicting the Effects of Forest Roads on Streamflow Using a Distributed Hydrological Model. *EOS Transactions of the American Geophysical Union*. 77 (46) Fall Meeting Supplement.

Haddeland, I. and D.P. Lettenmaier. 1995. *Hydrologic Modeling of Boreal Forest Ecosystems*. Water Resources Series. Technical Report-145. University of Washington. Seattle, WA.

* Kenward, T. 1997. *Assessment of Required Accuracy of Digital Elevation Data.* M.Sc. Thesis. University of Washington. Seattle, WA.

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