Hydrologic Modeling of the Tsitika River Watershed:
An Application of Rainfall-Runoff Model Construction, Calibration and Validation

by

Martina Szabová
M.Sc., Comenius University, 1998

A Thesis Submitted in Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

in the Department of Geography

Supervisor: Dr. K. Olaf Niemann

Abstract

A lumped conceptual rainfall-runoff model based on the MIKE 11/NAM modeling code has been applied to the 372 km^2 Tsitika River Watershed. The model was constructed on the basis of readily accessible data of precipitation, temperature, land cover and topography, and was calibrated against the river discharge at the watershed outlet. Several validation tests were carried out and model performance evaluated in terms of the water balance error and the agreement of general hydrograph shape. Sensitivity analysis was conducted to explore the variability of simulation response produced by uncertainty associated with parameter values. In general, the model captured the dynamics of river discharge moderately well with most problems arising during the simulations of the snowmelt season. The differences between observations and model output were attributed to the insufficient spatial coverage of meteorological input data, errors in model structure resulting from a simplified model set-up, and errors caused by inevitable simplifications of temporal and spatial characteristics of the hydrologic behaviour of a very complex natural system.

Supervisor: Dr. K. Olaf Niemann, (Department of Geography)

Table of Contents

List of Tables

List of Figures

Acknowledgements

Numerous people have accompanied me during the study adventure at the University of Victoria and made my graduate experience both intellectually stimulating and personally rewarding. Although too many to name individually, each and everyone is appreciated for his/her own contribution. I do wish, however, to mention a number of people who have provided me with their invaluable advice, encouragement and support over the past few years.

First, I am most grateful to my supervisor, Dr. K. Olaf Niemann, for offering me the opportunity to expand my horizons at the UVic's *multispectral* academic and cultural environment. I thank him for introducing me to the research and personnel of the Spatial Sciences Laboratories, for his guidance and assistance throughout my studies, and for his continuous encouragement and suggestions for the way forward at several stages of my research.

I would also like to thank the other members of my thesis committee, Dr. Ian J. Walker, Dr. Fred Wrona and Dr. Asit Mazumder, for their constructive comments and contribution to the improvement of the thesis draft.

I thank Dr. Terry Prowse and Martin Lacroix for sharing their thoughts about hydrologic modeling and for giving me a chance to explore the couplings of geomatics and hydrologic research. Thanks to Ole Heggen for transforming Figure 3-5. into a readable graphics.

I acknowledge the DHI Water & Environment for generously providing the MIKE 11 modeling package for the use in the thesis project.

My gratitude is extended to the faculty, administrative and technical staff members of the Department of Geography for their advice and help in their respective roles. I especially thank Dr. Maycira Costa for her enthusiastic and inspiring insight into the principles of remote sensing science. Thanks to Rick Sykes for helping to overcome the difficulties with which the computer hardware and software have challenged us.

I would like to make a special mention of those people who stood by me and enriched my life with their friendship, care and smiles. My thanks go to my fellow students Carrie Steckler and Eddie Loos for all their scholarly and personal help, particularly (but not exclusively) during my first year as a graduate student. Many thanks to Manami Kaku and Laura Johnson for their friendship and constant support amid talks over manifold subjects. It was a pleasure sharing the lab with Eleanor Setton, Jon Corbett and other lab-mates from the Spatial Sciences Laboratories who made my studying and work amongst them enjoyable. Special thanks to my kindred spirits Nandan Divakaran Nair and Kathy Ganz for the generosity of their hearts, (not only) deep-thought conversations, and for always being ready to help with a smile. Thank you to Jutta Gutberlet for being a supportive friend and an excellent tennis playmate. Thank you to Ken Josephson for inspiring me with his artistic work and presenting a piece of it to me on my birthday as a genuine gesture of friendship. I am grateful to Tony, Edith and Julia Gvora for welcoming me into their family and for being a connection between the Slovak and Canadian cultures. I would like to express my sincere thanks to Juraj Kopanický for his personal and spiritual support and for providing me with a refuge whenever I went to Vancouver. I am also thankful to my dear friends in Trnava who stood by me when I left, when I came back and all the time in between.

I owe a huge debt of gratitude to Jill and Saman Jahansoozi for opening both their home and hearts to me. Their wisdom, exceptional devotion, spirit of optimism, and determination with which they respond to life's challenges has touched me in a very profound way and has led me to strive for this in my own life. I am forever thankful for all those precious evenings when my heart was nourished with unconditional love and gentle care, and my body strengthened with delicious food. I furthermore thank Jill for listening to me when I needed it, for assenting to long walks at short notice, and for her willingness to proof-read the thesis draft. *Motshakeram.*

None of this could have happened without the immense support of my family. I would like to express my deep gratitude especially to my mom Eva and my sister Janka. Their unwavering love, unquestioning faith in me and my abilities, and steadfast support has been a major stabilizing force in my life. Thank you for understanding my dreams and encouraging me to follow them even when at times it means living thousands of miles away. Thanks to my sister for always being there for me, for sharing the laughter, cheering me up when things did not look that bright, and for enduring (for the second time) the final stages of my thesis writing. *Ďakujem za všetko.*

Finally, Adam Mackerle deserves my special thanks for his continuous support, love, patience, for accompanying me through the ups and downs of the past several years, and for treasuring my dreams even when not always understanding them. For this, and for many other things, I would like to say my *mockrát děkuji*.

Dedication

To my sister Janka, our mom Eva and dear friend Jill,

the three extraordinary women

who have been my inspiration and strength

1. INTRODUCTION

1.1. Introduction

Numerical simulation models have often been applied to assist in better understanding of hydrologic processes operating in watersheds and to provide information related to water quantity and water quality. Some of the models have been used for purely research purposes, the others help water and land resources managers in making decisions about optimal logging scenarios, sustainable resource management, flood protection, etc. Modeling systems vary widely in the number of parameters they use, in the degree to which their structure can be related to the catchment-scale processes, or in the way they describe the spatial heterogeneity of the catchment. The majority of modeling systems currently used in the rainfall-runoff modeling practice can be characterized as lumped conceptual. These models are typically less data-demanding, have a simple structure and require few parameters. They involve spatial averaging of catchment characteristics and their parameters are not directly related to the physical conditions of a watershed. These models are applicable in simulations of spatially integrated hydrologic fluxes.

Another approach, physically based spatially distributed modeling, aims at accounting for the spatial variability of watershed characteristics and meteorological data within the entire modeling area. Physically based spatially distributed modeling systems simulate the hydrologic processes by solving the partial differential equations. Their parameters are more related to the physical characteristics of a watershed. Such modeling systems are assumed to be applicable in ungauged catchments, in areas with significant variations in rainfall input or hydrologic variables, and in studies dealing with the evaluation of land use changes. Naturally, these systems have higher computational demands and require large amounts of data, which are difficult to obtain for ordinary regions.

The question whether the detailed spatial representation leads to an improvement of the model performance and to better understanding of a watershed behaviour has been much debated in the literature. Different views on relative merits and drawbacks of simplified versus complex concepts have been expressed (Abbott et al., 1986; Beven, 1989; Beven, 2001a; Grayson et al., 1992; Smith et al., 1994). However, there appears to be a high degree of consensus regarding the need of practical modeling applications and the necessity of relevant tests to be carried out for assessing the capability and limitations of different modeling strategies and hydrologic modeling systems. The present study attempts to contribute to recent experiences in rainfall-runoff modeling and to provide insight into the feasibility, competence and limitations of a lumped conceptual model for simulating the dynamics of river discharge and the water balance in a medium-sized watershed.

1.2. Research goal and objectives

The originally proposed thesis project aimed at conducting an intercomparison study of the two rainfall-runoff modeling systems and assessing their capabilities to describe the effects of land use/land cover change on runoff in a medium-sized watershed. The goal of the project was to construct hydrologic models for the Tsitika River Watershed that are based on different approaches, i.e. lumped conceptual and spatially distributed physically based, to compare the performance of models, and to evaluate their efficiency in runoff simulation. MIKE 11 and MIKE SHE commercial software packages were selected as suitable candidates for the use in the study. These modeling codes are able to perform continuous simulations, consider the main processes active in watershed, including the processes that in particular might be affected by the land cover changes, and have been previously applied in similar studies. At the initial stage of the project, it was assumed that the data available from ordinary sources would be adequate for input into the hydrologic models. Unfortunately, data collected and inspected during preliminary analysis have not confirmed this assumption. Data inadequacy experienced, together with insufficient knowledge of local hydrologic conditions encountered, and poor identifiability of the change in watershed response to deforestation/afforestation detected when relying solely on streamflow measurements, were factors that have led to reconsideration of the original research design and reformulation of the objectives of the case study. The focus has shifted more towards a procedure of a calibration and validation of a lumped conceptual model and the inspection of uncertainties associated with model parameters.

Therefore, the principal goal of the thesis project is to present and discuss the methodology for the construction, calibration, and validation of a lumped conceptual hydrologic model. Specific objectives established in the present study are as follows:

- To test the usefulness of conventional data for the construction and calibration of a hydrologic model for the Tsitika River Watershed.
- To identify the limitations of the model performance when only ordinary data are available for the model set-up.
- To address parameter uncertainty issues through a comparison of parameter values derived by the model calibration for two modeling periods.

- To assess the effect of land cover changes on watershed runoff and modeling performance.

1.3. Thesis outline

The thesis is organized as follows. In Section 2., the terminology and general hydrologic modeling methodology are defined. Also discussed are some aspects of hydrologic modeling comprising the spatial variability and scale issues, incorporation of GIS and remote sensing data in hydrologic modeling, and the simulation of effects of land use/land cover change on watershed runoff. Section 3. describes the study watershed and documents preliminary analyses performed on available climate, discharge, topographic, and remote sensing data. In Section 4., a modeling protocol followed in the case study is presented, including the description of the NAM modeling system, the selection of modeling periods and the definition of performance criteria employed. Model parameterization, several calibration strategies and the split-sample testing procedure are presented too. Section 4. also explores the uncertainty associated with model parameters and the variability in simulation response produced by uncertainty in parameter values. Discussion is presented with focus on sources of modeling errors. Finally, concluding remarks are provided in Section 5.

2. RESEARCH BACKGROUND

2.1. Hydrologic models

Hydrologic models are simplified representations of hydrologic processes active in watersheds. Rainfall-runoff models reflect our perception and understanding of various processes associated with the movement of water in drainage basins. The models contain more or less complex mathematical equations that describe the flow of water over the land surface and in the subsurface environment and simulate the watershed's response to a variety of weather events over time.

There are many reasons for developing and using rainfall-runoff models. In the research area, hydrologic models offer a means of generalizing our understanding of hydrologic systems. Scientists explore how theoretical assumptions about the behaviour of natural processes in real world systems correspond or are in conflict with reliable control data (Beven, 1989; Beven, 2001b). Field measurements that provide information about hydrologic systems are limited in time, in space, and in the range of available measurement techniques. Mathematical models help to fulfill the need for data extrapolation into areas where observations are difficult to make or are not available, and/or into the future where observations cannot be carried out yet (Beven, 2001b). Models may also be applied as decision-making tools to predict the likely future behaviour of natural systems during simulated events or to assess probable implications of future hydrologic change (Beven, 1989; Beven, 2001b). Applications of rainfall-runoff hydrologic modeling can therefore be found in (1) practical operational use of simulation models for improving water and land resources management, (2) flood forecasting and control, (3) prediction and mitigation of pollutant contamination, or (4) logging effects estimation among others.

Hydrologic simulation models vary widely in a number of different variables and parameters they use, in a degree to which their structure can be related to the watershed-scale processes, or in the way they describe the spatial heterogeneity of watersheds. A parameter, for example hydraulic conductivity or porosity, can be defined as a quantitative characteristic of a watershed area or a flow domain that usually remains constant over time (Beven, 2001b; Clarke, 1973). A variable is understood as a measurable characteristic of a hydrologic system, which can vary numerically in time and space (Beven, 2001b; Clarke, 1973). Meteorological variables, for example precipitation or temperature, describe the time variable boundary conditions during the modeling at a given time step. The initial values of the state variables such as soil water storage or a depth to the water table define the state conditions at the beginning of a simulation and then change during a simulation process according to the calculations of the model. On the other hand, the variables depicting geometry of a watershed are usually kept constant over a simulation period. Their values differ in space domain (Beven, 2001b).

2.2. Classification of hydrologic models

The extensive research related to hydrologic processes has resulted in the development and use of numerous types of models. Consequently, many different classifications of hydrologic models, and rainfall-runoff models in particular, appear in the literature. *Table 2-1.* provides an overview of several types of models grouped into the categories according to the most commonly used classification criteria. More detailed description of model types follows a brief tabular summary.

Table 2-1. *Classification of rainfall-runoff hydrologic models.*

Classification criterion	Model type	Reference
Conceptual description of physical processes	Metric / Empirical	Beven, 1989
	Conceptual	Hydrocomp, 2001
	Physically based / Physics based	Kokkonen and Jakeman, 2001
Spatial description of physical processes	Lumped	Beven, 2001b
	Semi-distributed / Quasi-distributed	Clarke, 1973
	Distributed	Singh, 1995
Probabilistic description of physical processes	Deterministic	Beven, 2001b
	Stochastic / Probabilistic	Clarke, 1973
Temporal characteristics	Event-based	Hydrocomp, 2001
	Continuous	
Scope of model	Partial	Hydrocomp, 2001
	Complete / Comprehensive	
Parameter determination	Calibrated parameter	Hydrocomp, 2001
	Measured parameter	
Spatial scale I.	Small watershed	Singh, 1995
	Medium watershed	
	Large watershed	
Spatial scale II.	Laboratory	Song and James, 1992
	Hill-slope	
	Catchment	
	Basin	
	Continental / Global	

Kokkonen and Jakeman (2001) classify rainfall-runoff models into metric, conceptual and physics based according to the degree to which the model structure and parameters can be related to the catchment-scale processes. *Metric* models, also called *empirical* (Hydrocomp, 2001), are based only on the extraction of information from observations, and thus have minimal data requirements. They attempt to find a mathematical link between input and output catchment variables, for instance between the rainfall-excess and streamflow, and do not take into account the features or the processes of a hydrologic system (Kokkonen and Jakeman, 2001). *Conceptual* models describe the main processes of a hydrologic system in a simplified manner and often include empirical algebraic components. These models are relatively simple with lower data requirements and usually have a structure of interconnected storages representing appropriate processes of hydrologic cycle. *Physics based* models, called synonymously *physically based* in the literature (Beven, 1989; Michaud and Sorooshian, 1994; Refsgaard and Knudsen, 1996), involve the theoretical principles of classical continuum mechanics and simulate the catchment behaviour by solving the governing partial differential equations for the movement of water. Physics based models are very complex, require many input variables and parameters, and have high computational demands.

Depending on the spatial description of catchment processes, hydrologic models can be described as lumped, semi-distributed or distributed (Beven, 2001b; Clarke, 1973; Refsgaard and Knudsen, 1996; Singh, 1995). *Lumped* models take no explicit account of the spatial variability of hydrologic processes, input or output variables, parameters, boundary conditions, or geometry of a watershed. The system is treated as a single, homogenous unit with averaged values of watershed characteristics. In *distributed* models, inputs, outputs, parameters, and catchment processes operate within a distributed framework. The catchment is discretized into a number of elements, most often grid squares, for which a unique set of meteorological conditions, physical characteristics, or output variables is considered. Model parameters are supposed to be more directly related to the physical characteristics of a watershed. They describe the spatial variation of topography, soil, vegetation, or geology characteristics (Refsgaard and Knudsen, 1996).

In practice, the lack of data inputs often constrains the use of fully distributed models. To overcome the problem, a catchment might be divided into subcatchment computational elements called hydrologic response units (Beven, 2001b). The hydrologic response units are characterized by essentially homogenous hydrologic behaviour and uniform characteristics of vegetation type, slope, aspect, and meteorological conditions. Kite and Kouwen (1992) introduced a concept of grouped response units. A grouped response unit is made of groups of hydrologic response units that represent areas with similar hydrologic response characteristics, share the same meteorological conditions, drainage system within a subcatchment, but need not to be continuous. Runoff contributions from the grouped response units are calculated separately and then summed within a catchment before routing into the river system (Kite and Kouwen, 1992).

There are a number of models in usage that do not make calculations for every point in a catchment, but only for representative points of a distributed function of characteristics, such as a topographic index in the case of a TOPMODEL modeling system. The distributed function of topographic index allows for the calculations of runoff response that can be mapped, i.e. distributed, back into catchment-scale space (Beven, 2001b). Hence, the models depicting hydrologic similarity through either hydrologic response units or a distributed function of catchment characteristics can be classified as *semi-distributed* or *quasi-distributed* (Beven, 2001b; Kite and Kouwen, 1992; Singh, 1995).

If all components of a model are free from random variation, the hydrologic model is considered *deterministic* (Beven, 2001b; Clarke, 1973; Singh, 1995). A *stochastic* or *probabilistic* model allows for a certain degree of randomness and uncertainty in the model output. Its input variables, parameters, or boundary conditions are regarded as random variables having probability distributions (Beven, 2001b; Clarke, 1973; Singh, 1995). As many models represent a mixture of deterministic and stochastic components, Beven (2001b) suggests classifying a model as stochastic when the model outputs are associated with a probability dispersion and variance. If the output variables are calculated as single values at any simulation time step, the model is thought to be deterministic without taking into account the character of underlying calculations.

Hydrologic models can be event-based or continuous with respect to temporal characteristics (Hydrocomp, 2001). *Event-based* models are designed to reproduce a single hydrologic event with time scale of several hours or days. They require a careful and reliable set-up of initial conditions for each simulated event. *Continuous* models solve water balance equations over longer periods, usually in a range of months, years or decades, and determine flow rates and conditions both during hydrologic events and in the periods of no surface runoff.

According to the scope of a model, hydrologic models can be viewed as complete or partial (Hydrocomp, 2001). *Complete* or *comprehensive* models reflect in more or less detail all hydrologic processes significantly affecting runoff including the precipitation, evapotranspiration, and runoff generation and routing processes. *Partial* models focus only on a part of the overall runoff process, e.g. water yield models simulate runoff volumes but do not pay attention to peak discharges.

Calibrated parameter models have one or more of their parameters derived by fitting the calculated hydrographs to the observed hydrographs over extended period of simulation, usually several months or years (Hydrocomp, 2001). Parameters for the *measured parameter* models can be obtained from measurements or estimations of known watershed characteristics. For example, the geometry of a watershed can be extracted from topographic maps, or soil characteristics determined from laboratory measurements.

Based on the spatial scale used in the hydrologic modeling, Singh (1995) recognizes small watershed, medium-sized watershed, and large watershed models. Although the distinction between the three classes is not clear-cut, watersheds with an area of up to 100 km^2 are most often regarded as *small*, those with an area of hundreds of km^2 are *medium*, and watersheds with an area exceeding 1000 km^2 are viewed as *large* (Singh, 1995). Song and James (1992) outline a modified approach and classify hydrologic models according to the spatial scale criterion into laboratory, hill-slope, catchment, basin, and continental. *Laboratory-scale* models are one-dimensional, considering only vertical measurements and hydrodynamic equations. *Hill-slope* models can be two- or three-dimensional and describe processes for both the surface and subsurface flows. They may also employ processes such as a preferential flow through soil pores, for which parameters cannot be obtained in laboratory and have to be measured in the field (Singh, 1995; Song and James, 1992). *Catchment-scale* models account for topography to simulate the surface runoff, and for geology to model the baseflow. *Basin-scale* models include complicated storage and translation routing schemes to properly represent hydrograph peaks and low flows when combining catchment runoff of large river systems. In *continental*, *global-scale* models, the modeling is focused on simulation of atmospheric processes and their interactions with land-surface processes with attention paid to precipitation and evapotranspiration (Singh, 1995; Song and James, 1992).

2.3. Limitations of lumped conceptual and distributed physically based approaches

2.3.1. Lumped conceptual models

Advantages and difficulties associated with lumped conceptual and distributed physically based hydrologic modeling and the relative superiority of either of the methods have been much debated in the literature (see for example Beven, 1989; Beven, 2001a; Grayson et al., 1992; Klemeš, 1986a). As mentioned previously, lumped-parameter models treat a watershed as a single unit with equal characteristics, or a small number of sub-watershed units each having uniform properties. The description of watershed hydrologic processes is conceptual or empirical by nature based on the idea that the highly non-linear system will produce linear results, provided sufficient time and space is available for modeling the processes integrated over space and over time (Downer et al., 2003). Lumped conceptual models typically require less data, have relatively simple structure, are easier to implement, and have been successfully used in practical applications (Beven, 1989; Downer et al., 2003). However, difficulties arise in the use of lumped conceptual models because of the following reasons:

- The equations of lumped conceptual models are only approximations of real watershed processes and model structure thus incorporates errors (Beven, 1989). Furthermore, some models have a form of empirically derived mathematical formulas and have lost their connection to real world processes almost completely (Todini, 1988).
- Spatial heterogeneity of watershed processes might not be represented and reproduced properly by lumped conceptual models (Beven, 1989; Downer et al., 2003).
- Due to approximation in representation of hydrologic processes, a model requires extensive calibration in order to provide reasonably accurate simulation outputs (Downer et al., 2003). Consequently, the accuracy of model calibration and validation depends a great deal on the accuracy or errors associated with observations of input or output variables and set-up of initial and boundary conditions for simulation (Beven, 1989; Beven, 2001a; Todini, 1988).
- There is a great risk of overparameterization if one attempts to simulate all hydrologic processes assumed to be relevant for particular watershed, and to optimize parameters against an observed discharge series (Beven, 1989). Moreover, parameters calibrated on a "best-fit" basis may have physically unrealistic values incorporating errors in data and assumptions about real world processes (Todini, 1988).
- Calibrated parameters may exhibit a certain level of interdependence causing that not only one unique set of parameter values could produce equally good results (Beven, 1989). Comparable model performance can also be achieved by using different sets of parameters.
- The use of lumped conceptual models for predictive purposes or for simulations different from calibration conditions is limited, because parameters are fine-tuned for calibration conditions and may not describe adequately the behaviour of a system with changed characteristics (Downer et al., 2003).

2.3.2. Distributed physically based models

Distributed parameter physically based models (DPPB) are based on physical laws such as the law of conservation of mass and energy and the law of thermodynamics (Wilcox et al.,

1990) and attempt to accommodate spatial variability of watershed characteristics and underlying hydrologic processes. Most models use mathematical equations to describe different surface and subsurface flow processes and their interconnected functioning in watersheds. These equations, though complicated, still reflect simplified assumptions about the nature of acting hydrologic processes (Beven, 2002). Model parameters aim at having more direct physical meaning and operate within a distributed framework to account for the spatial variability of watershed properties (Refsgaard and Knudsen, 1996). Beven (2002) points out that a physically based model should be consistent not only with the theoretical assumptions about physical principles but should also involve consistency with data observations. Distributed models simulate hydrologic responses for all computational elements, most often pixels, thus being a good option for applications where distributed predictions of water flow is needed, for example as a basis for sediment transport or pollution modeling (Beven, 2002). DPPB models might be useful tools for (1) assessing the impacts of land use changes (Beven, 2002), (2) analyzing different management scenarios, (3) extrapolating the models outside calibration conditions (Downer et al., 2003), or for (4) providing framework within which researchers can test their understanding of physical systems (Beven, 1989; Grayson et al., 1992).

Grayson et al. (1992) see the application of DPPB modeling mainly in the research area, where the models are used in the analyses of data and in assisting of hypotheses testing in cooperation with field measurement programs. The models are also helpful in gaining a better understanding of physical processes and their interactions, and facilitate identification of weak process descriptions. For management projects the authors recommend the usage of simpler, less ambitious models that have reduced data requirements and are more in correspondence with the available level of information.

Although the DPPB models have been utilized more and more during the last decades, Beven (1989) cautions against their uncritical use in practice. He reasons that physically based models experience the same kind of problems as lumped conceptual models and often their theoretical advantages have not been practically demonstrated (Beven, 1989; Loague and Freeze, 1985). The equations describing the underlying physics of hydrologic processes are appropriate for homogeneous systems (and usually derived under laboratory physics assumptions), but cannot be reliably extrapolated to real world, extremely heterogeneous systems (Beven, 1989; Grayson et al., 1992). In addition, model parameters do not keep their physical significance due to inconsistency in scale in which they were derived and in which they are used in models. Field measurements give values of variables and parameters at specific discrete points but it is questionable to what extent they represent the actual values at spatial element scale (Beven, 1989;

Beven, 2001a; Grayson et al., 1992). In practice, the small-scale physics is lumped up to the grid scale without any theoretical framework to support the averaging of subgrid processes, which led Beven (1989) to refer to distributed physically based models as lumped conceptual models (at a grid scale). In this light Beven (2001a) recognizes the need for a development of scale consistent descriptions of controlling hydrologic processes, which would take into account the effects of subgrid scale heterogeneity. However, the problem arises from the fact that hydrologic models need to be applied for particular watersheds with their own unique characteristics. Considering the difficulties associated with errors in data observations and with local heterogeneities of the flow domain for a specific watershed, even the most complicated model (supposed to "perfectly" describe watershed processes) requires the estimation and calibration of some parameters (Beven, 2001a).

Limited availability of measurements, insufficient knowledge about the functioning of surface and subsurface processes are the usual reasons why only one set of model parameters or one specific model structure can not be identified as optimal. A user has a flexibility to obtain good fit to measured data and acceptable simulation outputs by using a wider range of model structures and parameter sets (Beven, 2001a; Grayson et al., 1992). Beven (2001b) suggests the Generalised Likelihood Uncertainty (GLUE) Methodology or the alternative blueprint as a method (Beven, 2002) to select an acceptable and reject unsatisfactory model structure and parameter set combinations. In order to take full advantage of DPPB models and to ensure their agreement with processes operating in real world watersheds, especially for applications where a physically correct simulations of distributed flow characteristics and parameters is of a great importance, the mathematical modeling should be undertaken in cooperation with a program of field observation (Beven, 1989). According to Grayson et al. (1992) data such as "runoff velocities at points within a catchment, subsurface flow responses within a catchment, distributed measurements of flow depth, conversion rates of rainfall to runoff areas of similar size to a model element, and growth and decline of saturated areas during an event" would facilitate more complete development and testing of models. At the same time the authors are aware of the current situation and the need for a development of new measurement techniques.

Future developments of physically based modeling should also involve the work on a theory of the lumping of subgrid scale processes, examine the consistency in scale between model predictions and field measurements, assure the correspondence between model equations and real world processes, and pay attention to accurate assessment of uncertainty in model predictions (Beven, 1989). Although Beven (2001a) certainly does not underestimate the importance of proper scientifically based approaches, he recognizes the need of practical applications such as the assessment of effects of land use change, the prediction of non-point source pollution, or the evaluation of risks and impacts of erosion and he states that "the future of distributed modeling lies not so much in the development of new theories for scaling or process representation but in the application of models and their use over a period of time in specific catchments". The continuous use of models for individual watersheds would offer a great potential for the evaluation of models, post-simulation analyses, learning about the uniqueness of places and processes within watershed areas, and improving the model representation of physical processes (Beven, 2001a).

2.3.3. Model comparison studies

The relative benefits and drawbacks of simple lumped conceptual models and more complex DPPB models have been evaluated and discussed in a number of studies. Franchini and Pacciani (1991) compared seven different lumped conceptual models in their ability to reproduce the measured flow rates in the Sieve watershed, and in their relative ease of application with respect to the structure of models, the difficulties associated with calibration and estimation of the parameters, and with the physical correspondence of parameters. The authors found out that regardless of the wide range of the structural complexity all the models but one offered similar and equally valid results. However, the degree of complexity proved to be significant in the calibration phase when the calibration times were generally proportional to the complexity of models. The authors conclude that a conceptual model should balance two contrasting demands - to present the greatest structural simplicity and to respect the physics of the problem. When a model structure is too simple, it loses a link with the physics of the processes and the possibility of using prior knowledge of the geomorphologic nature of the watershed. Conversely, the structure too complicated is not beneficial for computational purposes and a large number of parameters can cause the difficulties in the calibration procedure.

Kokkonen and Jakeman (2001) evaluated empirical and conceptual modeling approaches in terms of calibration and simulation performance of the models and the consistency of parameter estimates. They applied two models of equal complexity, i.e. having the same number of parameters, but of different level of conceptualization, i.e. the degree to which the model structure and its parameters can be related to catchment-scale hydrologic processes, to two small-sized (area < 1 km^2) watersheds. Modeling results showed that the empirical model yielded a more accurate reproduction of streamflow, especially when applied to the drier catchment. The superior performance of the metric model was even more apparent during the simulation period. When the conceptual model was modified by changing the relationship between actual and potential evapotranspiration, estimated streamflows were very much alike, but the evapotranspiration time series differed drastically for the two modifications. Therefore, the authors suggest a careful use of the reproduction of mass fluxes where no measured data are available.

Loague and Freeze (1985) used three event-based rainfall-runoff models – a regression model, a unit hydrograph model, and a quasi-physically based model to simulate runoff peaks and to assess model performance on three small upland catchments ranging from 10 ha to 7.2 km^2. The two empirical models were calibrated against runoff data and the parameter values for the quasi-physically based model were derived directly from the field data. All the models were validated on independent streamflow dataset using the split-sample test approach. Loague and Freeze (1985) found out that all three models performed surprisingly poorly in a forecasting mode (i.e. where an evaluation of model efficiencies was based on a comparison of the observed and predicted values of the summary variables for individual verification events on an event-by-event basis). The performance of models under predictive mode (in this case the evaluation was based on the analysis of ranked events and the comparison of means and standard deviations of observed and predicted frequency distributions) was better than under forecasting mode. For one catchment, the quasi-physically based model was applied with and without calibration of one key model parameter, but such calibration had only little impact on the model performance during the validation period. The authors conclude that the main barrier to the successful practical application of physically based models lies in the scale problems associated with the immeasurable spatial variability of rainfall and soil hydraulic properties.

In the study of Wilcox et al. (1990) daily, monthly and annual runoff was simulated to evaluate prediction capabilities of a conceptually simple model based on the Soil Conservation Service (SCS) curve number method and a process-oriented model based on the Green and Ampt equation. Simulations were carried out for six small rangeland catchments (each having a size of few ha). Parameter values were related to physical characteristics of each catchment and acquired from the readily available sources such as soil descriptions, topographic maps or published literature. No calibration was performed for either model. The results indicated that the SCS curve number model simulated runoff about as well as did the more complex Green and Ampt model.

To compare a simple lumped, simple distributed and a complex distributed model and to compare hydrologic simulations with and without calibration, Michaud and Sorooshian (1994) ran rainfall-runoff simulations for the medium sized (150 km^2) semiarid experimental watershed. They evaluated the performance of an event-based distributed model KINEROS and a model based on the Soils Conservation Service method with two configurations –spatially lumped and distributed, accounting for spatial variations in rainfall, antecedent conditions and curve numbers. The models were calibrated using six thunderstorm events with additional 24 events used for validation. None of the models were able to accurately simulate peak flows and runoff volumes for individual events, though the models were more successful in predicting time to peak and the ratio of peak flow to volume. Without calibration, the complex distributed model KINEROS performed better in simulating peak flows and volume than the simple distributed SCS model. Their performance was similar for time to peak. The spatially lumped model yielded poor results both for calibrated and uncalibrated simulation.

Refsgaard and Knudsen (1996) present the results of a case study on validation and intercomparison of three different models on three medium- to large-sized watersheds (areas of 254 km^2, 1040 km^2, and 1090 km^2). Three models were used for continuous runoff simulation – the first one based on a lumped conceptual modeling system NAM, the second one on semi-distributed modeling system WATBAL, and the third one on a fully distributed and physically based modeling system MIKE SHE. All models were subjected to a rigorous analysis of their performance including the split-sample test (SS), the differential split-sample test (DSS), the proxy-basin test (PB), the modified proxy-basin test (M-PB), and the proxy-basin differential split-sample test (PB-DSS). The split-sample and the proxy-basin tests showed that all models were able to provide a very good representation of the overall water balance and the general flow pattern, though the assessed uncertainty interval for the annual runoff predictions in the PB test was significantly larger for the NAM than for the other two cases. The M-PB test - the calibration on the one year of runoff data was allowed - revealed that the overall performance of all models was improved and appeared to be particularly significant for the simple lumped model. For the DSS test, the model calibrations were based on data from wet years and models were validated on data from dry years. All models were able to simulate the flows in the right order of magnitude and correct pattern but none of them had consistently better results than the others for all evaluation criteria. As a summary of their experience, Resgaard and Knudsen (1996) suggest to utilize the lumped conceptual model when calibration data are available because of its technical and economical feasibility. However, for ungauged watersheds a distributed model might provide better results when appropriate data on watershed characteristics can be acquired.

2.4. Modeling terminology and methodological framework

2.4.1. Terminology

In the scientific community, there is no unique and generally accepted terminology and methodology used with regard to hydrologic modeling. Refsgaard and Henriksen (2004) present a review of several existing modeling methodologies and guidelines for practical modeling applications. They make connections to underlying philosophical aspects of environmental modeling and point out the confusion in terminology when the same terms, namely the validation and verification, are often used with different meanings by different authors. Following and expanding the work related to terminology and validation of hydrologic models as described in Refsgaard (1996) and Refsgaard and Knudsen (1996), Refsgaard and Henriksen (2004) propose a framework for quality assurance modeling guidelines. They suggest a consistent terminology and methodology bridging the gap between scientific philosophy and pragmatic modeling. According to the authors, the most important elements of the modeling terminology and their relationships (shown in *Figure 2-1.*) can be described as follows:

- *Reality* – the natural system, the study area.
- *Conceptual model* – the user's perception of the main hydrologic processes and the natural system elements in the study area, and their corresponding description in terms of verbal descriptions and mathematical equations that are required for the specific purpose of modeling.
- *Model code* – a generic computer program that can be used to establish models for various study sites without the need of a source code modification, but allowing different input variables and parameters to be utilized. NAM (DHI, 2003a), TOPMODEL (Beven, 2001b), or MIKE SHE (DHI, 2003b) are examples of model codes.
- *Model* – a site-specific model established for a particular watershed with specific input variable and parameter values, e.g. a NAM-based model for the Tsitika River Watershed presented below in the thesis. Note: Generally in the literature and practice, the term model is understood as an analogy, abstraction, or a simplified representation of a system it is supposed to describe. In the terminology of Refsgaard and Henriksen (2004) a distinction is made between different meanings of the general term model – a conceptual model, model code, and a site-specific model.
- *Model confirmation* – the scientific confirmation of theories and assumptions included in the conceptual model.

- *Code verification* – the evaluation of a model code to adequately describe the theory and mathematical equations defined in the conceptual model within specified limits of application and accuracy.
- *Model calibration* – the procedure of adjustment of parameter values so that the model response corresponds to the reality response within the accuracy range defined in the performance criteria.
- *Model validation* – the evaluation of a site-specific model to produce simulation results within the range of accuracy specified in the performance criteria for a particular study.
- *Model set-up* – the establishment of a site-specific model using a model code including the definition of boundary and initial conditions, and the assessment of parameter values from field data.
- *Simulation* – the usage of a validated model for gaining knowledge about the reality or for obtaining predictions for water management.
- *Performance criteria* – the level of acceptable agreement between the model and reality.

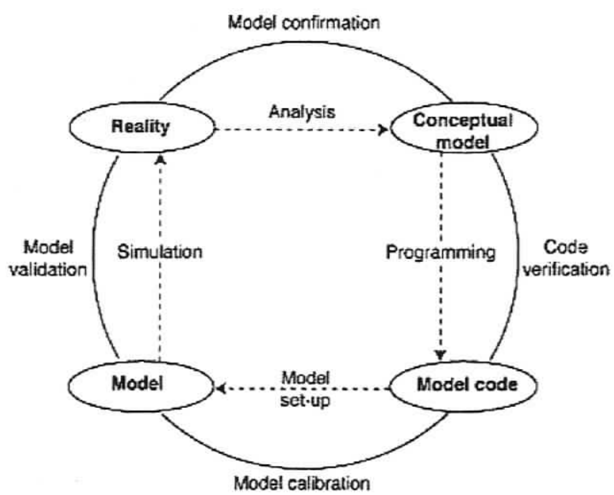


Figure 2-1. *Elements of modeling terminology (After Refsgaard and Henriksen, 2004).*

The consistency between reality, conceptual model, model code and model are evaluated through the processes of confirmation, code verification, model calibration and validation. Conceptual models should be subjected to confirmation or falsification procedures, as are the scientific theories. This involves confrontation with field data, critical peer reviewing, or analyzing the feedback from the calibration and validation processes (Refsgaard and Henriksen, 2004). However, Refsgaard and Henriksen (2004) also acknowledge that it is impossible to prove that a conceptual model is true, because a site-specific model shown to be valid for particular conditions may, due to non-uniqueness, work well for the wrong reasons. It does not mean that the model confirmation would be a useless work. It only implies that the model might not be correct for all circumstances and should be used with restrictions to domains of applicability and levels of accuracy (Refsgaard and Henriksen, 2004).

The purpose of model code verification is to ensure that a computer program solves accurately the equations included in a mathematical model. It can by accomplished by comparing a numerical output generated by a software package with an analytical solution or with a numerical solution from different verified codes. As it is hardly possible to verify a code universally, a given range of application and corresponding range of accuracy, for which a code was verified, should be specified (Refsgaard and Henriksen, 2004).

A model calibration involves the application of a model code for setting up a site-specific model that simulates the hydrologic behaviour of a study area. The model is then subject to validation to assess its capability to provide predictions about reality within the user-specified limits of errors. Thus the model's validity is always relevant for certain space, time, boundary conditions, and types of application (Refsgaard and Henriksen, 2004).

In order to establish suitable quantitative performance criteria for the model calibration and validation tests and the accuracy requirements for model predictions, a close cooperation between a water resources manager and a modeller is necessary. Refsgaard and Henriksen (2004) see the responsibilities of a manager in specifying the objectives, defining the acceptable limits of accuracy for performance criteria for the model application, and in defining the requirements for code verification and model validation. The modeller plays a role in the selection of an appropriate model code, in set-up, calibration and validation of a site-specific model, and in preparing validation documentation with clearly reported domain of applicability and the range of accuracy of the model. It is recognized that for practical operational applications, no universal accuracy requirements can be established. They differ from case to case with respect to the model's intention of use, costs associated with data collection and modeling work, and possible benefits resulting from more accurate results if different modeling approaches were to be taken (Refsgaard and Henriksen, 2004).

2.4.2. Model calibration

The process of model calibration involves the selection of parameter values so that the model simulates the hydrologic behaviour of a real system as closely as possible. Sorooshian and Gupta (1995) recognize two types of model parameters:

- *Physical parameters* – represent physically measurable properties of the study site such as the area of a watershed, surface slopes, etc.
- *Process parameters* – describe watershed properties that are not directly measurable, for example the effective depth of surface soil moisture storage or the effective lateral flow rate.

There are two main steps in model calibration (Sorooshian and Gupta, 1995):

- *Parameter specification* – prior knowledge about the study area is used to specify initial estimates of model parameters.
- *Parameter estimation* – various techniques of manual or computer based calibration are applied to reduce the uncertainty in the estimation of process parameters. Initial estimates of parameter values are adjusted so that the model simulates the watershed behaviour more closely.

In *manual calibration*, a trial-and-error procedure is employed for parameter adjustments. The goodness-of-fit of a model is evaluated by visual comparison of observed and simulated hydrographs. The main weakness of this method is that there is no generally accepted objective measure of comparison. It is difficult to explicitly assess the confidence of the model simulations because of the subjective judgment involved. Furthermore, the calibration might be difficult and time-consuming for inexperienced modellers (Madsen, 2000; Sorooshian and Gupta, 1995; Yapo et al., 1998).

In *automatic calibration*, parameters are adjusted by computer program with respect to a specified search scheme and numerical measures of the goodness-of-fit. The process is relatively fast and the confidence in model simulations can be explicitly reported (Madsen, 2000). The procedure of automatic parameter estimation consists of four major elements (Sorooshian and Gupta, 1995): (1) objective function, (2) optimization algorithm, (3) termination criteria, and (4) calibration data. Model validation and parameter sensitivity analysis should be carried out to establish the confidence in the results (Refsgaard and Henriksen, 2004; Sorooshian and Gupta, 1995).

Objective function

The *objective function* is an equation used to calculate the difference between the observed catchment output and the output provided by model simulations. It is a numerical measure of the goodness-of-fit of the calibrated model. Automatic model calibration attempts to find the values of model parameters that optimize, i.e. minimize or maximize with regard to a particular application, the numerical value of the objective function (Sorooshian and Gupta, 1995). The least square methods and the Maximum Likelihood methods are the most commonly used objective functions (Sorooshian and Gupta, 1995). The most successful ones seem to be those that are derived from the theory of maximum likelihood and account for the autocorrelation and changing variance of data errors (Beven, 2001b; Sorooshian and Gupta, 1995). Several numerical performance criteria generally used for the evaluation of model simulations are summarized in *Table 2-2.*

Table 2-2. *Statistical criteria for the assessment of model performance.*

Objective function	Formula	Description
Overall volume error (Water balance error) (DHI, 2003a)	$F_{bal} = \left\| \frac{1}{N}\sum_{i=1}^{N}\left(Q_{obs,i} - Q_{sim,i}\right)\right\|$	A measure of the agreement between the average simulated and observed runoff volumes
Overall root mean square error (RMSE) (DHI, 2003a)	$F_{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{N}\left(Q_{obs,i} - Q_{sim,i}\right)^2\right]^{1/2}$	A measure of the overall agreement of the shape of the hydrograph
Nash and Sutcliffe coefficient (Nash and Sutcliffe, 1970)	$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(Q_{obs,i} - Q_{sim,i}\right)^2}{\sum_{i=1}^{N}\left(Q_{obs,i} - \bar{Q}_{obs}\right)^2}$	A measure of the overall agreement of the shape of the hydrograph The coefficient is a transformed and normalized (with respect to the variance of the observed hydrograph) measure of the overall RMSE
Average RMSE of peak flow events (DHI, 2003a)	$F_{peak} = \frac{1}{M_p}\sum_{j=1}^{M_p}\left[\frac{1}{n_j}\sum_{i=1}^{n_j}\left(Q_{obs,i} - Q_{sim,i}\right)^2\right]^{1/2}$	A measure of the agreement of peak flows
Average RMSE of low flow events (DHI, 2003a)	$F_{low} = \frac{1}{M_l}\sum_{j=1}^{M_l}\left[\frac{1}{n_j}\sum_{i=1}^{n_j}\left(Q_{obs,i} - Q_{sim,i}\right)^2\right]^{1/2}$	A measure of the agreement of low flows

Where: $Q_{obs,i}$ is the observed discharge at time i, $Q_{sim,i}$ is the simulated discharge at time i, $\bar{Q}_{obs}$ is the average observed discharge [can be determined either from the year or period in question, or from earlier years as a long-term average; (Martinec and Rango, 1989)], N is the number of time steps in the simulation period, M_p is the number of peak flow events, M_l is the number of low flow events, and n_j is the number of time steps in peak/low flow event no. j. Peak/low flow events are defined as periods where the observed discharge is above/below a given, user-defined, threshold.

Automatic calibration techniques have been focused mainly on using a *single objective* function to assess the goodness-of-fit in hydrograph simulations. However, a single measure might not be adequate to properly take into account all characteristics of a natural system that are important for the simulation and are represented in the observations (Madsen, 2000; Madsen et al., 2002; Yapo et al., 1998). Therefore, automatic routines based on the *multi-objective* formulation of the calibration problem have been introduced into rainfall-runoff modeling (Madsen, 2000; Madsen et al., 2002; Yapo et al., 1998). Different calibration objectives can be considered, for instance: (1) a good water balance depicted as a good agreement between the average observed and simulated watershed runoff volume, (2) a good agreement of the overall shape of the hydrograph, or (3) a good agreement of the peak and low flows with respect to timing, rate and volume. Usually, a trade-off exists between the objectives, because a certain set of parameter values might provide a good simulation of runoff volume, but might not work very well for simulation of extreme flows (Madsen, 2000).

A multi-objective calibration can be transformed into a single-objective optimization problem by defining a scalar that aggregates various objective functions having different weights and priorities assigned to them (Madsen, 2000). Generally, no unique single set of parameters leads to a solution that optimizes all calibration objectives. The solution for multi-objective calibration consists of the so-called Pareto Optimal Set of solutions. It is a group of models with different parameter combinations that are dominant over the models outside the group, but none of the models within the Pareto Set can be said to be "better" than any of the other models from the Set (Beven, 2001b; Madsen, 2000; Yapo et al., 1998). To derive a single solution from the Pareto Optimal Set, Madsen (2000) suggests the use of a balanced aggregated objective function that puts equal weights to different objectives and might be an effective compromise solution for practical applications. Khu and Madsen (2005) proposed a novel automatic calibration method, which combines an effective optimization routine, based on multi-objective genetic algorithm (the Elitist non-dominated sorting genetic algorithm in the case of their study), and Pareto preference ordering. The procedure results in a small number of preferred solutions selected from numerous Pareto-optimal sets obtained for different objective functions.

Optimization algorithms

A surface that originates from plotting the resulting values of the goodness-of-fit in the *parameter space*, defined by the ranges of parameters, is called *response surface* (Beven, 2001b; Sorooshian and Gupta, 1995). An *optimization algorithm* is used to search the response surface for an optimal (minimal or maximal, depending on the application) value of the objective function (Sorooshian and Gupta, 1995).

Optimization methods can be classified as local search or global search strategies (Sorooshian and Gupta, 1995). *Local search* methods are efficient for finding the optimal value of the unimodal function, where a hill-climbing search will eventually reach the global optimum regardless the position of point on the response surface where the search has started. *Direct search* algorithms, for example the simplex method, use only the objective function value to find the optimum, whereas *gradient search* techniques use both the function value and the function gradient in the decision process (Beven, 2001b; Sorooshian and Gupta, 1995). The application of local search methods in the calibration of hydrologic models is often problematic because these models have multimodal response surfaces. Thus it is hard to know if the algorithm found the optimum that is "local" or whether it is a "global" optimal value of the objective function (Sorooshian and Gupta, 1995).

Global search optimization methods have been designed to efficiently locate the global optimum of multimodal functions and not to terminate the search when reaching local optima (Madsen, 2000; Sorooshian and Gupta, 1995). *Random search* methods use randomly sampled points from the parameter space and search for improved objective function values. *Multi-start* algorithms start the search from a number of different randomly chosen points in the feasible parameter space and compare the results to determine if a single optimum has been found or not (Sorooshian and Gupta, 1995). Other global search strategy based on the concepts drawn from the principles of natural biological evolution is the *Shuffled Complex Evolution* method (Duan et al., 1992). The parameter space is randomly sampled for starting points and different simplex searches are carried out concurrently. After each iteration of parallel searches, the current parameter values are shuffled to form new simplexes, which become new starting points for the next iteration. The shuffling allows the sharing of information about the response surface and hence the algorithm is usually successful in finding the global optimum (Beven, 2001b; Sorooshian and Gupta, 1995). Soorooshian and Gupta (1995) state that the Shuffled Complex Evolution method might be the best method currently available for parameter estimation for conceptual rainfall-runoff models.

However, from their study of the automatic calibration of four conceptual rainfall-runoff models Gan and Biftu (1996) concluded that all three applied methods – the Shuffle Complex Evolution, the Multiple-start Simplex, and the Local Simplex, produced parameter sets of comparable local-optimum quality. The authors report that some of the parameter values derived by different optimization algorithms for the same catchment cases were quite different from each other. They attributed the differences and inability to achieve global convergence in the parameter search to the limitations of calibration data, inadequacies in model structure, and parameter identifiability problems.

Madsen et al. (2002) also illustrate the problem of non-uniqueness in model calibration. They used the Shuffled Complex Evolution Method, the method based on combination of clustering and simulated annealing, and the knowledge-based expert system requiring the user intervention during the entire calibration process for multi-objective calibration. The researchers found that different methods put emphasis on different aspects of response modes of the hydrograph and that none of them were superior with respect to all considered performance measures, i.e. the water balance error, general shape of the hydrograph, and simulation of high and low flow events.

These studies indicate that it is usually difficult to obtain a single, unique set of optimal parameters for a hydrologic model when using automatic calibration methods. Sorooshian and Gupta (1995) identify several major characteristics that complicate the optimization:

- Several major regions of attraction into which a search strategy may converge exist.
- Each major region of attraction contains many local optima. They occur both close to, and at various distances from, the best solution.
- The objective function surface in the multi-parameter space is not smooth, may not be continuous, and has discontinuous derivatives that can vary in an unpredictable manner through parameter space.
- The response surface in the region of the global optimum is not necessarily convex. It might demonstrate widely varying degrees of sensitivity to the model parameters.

Termination criteria

In theory, the optimization procedure should stop at the point in the parameter space where the objective function value is optimal and where the slope of the function response surface is zero (Sorooshian and Gupta, 1995). It is hard to know if this point has been reached or not. Therefore, in practical calibration, the search might be terminated: (1) when the algorithm is not able to considerably improve the value of the function over one or more iterations (function convergence criterion), (2) when the algorithm is not able to sufficiently change the parameter value (parameter convergence criterion) and at the same time to improve the function value over one or more iterations, or (3) when a specified maximum number of iterations has been exceeded (maximum iterations criterion), unless the function or parameter criteria were met first (Sorooshian and Gupta, 1995).

Calibration data

It is suggested to use as much data as are available for the model calibration, provided a part of data has been set aside for the validation procedure. Although there is not a general rule of thumb of how much data are necessary and sufficient for the calibration, Sorooshian and Gupta (1995) suggest to use the dataset at least 20 times longer than is the number of parameters to be estimated.

The quality of calibration data is also important. The data should contain sufficient hydrologic variability so that the different modes of hydrologic processes are represented, i.e. the dry, medium, and wet hydrologic regimes or periods (Sorooshian and Gupta, 1995). Measurement or processing related errors also affect the quality of calibration data and ultimately the credibility of parameter estimates. Although these errors cannot be completely avoided, it is advisable that the data selected for calibration be at least examined for obvious errors, such as the periods where the hydrograph rises without corresponding records of precipitation (Sorooshian and Gupta, 1995).

2.4.3. Model validation

The purpose of model validation is to demonstrate that a site-specific model is capable of making accurate predictions for periods outside the calibration interval. A validation test should be carried out against the data that have not been used in calibration. The validated model then should show how well it can perform the tasks which it is intended to be applied for later on (Klemeš, 1986b; Refsgaard and Henriksen, 2004). The multi-site validation is required if the predictions of spatial patterns are needed. Multi-variable validation tests are necessary if the predictions of the behaviour of individual watershed subsystems are of an interest (Refsgaard and Henriksen, 2004).

A comprehensive hierarchical testing scheme for model validation was proposed by Klemeš (1986b). The testing system is supposed to be applicable: (1) for models intended to be used in planning, design, or operational decisions, (2) where the performance criteria are user-oriented, meaning that they measure only the correctness of generated numerical output and not the hydrologic soundness of the model, and (3) where the judgment about the model performance is based on a comparison of model estimates with real observations. The author distinguishes between the simulations conducted for the same station or basin as were used for the calibration, and simulations run for different stations and basins, for example for ungauged basins. A distinction is also made between the cases where climate and/or land-use remain unchanged, i.e.

stationary conditions, and where watershed characteristics have undergone a change, i.e. nonstationary conditions. Four categories of modeling tests were defined (Klemeš, 1986b):

- *The split-sample test* – involves the splitting of the data record into two segments. A hydrologic model is calibrated on one segment of the observed data and validated against the other one.
- *The differential split-sample test* – applicable for cases with nonstationary watershed conditions. First, a model is calibrated on data before the change occurs. Then, model parameters are adjusted to correspond to the change. Finally, a model is validated on data from the period of changed conditions.
- *The proxy-basin test* – a test for geographical transposability of a model. If a simulation of a variable in the ungauged catchment is required, two catchments with similar characteristics are to be selected. The model should be calibrated on the first gauged catchment, validated on the second gauged catchment, and vice versa. If the two validation tests are acceptable, a model might be applied to the ungauged catchment. A transfer of the model also includes the adjustment of parameters to represent specific conditions of a particular catchment.
- *The proxy-basin differential split-sample test* – a test for models that are transposable both geographically and climatically, or land-use-wise. To test a model's capability for simulating the changed conditions in ungauged catchment, the model is calibrated on data from the first gauged catchment that correspond to the period before the change. Then the model is validated against the data from the second gauged catchment with changed conditions. Again, the differential split-sample test is repeated with calibration on the second and validation on the first gauged catchment. Only then the model might be transferable to the ungauged catchment.

A good example demonstrating the application of the above described methodology is presented in Refsgaard and Knudsen (1996). The three modeling systems have been subject to rigorous testing scheme on data from three Zimbabwean watersheds. A case study illustrated a split-sample, differential split-sample, proxy-basin, and proxy-basin differential split-sample approach to model validation.

Another approach to model validation has been proposed by Ewen and Parkin (1996). Their *"blind" validation technique* is designed to demonstrate a capability of a model to predict the impacts of environmental changes by accounting the sound representation of catchment responses and the uncertainty in model parameterization. It is based on the idea that a model that demonstrates its capability to predict current conditions is assumed to be capable of predicting future conditions, provided this is done within the limitations, which apply when predicting future conditions. The main features of the blind validation are (Ewen and Parkin, 1996):

- The method implies a model's fitness for purpose, which is specified prior to the test. A model is thus used to provide a particularly required output.
- Simulations are made "blind", meaning that a modeller does not have a sight of measured catchment response data for testing the ability to predict the impact of future change.
- Hydrologic responses of the catchment are chosen to test the aspects of catchment behaviour that are the most relevant to the application, and for which observed data are available.
- The uncertainty of output is quantified by specifying the limits for the magnitude of the response feature or variable. To determine the uncertainty bounds, a modeler is allowed to use any method or information source that does not make direct or indirect use of the measured catchment response data.
- Criteria for the assessment of the sources of the validation are set up prior to the test.

Parkin et al. (1996) and Bathurst et al. (2004) report the application of the blind testing procedure for model validation. Parkin et al. (1996) applied hydrologic modeling system SHETRAN to simulate water flows in a small Mediterranean watershed. The validation test involved quantification of the uncertainties in prediction of four features of the catchment response (namely continuous hydrograph, peak discharge rates, monthly runoff, and total runoff), and comparison of the predicted ranges for these features with observations. The paper of Bathurst et al. (2004) presents the results of a blind validation test of a SHETRAN-based model for a small watershed in north-eastern England. The validation procedure considered internal catchment conditions as well as outlet discharge. Blind predictions were made and model performance assessed for ten features of the phreatic surface, soil water potential, and surface runoff responses.

2.4.4. Reliability estimation

Model predictions obtained from the simulation should be associated with uncertainty assessments, on which the confidence in model outputs can be based. There are many sources of uncertainty that can affect hydrologic modeling (Melching, 1995): (1) random temporal and spatial fluctuations inherent in natural processes of runoff generation, (2) data, (3) model parameters, and (4) model structure. Melching (1995) provides a review of several approaches for uncertainty estimation including methods based on Monte Carlo simulation, Latin Hypercube simulation, mean-value first-order second-moment estimation, advanced first-order second-moment method, Rosenblueth's point estimation method, and Horr's point estimation method. All methods are based on different ways of sampling the response surface for the performance measure in the parameter space.

Beven and Binley (1992) have proposed an overall procedure for model calibration and reliability estimation. The Generalized Likelihood Uncertainty Estimation (GLUE) methodology is based on the idea of equifinality of model parameter sets. It suggests that there may be many different sets of parameter values that can represent the catchment processes equally well. The implementation of the GLUE methodology requires a number of (subjective but explicitly stated) decisions to be made (quoted from Beven, 2001b):

- Decisions about the models to be included in the analysis.
- Decisions about the feasible range for each parameter value.
- Decisions about a sampling strategy for the parameter sets.
- Decisions about an appropriate likelihood measure.

The procedure consists of: (1) specifying the likelihood measure of the objective function, (2) determining an appropriate range for initial distribution of parameters, (3) running Monte Carlo simulations with randomly sampled parameter values to generate a large number of model outputs, (4) assessing the acceptability of each simulation through the function that compares predicted and measured outputs, (5) rejecting the unacceptable simulations, (6) normalizing the likelihood values for the parameter sets that have provided acceptable simulations, and (7) generating uncertainty bounds on the modeling output (Beven, 2001b; Melching, 1995). Due to the high computing requirements, the application of the GLUE method has been usually restricted for relatively simple models with few parameters, although Christiaens and Feyen (2002) present the application of the GLUE framework within the context of the distributed hydrologic modeling code MIKE SHE. The variability in simulation response of complex models has been usually explored by carrying out a sensitivity analysis where responses produced by a combination of few parameters and their values have been evaluated. Examples can be found in papers of Anderton et al. (2002), Andréassian et al. (2004), Bathurst (1986), and Eckhardt et al. (2003).

2.5. Spatial variability and scale in hydrologic modeling

In nature, things are organized in many different scales depending on their material substance and on the balance between the interacting forces (Klemeš, 1983). The main levels of scale, for instance atomic, molecular, level of macroscopic bodies of "human scale", or planetary level, seem to be concentrated around discrete states that are rather far apart and have different physical laws dominating in them (Klemeš, 1983). Naturally, human beings have the best understanding of things that appear within the "human scale" *(Figure 2-2.)* and are directly accessible to their senses, i.e. ranging from a tenth of a millimeter to a few kilometers in space and from a tenth of a second to a few decades in time (Klemeš, 1983). The problem in formulating the concepts describing hydrologic processes arises from the fact that they lie mostly outside the scale for which the human beings have a direct sensory comprehension and "intuitive feel" (Klemeš, 1983). As Klemeš (1983) puts it:

> "I would attribute many if not most of our difficulties with conceptualization in hydrology and the resulting lack of understanding of hydrologic processes on the one hand to the fact that their scale is not far enough from the human scale to prevent us from seeing clearly the difficulties arising from using our human-scale concepts and, on the other, to our inherent handicap in the formation of clear concepts at scales immediately bordering on the human scale."

He goes even further and in agreement with Kartvelishvili's opinion states that "the development of an adequate hydrologic theory may be more demanding than was the development of the theory of relativity or the quantum theory".

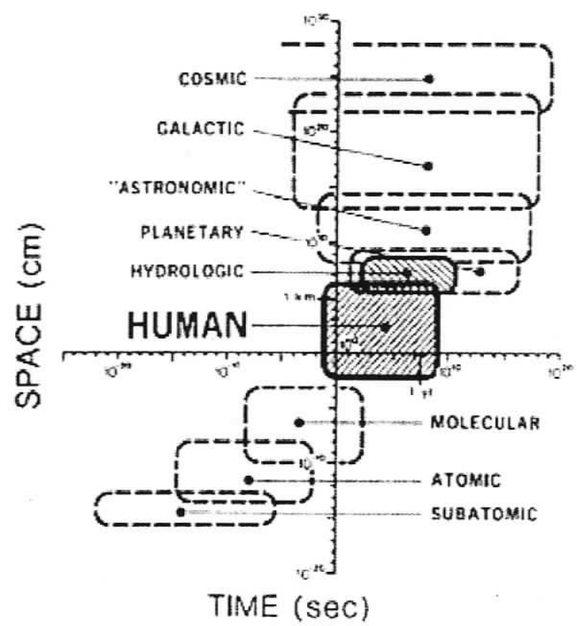


Figure 2-2. *"Human" scale shown in the context of "hydrologic" scale and of the approximate space and time ranges corresponding to the main levels of scale used for conceptual representations of physical processes (After Klemeš, 1983).*

The search for an appropriate way of describing hydrologic processes may take an *upward* approach, termed *upscaling* in Vázquez et al. (2002) and *aggregation* in Beven and Fisher (1996) or Song and James (1992), or may proceed *downwards* (Klemeš, 1983). The *upward* approach combines the theoretical knowledge and empirical facts tested at a lower scale into theories that can predict hydrologic events at a higher-level scale. An example would be an assumption that mathematical equations describing the movement of water at a hydrodynamic level are also valid at a larger scale, for example catchment scale. The *downward* operation attempts to find a "vantage point" from which a hydrologic concept can be recognized at a particular level of interest, and then tries to search for steps that could have led to it from a lower level (Klemeš, 1983). For instance, remotely sensed data reveal information about a hydrologic pattern, but then it is necessary to find out what are the dominant and important sources of hydrologic variability.

The problem of scale in hydrology is associated not only with the conceptualization of individual processes included in a catchment response, but also with the treatment of spatial variability at subcatchment level. Catchment runoff is generated through interactions among several processes such as interception, evapotranspiration or infiltration, which vary spatially according to the relevant physical, vegetative, and topographic characteristics (Song and James, 1992). However, as the spatial scale increases from points to larger areas, the runoff generation becomes less sensitive to the spatial variation of local precipitation or soil depths, and the rainfall-runoff response is more affected by macroscale catchment characteristics (Song and James, 1992; Wood et al., 1988). A not easy task is then to find an optimal scale, which "is not small to be dominated by local physical features, nor so large as to ignore significant hydrologic heterogeneity caused by spatial variability of catchment characteristics" (Song and James, 1992).

The description of spatial variability of catchment characteristics is ultimately reflected in the model discretization into modeling elements and in the spatial variation of model parameters. Kuo et al. (1999) inspected the effects of different grid sizes of input data, in this case topography, soil types and land use, on runoff and soil water content for a variable-source-area model. They found that among several types of input information changes, the changed scale in topography had the greatest effect on simulation results. The scale of topography is thus very important especially for landscapes with steep valleys, where the hydrologic behaviour is driven by the gradient of slope and slope curvature.

Vázquez et al. (2002) studied how the performance of a model and the modeling process in terms of running time were affected by applying different grid resolutions and corresponding effective parameter values. Two approaches to upscaling operation were investigated: (1) upscaling using effective parameters, where the smaller scale equations and derived parameters were assumed to be valid also at the larger scale, and (2) upscaling based on grid square effective parameters, where parameters representing the overall behaviour of a particular heterogeneous grid were uniquely estimated for every grid scale.

2.6. GIS and remote sensing applications in hydrologic modeling

Hydrologic processes vary inherently in space and time. The spatial nature of meteorological, topographic, land-use, or soil characteristics is directly reflected especially in distributed hydrologic models. Considering the large data volumes, data organization and manipulation required in distributed hydrologic modeling, it is natural that geographic information systems (GIS) have been incorporated in hydrologic studies (Singh, 1995; Vieux, 2001). Geographic information systems are computer-based tools (in a broader sense GIS can be viewed as a science, an application or a tool (Koren, 1995) but the first two meanings are not directly considered in the context of this work) that facilitate the storage, retrieval, analyses, manipulation, management, and visualization of a spatial database.

Integration of GIS and hydrologic modeling has proved to be useful at different stages of the design, calibration, modification, and comparison of hydrologic models (Singh, 1995). In order to provide the spatial and temporal distribution of input variables and parameters, GIS assist in the following areas (Vieux, 2001):

- Data pre-processing in terms of format conversion, coordinate system transformation, and metadata documentation.
- Generation of a two-dimensional surface from point data - using various interpolation methods such as linear interpolation, distance weighting, splines, or Kriging.
- Assessment of the effects of grid resolution and resampling techniques on hydrologic modeling - for example by measuring information content, i.e. entropy, as an indicator of spatial variability and evaluating the information loss due to resampling to larger grid cell sizes (Kuo et al., 1999).
- Watershed delineation and extraction of drainage network from elevation data - using for instance the D8 method (eight flow directions) introduced by O'Callaghan and Mark (1984) and further improved by Jenson and Domingue (1988), or the D∞ method (an infinite number of possible flow directions) proposed by Tarboton (1997).
- Estimation of infiltration parameters from soil maps and associated databases of soil properties (Rawls et al., 1983), estimation of evapotranspiration parameters and hydraulic roughness coefficients from land use/land cover maps.
- Spatial subdivision of a watershed into hydrologically homogenous subunits (Fortin et al., 2001; Schultz, 1997).

The potential for the use of earth observation data in hydrologic research and water resources management has long been recognized, with the first applications of satellite data in hydrologic modeling dating back to the mid-1970s (Koster et al., 1999; Schultz, 1988). The benefits of using remote sensing technology in hydrologic sciences can be summarized as follows (Schultz, 1988):

- Produces areal measurements instead of point measurements.
- All information is collected and stored at one place.
- Offers relatively high resolution in space and/or time.
- Data acquisition instruments do not interfere with the processes being observed.
- Data can be acquired from remote regions where in-situ measurements are difficult to obtain.
- Once the remote sensing networks are installed, the data measurements can be quite inexpensive.

Several papers and books have discussed the perspectives of the applications of remote sensing data in hydrology and hydrologic modeling. Comprehensive reviews can be found in Engman (1995), Kite and Pietroniro (1996), Schultz (1988), Schultz and Engman (2000), Shih (1996) and Stewart and Finch (1993).

Although satellite data can provide large amount of spatial and temporal information, their extensive use in hydrologic modeling has been restricted because of the following reasons (Biftu and Gan, 2001; Koster et al., 1999):

- Remote sensing does not generally provide information that is directly hydrologically relevant. Remotely sensed data in the form of emitted and reflected radiances need to be processed and interpreted into information useful in hydrology. However, there is a lack of universally applicable operational methods for deriving hydrologic variables from satellite data.
- Remote sensing data represent the averages over pixels and thus remove much of the point detail to which hydrologists are used.
- Current remote sensing observations are seldom optimized to produce the temporal resolution required to capture certain changes in hydrologic processes.
- Only few models can utilize remotely sensed data at different resolutions from different satellite platforms.
- Users do not have sufficient technical education and training to use the satellite data comfortably.

Nevertheless, remote sensing is beginning to prove its effectiveness in supplying hydrologically useful information. Optical and radar data are used in the following areas (Boegh et al., 2004; Engman, 1995; Singh, 1995): (1) to make an inventory of water bodies like lakes, rivers, flooded areas, (2) to determine watershed geometry and drainage network, (3) to identify the areas of snow cover, (4) to estimate the area and intensity of precipitation, (5) measurements of the reflected solar radiation form the basis for estimating albedoes, (6) vegetation indices calculated from remote sensing data are applied to assess the bio-physical parameters such as the leaf area index or canopy resistance required for the modeling of evapotranspiration, (7) data from thermal sensors offer information about the surface temperature for improving the simulation of energy balance components, and (8) microwave sensors measure the dielectric properties from which information about the moisture content of surface soil or snow can be derived.

Satellite data can be directly assimilated in hydrologic modeling with the purpose of initializing, driving, updating or recalibrating the model, or can also be used to compare and evaluate model performance (Boegh et al., 2004). Studies where the earth observation data were used in distributed hydrologic modeling both as an input to the model and as a validation of the model simulations are reported by Sandholt et al. (2003) and Biftu and Gan (2001).

Despite the fact that the early optimism and expectations for assets of remote sensing technologies have not yet found the same intensity in practical applications, the following words of Schultz (1988) remain true:

> "The advent of remote sensing and space technology has added a new dimension to hydrology, offering opportunities which are not only very useful and progressive, but to the pleasure of the hydrologists involved also most fascinating and rewarding."

2.7. Land use change and forest hydrology

2.7.1. Effects of land use change on hydrologic processes

The changes in land cover/land use may affect the hydrologic regime of various river basins on a local, regional, or global scale. Human activities like urbanization, agriculture practices, and logging influence the generation of runoff in watersheds. Man-made modifications of river systems and river engineering alter discharge processes in river networks.

Globally, the largest change, both in terms of area affected and in terms of hydrologic consequences, is caused by afforestation (also termed reforestation in the literature) and deforestation (Calder, 1993). Calder (1993) summarizes the potential impacts of afforestation (with deforestation having an opposite effect) on major hydrologic processes (*Table 2-3.*).

Table 2-3. *Major hydrologic effects of land-use change (After Calder, 1993).*

Land-use change	Component affected	Principal hydrologic process involved	Geographic scale and likely magnitude of effect
Afforestation (deforestation has converse effect except where disturbance caused by forest clearance may be of overriding importance)	Annual flow	Increased interception in wet periods Increased transpiration in dry periods through increased water availability to deep root systems	Basin scale; magnitude proportional to forest cover, world average is 34 mm year^{-1} reduction for 10% increase in forest cover
	Seasonal flow	Increased interception and increased dry period transpiration will increase soil moisture deficits and reduce dry season flow	Basin scale; can be of sufficient magnitude to stop dry season flows
		Drainage activities associated with planning may increase dry season flows through initial dewatering and also through long-term effects of the drainage system	Basin scale; drainage activities will increase dry season flows
		Cloud water (mist or fog) deposition will augment dry season flows	High-altitude basins only; increased cloud water deposition may have a significant effect on dry season flows
	Floods	Interception reduces floods by removing a proportion of the storm rainfall and by allowing buildup of soil moisture storage	Basin scale; effect is generally small but greatest for small storm events
		Management activities: cultivation, drainage, road construction, all increase floods	Basin scale; increased floods for all sizes of storm events

Different components of water balance may be affected by forest canopy removal, canopy regrowth, and forest road construction. Timber harvesting greatly decreases evaporation from the canopy, transpiration, cloud water interception, and the canopy's capacity to store water (Jones, 2000; Pike and Scherer, 2003). Reduced canopy evaporation and canopy storage lead to increase in throughfall and subsequently more water can be delivered to the soil. Decrease in transpiration demands allows the increase in soil moisture storage. The combined evapotranspiration effect generally causes an increase in runoff. In the Pacific Northwest, evapotranspiration is important for controlling the soil moisture especially during fall and spring when moisture and temperature are optimal for transpiration by canopies of coniferous forests (Jones, 2000). In the coastal, fog-affected forests of the Pacific Northwest region, logging can reduce cloud water interception leading to decreased throughfall and hence the soil moisture storage and runoff (Jones, 2000; Pike and Scherer, 2003). The evapotranspiration and cloud water interception effects act in an opposite way upon runoff with the possibility of offsetting one another. In winter the removal of forest canopy may reduce canopy evaporation and increased throughfall can result in greater snowpack accumulation in small openings (relative to forest). On the other hand, in large openings, where the snow is more exposed to winds and sublimation, less snow is usually retained (Jones, 2000; Pike and Scherer, 2003). The snowpack melting is usually faster in openings than in forested areas leading to increased peak discharges after canopy removal (Pike and Scherer, 2003). Snowpack dynamics effect can be large and varies by season, elevation, and forest canopy structure (Jones, 2000).

Forest road construction is often associated with a relatively permanent canopy removal influencing the amount of local canopy water storage, snowpack accumulation and melting, or infiltration to the soil. Furthermore, roads may alter water routing to streams and speed up the water delivery into the stream network, thus potentially increasing the magnitude of peak discharges but not the streamflow volume (Jones, 2000). The effect of road building upon water routing depends on the density and maintenance of road network, road configurations relative to water flow paths, hydrologic regime, and other local factors (Jones, 2000; Pike and Scherer, 2003).

Both researchers and managers have been long concerned about the effects of logging activities on the quantity and quality of water available from forested watersheds. Bosh and Hewlett (1982) reviewed 94 catchment experiments at different locations in the world dealing with evapotranspiration and water yield changes due mainly to deforestation and afforestation. From analysis of annual flow results they concluded that, in general, reduction in forest cover increases water yield. Coniferous and eucalypt cover types caused about 40 mm change in annual flow per 10 % change in cover with respect to grasslands. The equivalent response of deciduous hardwoods and bush per 10 % change in cover was found to be 25 mm and 10 mm change in water yield respectively. The results from experiments showed that maximum increases in annual water flow were observed during first five years after deforestation, while water yield gains diminished proportionally to the rate of the recovery of the vegetation. Bosh and Hewlett (1982) also conclude that "reductions in forest cover of less than 20 % … cannot be detected by measuring streamflow".

Jones (2000) studied the interactions among hydrologic processes, peak discharge responses and forest removal, regrowth, and roads in ten pairs of experimental basins in Oregon.

The author reported significant increases (31–116 %) in peak discharges during the first post-harvest decade. The events affected occurred mainly in the fall, when the soils were in moisture deficit, and were those of a small recurrence period. The increases tended to disappear after the regrowth of the forest canopy. The harvesting also modified the snowpack dynamics. Increases in snowmelt contributions to peak discharges during winter rain-on-snow events were found. The peak discharges of events with one year return period increased by 13-36 % after the construction of forest roads.

However, the study conducted by Bowling et al. (2000) in 23 catchments in western Washington demonstrated diverse trends in annual streamflow series after harvesting practices. The results of trend analysis showed that observed annual discharge records were influenced more by regional climate fluctuations than by changes in the land cover. Using paired catchment analysis, increasing trends in the minimum flows were observed after logging. Both positive and negative trends were detected in the annual maximum series and the absence of trends in the peak flow series was found.

Many researchers thus caution against deriving general conclusions and predictions of forestry treatment effects, because hydrologic response of a harvested watershed is greatly affected by the forest type, the logging method applied, the location of forest removal within a river basin, regional rainfall regime, individual storm events characteristics, impacts of natural processes such as climate change, by soil types and depths appearing in a watershed, or a basin topography (Alila and Beckers, 2001; Bosh and Hewlett, 1982; Jones, 2000).

2.7.2. Hydrologic modeling of land use changes

Different mathematical models have been developed to better describe characteristics and to simulate hydrologic behaviour of watersheds. However, not all are suitable for quantitative assessment of impacts of the past or assumed changes in the land surface management on the hydrologic system. Both Alila and Beckers (2001) and Bronstert et al. (2002) emphasize the need to use the process-oriented models, i.e. those that more accurately simulate relevant physical processes like rainfall, snowmelt, evapotranspiration, and runoff and factors such as road length, harvest level, elevation, or slope and aspect of the terrain. In the models, the vegetation properties assumed to be important for relevant hydrologic processes are usually characterized by parameters specific for various vegetation species. The simulation of land cover changes then involves an alteration of parameter values in particular areas within a watershed. Thus uncertainty in the parameterization of land covers, associated either with the problematic observation of certain parameters, the regionalisation of point measurements, or the spatial averaging of vegetation characteristics, and the (in)ability of two different land covers to provide a significantly different model response have a major influence on the uncertainty associated with model predictions of land cover change effects (Eckhardt et al., 2003).

One of the first studies dealing with the use of mathematical models for predicting the effects of land use modifications on runoff was presented by Onstad and Jamieson (1970). By changing the values of measurable parameters in a model, they simulated the changes in watershed response corresponding to different conservation practices. However, no real data were available for comparison with modeling outputs.

Similar approach was adopted by Bultot et al. (1990) where a conceptual hydrologic model was used to simulate the effects of assumed land use changes in a mid-sized catchment in Belgium. Again, because of the lack of data, no rigorous model validation was carried out.

Kuczera et al. (1993) applied two different lumped conceptual models to a small experimental catchment subjected to a 6-year strip thinning treatment and simulated monthly water yields before and after the forestry activities. Results from the split-sample test showed that only one model provided a good description of water yields for changed land use conditions. Thus a careful use of lumped conceptual models for predicting land use change impacts on a watershed runoff is suggested, because the model might fail due to limitations in the conceptualization of the hydrologic processes involved.

A more comprehensive and rigorous methodology for identifying and assessing long-term impacts of land use change on runoff in semi-arid medium-sized watersheds in Zimbabwe was presented by Lørup et al. (1998). A lumped conceptual hydrologic model was calibrated on flow data from the first part of the reference period and validated on data from the other part of the reference period. The model was generally able to simulate the observed discharges very well. After the validation procedure the model was used to simulate runoff for the test period thus providing the streamflow record, which would have occurred in the absence of land use changes. The model output was then compared with real observations for quantitative assessment of past land use changes.

3. DATA COLLECTION AND PRELIMINARY ANALYSIS

3.1. Study area description

The Tsitika River Watershed is located on the northeastern coast of Vancouver Island (*Figure 3-1.*). The main channel of the Tsitika River is 42 km long (TPC, 1978). The river flows in a northerly direction and drains into Johnstone Strait, approximately midway between Port McNeill and Sayward.

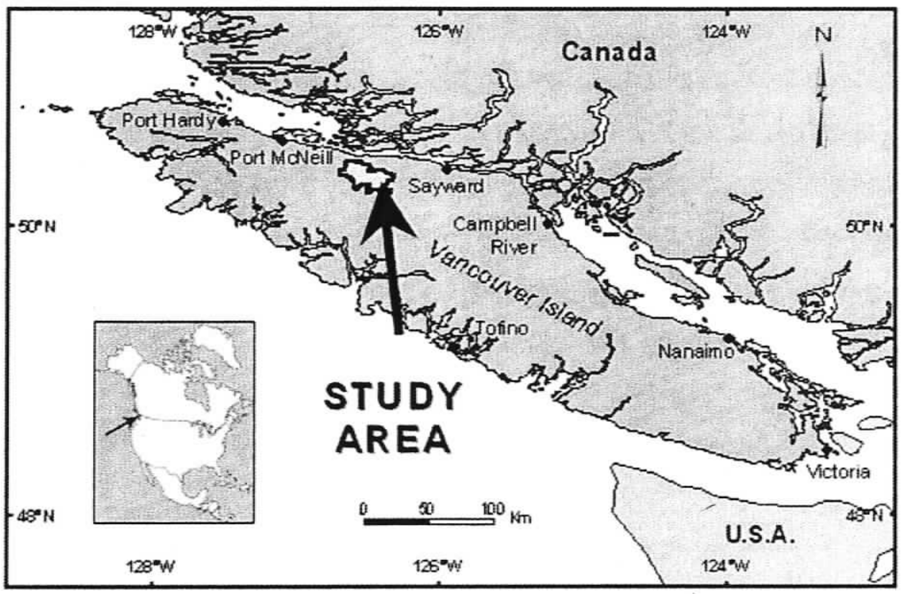


Figure 3-1. *Location of the study area on the northeastern coast of Vancouver Island.*

The Tsitika Watershed covers an area of about 395 km^2 and is extremely rugged, with elevations ranging from the sea level to more than 1750 m (TPC, 1978). The terrain characteristics are underlain by two main bedrock formations (Hudson, 2001; NISG, 1975). Steeper-sided valleys occurring in the northern two thirds of the watershed are formed by the Upper Triassic Karmutsen Volcanics that consist of submarine and subareal flood basalts. Jurassic-age Island Intrusives, represented mainly by diorite and granodiorite, appear in the southern part and give form to terrain with more gentle slopes and wider valleys (Guthrie, 1997; Hudson, 2001; NISG, 1975). The surficial materials within the watershed consist primarily of glacial till, colluvium, and alluvium among extensive areas of exposed bedrock (Hudson, 2001; TPC, 1978). Morainal deposits from the Pleistocene glaciation can be found at the middle and lower slopes in the whole watershed area (Hudson, 2001; NISG, 1975). Fluvial sediments occur in the middle and lower parts of the valleys of the Tsitika River and Catherine Creek (Guthrie, 1997; Hudson, 2001).

The climate of the area is influenced by the vicinity of the coast and by the local topography. The watershed has a moist, cool climate with moderate winter temperatures and generous rainfall and snowfall. Over two thirds of the annual precipitation fall from October to March (Hudson, 2001). The nearest long-term climatic station is at Alert Bay, located about 27 km northwest of the mouth of the Tsitika River. Mean daily temperature at this station is 8.5° C and mean annual precipitation is about 1600 mm (Guthrie, 1997). However, the vegetation in the lower Tsitika valley indicates that this area receives a higher precipitation input, probably between 1800 mm to 2550 mm (NISG, 1975). Higher elevation areas receive even more precipitation with much of it falling as snow during the winter period (TPC, 1978).

The Tsitika Watershed lies in the three Biogeoclimatic Zones - Coastal Western Hemlock Zone, Mountain Hemlock and Alpine Tundra (NISG, 1975; TPC, 1978). The Coastal Western Hemlock Zone can be found at elevations below 800-900 m. This area has mainly podzolic soils and is occupied by communities of coastal western hemlock, balsam fir, and western red cedar. The Mountain Hemlock Zone spreads above the Coastal Western Hemlock Zone and is characterized by podzolic soils, communities of mountain hemlock, balsam fir and yellow cedar, and winter mean temperatures commonly being below the freezing point (NISG, 1975; TPC, 1978). In this zone almost 30% of precipitation may occur in the form of snowfall (Guthrie, 1997). The Alpine Tundra starts above 1200 m on gentle slopes or under wind-protected conditions, and above 1500 m on steep slopes. Dominant vegetation in this zone is the community of alpine heath (NISG, 1975; TPC, 1978). The growing season is short. In this low temperature regime, approximately 70% of precipitation can fall as snow (Guthrie, 1997). The major tree species in terms of occurrence in the watershed are western hemlock, Pacific silver fir, mountain hemlock, western red cedar, yellow cedar, Sitka spruce, lodgepole pine, red alder, Douglas fir, and western white pine (NISG, 1975).

Significant features of the Tsitika Watershed are the wetland type areas. They occur as tidal marshes at the mouth of the Tsitika River, sedge meadows in low and medium elevations, subalpine wet meadows, or Sphagnum and transitional bogs (NISG, 1975).

The Tsitika River Watershed is a representative ecosystem of interior mountain regions on the east coast of Vancouver Island. Many populations endemic to the Island, like the Roosevelt elk or the Vancouver Island wolf, occur there. The Tsitika River and its tributaries support one of the most diverse fishery resources on Vancouver Island. The estuary at the mouth of the Tsitika River is the habitat for killer whales (NISG, 1975). Owing to the values of its natural environment, wide potential for scientific research, recreation, and also for commercial timber harvesting, the watershed has become an area of conflicting interests for conservation groups, academics, people in government services, and those involved in the industry. Until 1975 the Tsitika River Watershed was the last major unlogged watershed on the east coast of Vancouver Island. However, in 1978 the provincial Environment and Land Use Committee approved the Tsitika Watershed Integrated Resource Plan for applying integrated resource management principles and ensuring a sustained harvest of economically viable timber over a period of 80 years (BCMF, 1990). The area and timing of harvesting have been scheduled according to this plan. Nine percent of the watershed has been harvested by December 31st, 1989 (BCMF, 1990).

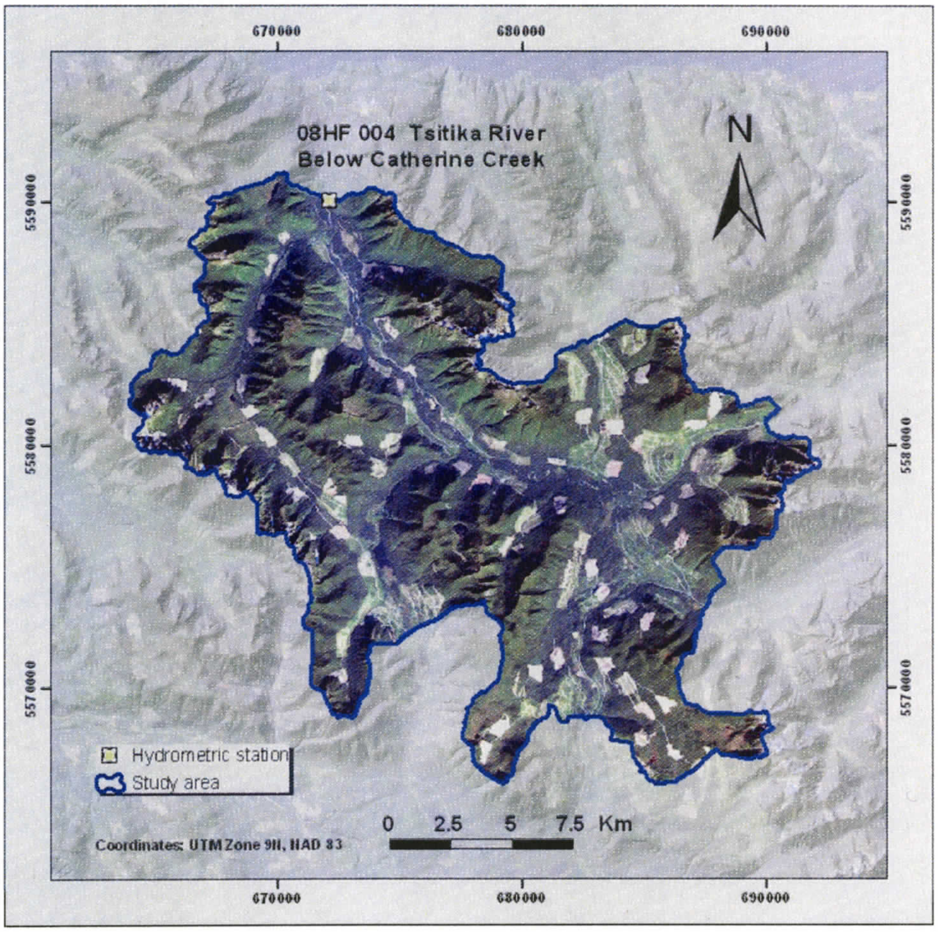


Figure 3-2. *Study area – the watershed delineated upstream of the hydrometric station Tsitika River Below Catherine Creek.*

The environment of the Tsitika River Watershed has changed from its natural conditions to that affected by forest cutting during the last three decades. This makes it a unique region to study the impact of harvesting practices on hydrologic cycle. The hydrometric station 08HF004 with the record of streamflow data used in the study is situated at the Tsitika River below Catherine Creek (Canada, 2000). The study area is a 372 km^2 watershed delineated upstream of this location (*Figure 3-2.*).

3.2. Input data collection, preprocessing and preliminary analysis

3.2.1. River discharge

The river discharge data were obtained from Environment Canada. The records of mean daily discharge of the Tsitika River were extracted from the National Water Data Archive database provided on the HYDAT CD-ROM. The series consists of 8766 measurements taken daily from January 1, 1977 to December 31, 2000 at the hydrometric station 08HF004 Tsitika River Below Catherine Creek, latitude: 50°26'13", longitude: 126°34'27", elevation: 360 m a.s.l. (*Figure 3-2.*).

Figure 3-3. shows mean daily and mean monthly discharge time series for the period of years 1977-2000. A subset of years 1987-1989 has been enlarged. Visible is the seasonal periodicity with higher discharges occurring during the winter season and low discharges prevailing during the summer months.

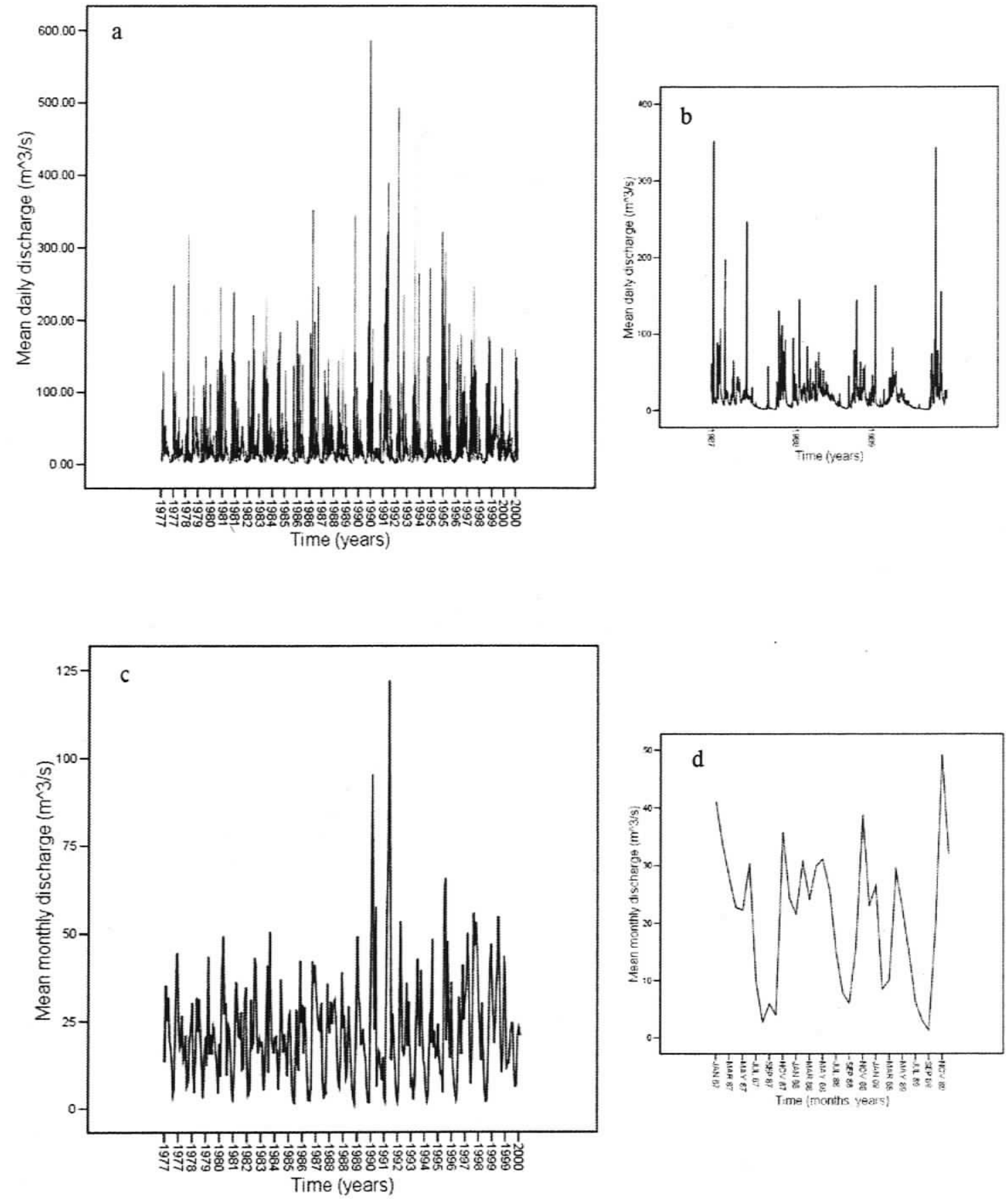


Figure 3-3. *(a) Mean daily discharge time series for years 1977-2000. (b) Detail of the daily series for years 1987-1989. (c) Mean monthly discharge time series for years 1977-2000. (d) Detail of the monthly series for years 1987-1989.*

Table 3-1. provides the main statistics of the mean daily river discharge series and mean monthly river discharge series for the period of years 1977-2000.

Table 3-1. *Statistics of the mean daily and mean monthly river discharge series.*

	Mean	Standard Deviation	Median	Minimum	Maximum	Skewness	Kurtosis
Daily series	22.03 m^3/s	31.15 m^3/s	13.45 m^3/s	0.77 m^3/s	586.00 m^3/s	5.70	57.08
Monthly series	22.07 m^3/s	15.87 m^3/s	18.81 m^3/s	1.31 m^3/s	122.01 m^3/s	1.75	6.35

Boxplots of daily and monthly discharge data (*Figure 3-4.*) offer a visual summary of essential series characteristics such as the median, interquartile range, skewness and the presence of outliers. The taller top box halves and whiskers indicate a right-skewed distribution of both data sets. The occurrence of outside values (values between 1.5 and 3 box lengths from the upper or lower edge of the box; marked by circles in the plot) and far outside values (values of more than 3 box lengths from the upper or lower edge of the box; marked by asterisk in the plot) also indicates heavy-tailed distributions, especially in the case of daily discharge data.

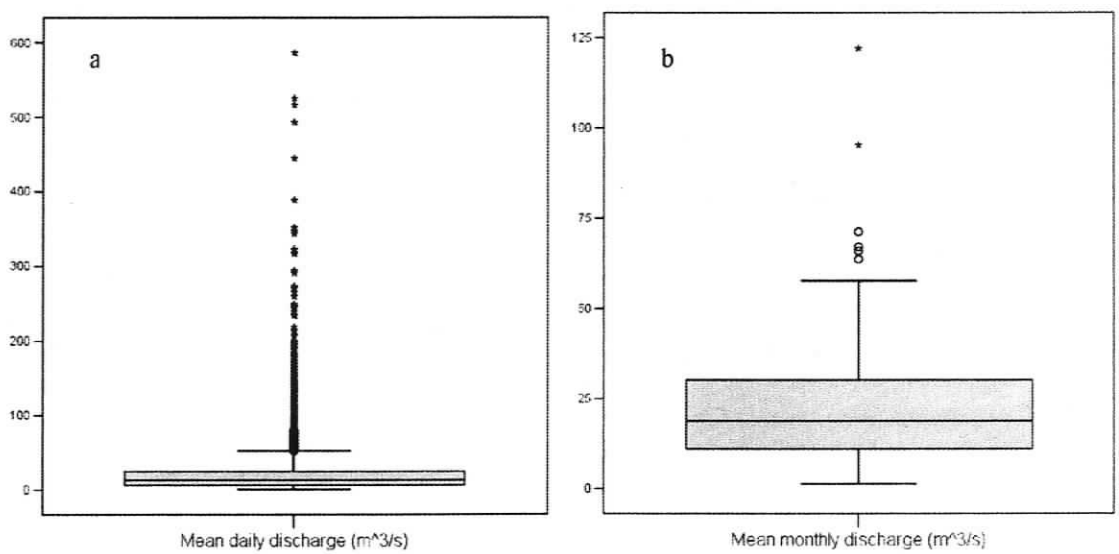


Figure 3-4. *Boxplots of (a) mean daily and (b) mean monthly river discharge data depicting the median, interquartile range, skewness of the series and the presence of outliers (note: the scale is different for the two plots).*

Mean daily and monthly river discharge data were subjected to spectral and time series analysis to show the relative magnitude of components such as trends, periodicities, autoregressions and random residuals (*Table 3-2.*). Due to the constraints in the computer program daily data were analyzed only for a period of 1985-2000. Monthly series were analyzed for the whole period of available data, i.e. covering years 1977-2000. In the time series analysis performed, the hypothesis is that a linear additive decomposition model (Kite, 1989; Kite, 1991) can represent a time series X_t as follows:

$$X_t = P_t + T_t + R_t$$

where P_t is a periodic or cyclic component, T_t a trend component, and R_t a stochastic component. Spectral analysis is done after each step to display different components of the series and to examine the results of the removal of these components. A relative importance of these components is then expressed as a percentage of the total variance of time series. A trend component is detected and removed by using a polynomial regression, a periodic component is analyzed and removed using Shuster's periodogram, and a stochastic component is assumed to be represented by the autoregressive (Markov) model. Kite (1991) provides further details about the model including the equations used for calculations.

Table 3-2*. Time series components expressed as a percentage of total variance of river discharge data.*

	Period analyzed	Linear trend	Periodicities	Auto-regression	Resid.	First order linear trend	
						Intercept	Slope
Daily series	1985 - 2000	0.0	56.6	28.2	15.3	-647.70	0.34
Monthly series	1977 - 2000	1.3	52.2	5.0	41.5	-487.10	0.26

The linear trend component accounts for only 1.3 % of variance in mean monthly river discharge series. The most significant component of the series is periodic, explaining 52 % of the variance. Five percent are due to the autoregression and over 40 % of the variance remains as residual unexplained by this model. The spectral analysis of the mean monthly river discharge data (*Figure 3-5.*) shows an initial spectrum with significant components at a frequency of 0.083 cycles per month (one year period) and at a frequency of 0.167 cycles per month (six months period), which confirms strong seasonal behaviour of river discharge. The spectral plot after the removal of linear trend displays a corresponding decrease in significance in the low frequency spectra. After the periodicities, and hence annual and half-year cycles, were removed, the spectral plot shows the significance of 24, 18 and 14 months periods (0.041, 0.056, 0.069 cycles per month respectively). No significant variance remained unexplained after the final step of the autoregressive component removal.

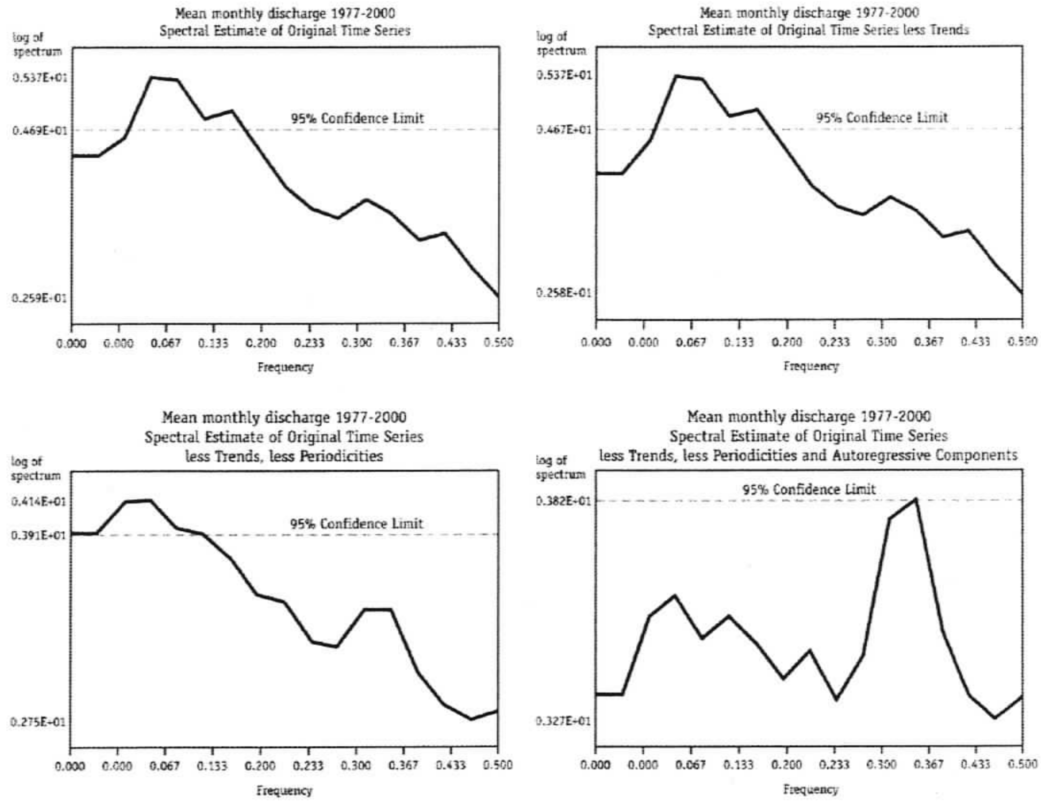


Figure 3-5. *The results of spectral analysis of mean monthly river discharge data for years 1977-2000. The figures show the spectral estimates and significance of various time series components for (a) an original time series, (b) a series with a linear trend removed, (c) a series with trend and periodic components removed, and (d) a series with trend, periodic and autoregressive components removed. The frequency corresponds to a number of cycles per month. Therefore the significance of the frequency of 'x' cycles per month indicates the importance of an 'x'-month period for explaining the variance of the series.*

The flood frequency curve based on the maximum daily discharge for years 1977-2000 was drawn and inspected to find out whether there has been any evident change in annual peak discharges. *Figure 3-6.* displays the flood frequency curve for the Tsitika River and almost linear behaviour of annual peak discharge values.

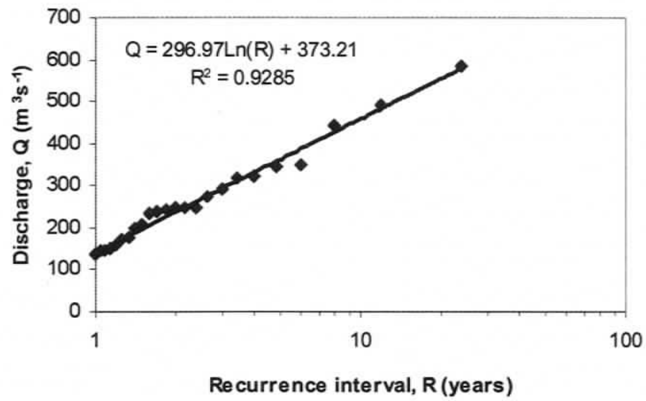


Figure 3-6. *Flood frequency curve for the Tsitika River Below Catherine Creek hydrometric station shows almost linear behaviour of annual peak discharge values. Based on maximum daily discharges for years 1977-2000.*

3.2.2. Climate

Daily series of precipitation and average daily temperature were available from Environment Canada. Unfortunately, no meteorological stations providing long-term climate data are located within, or in the vicinity of, the Tsitika River Watershed. The series of precipitation and temperature from several climate stations in the northeastern Vancouver Island were analyzed and the records from the climate station 1026270 Port Hardy A were selected for the use in the study. The nearest long-term climate station is at Alert Bay located about 27 km northwest of the mouth of Tsitika. However, the series of precipitation and temperature were fairly incomplete for certain days and the station was operational only until February 1994. Thus the Port Hardy A climate station, latitude: 50°41', longitude: 127°22', elevation: 22 m a.s.l., was chosen to provide the meteorological data for the period of January 1, 1977 to December 31, 2000. Missing data in daily precipitation (7 records) and temperature (13 records) series were interpolated by simple regression.

Figure 3-7. shows the subset of mean daily and mean monthly precipitation and temperature series for the period of years 1987-1989. It can be seen that precipitation falls mainly during the winter months and less events occur during the summer season. Temperature variation exhibits very regular annual cycle.

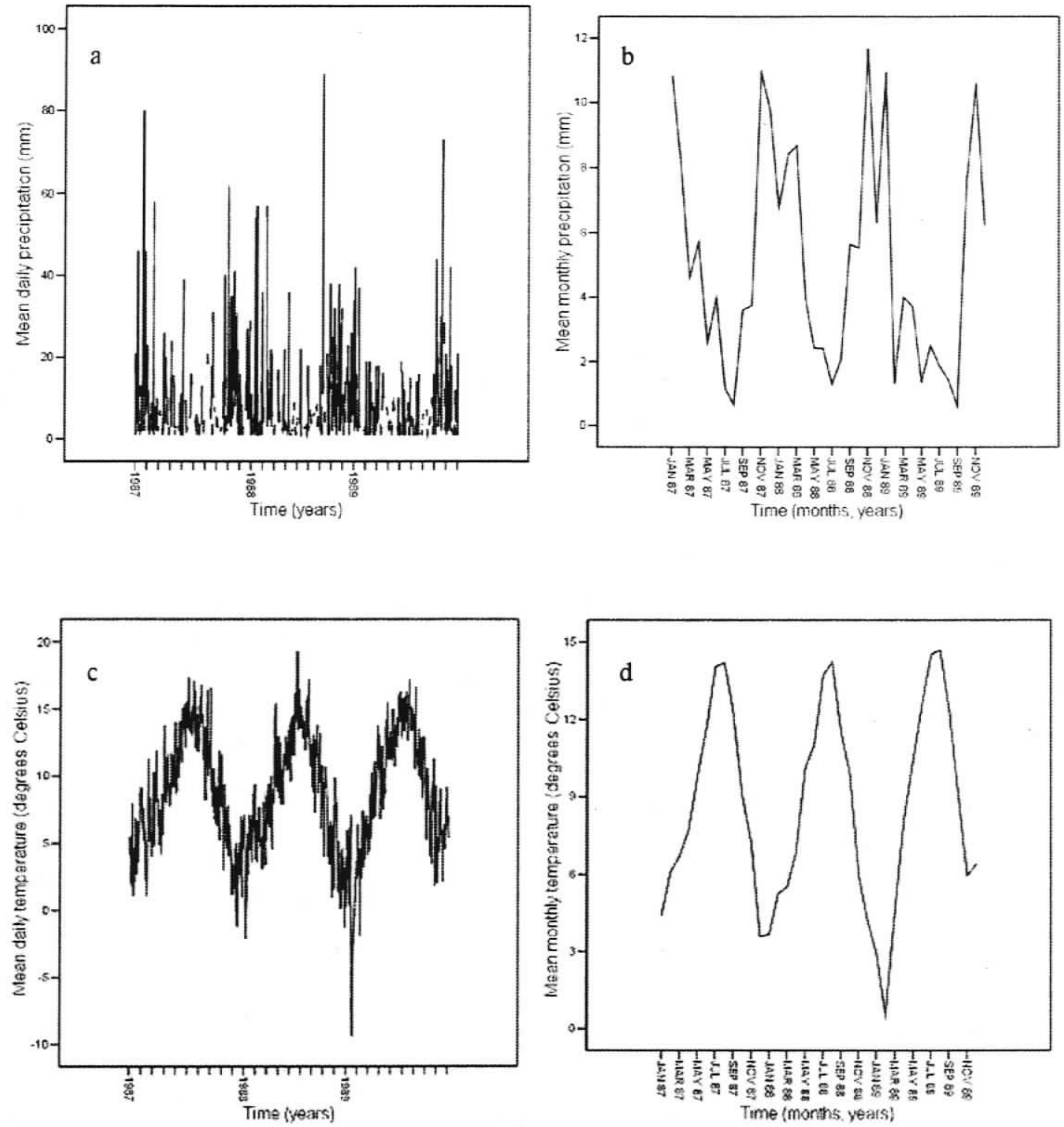


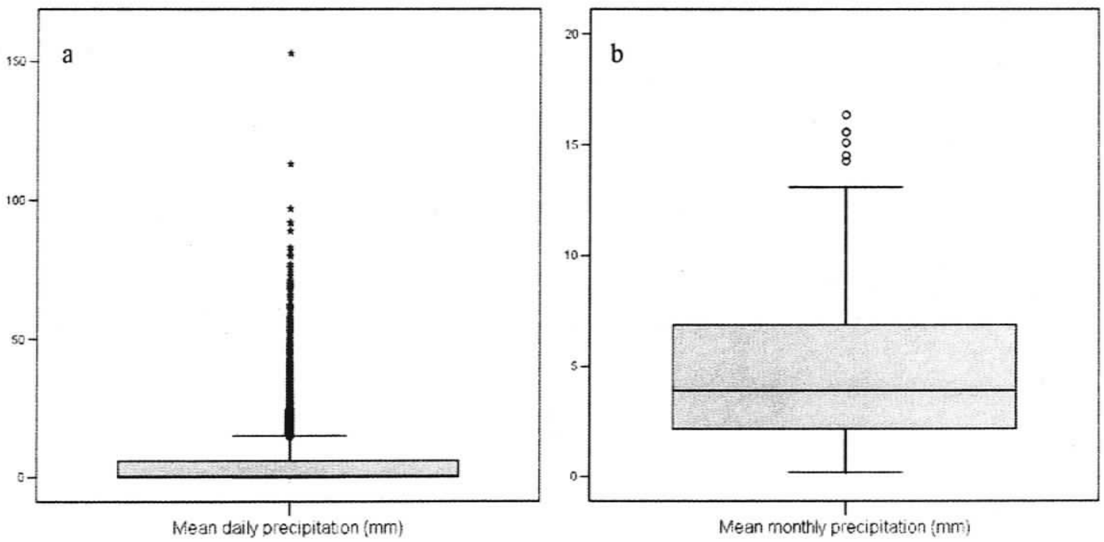
Figure 3-7. *The subset of (a) mean daily precipitation series, (b) mean monthly precipitation series, (c) mean daily temperature series, and (d) mean monthly temperature series for a period of 1987-1989. The figures illustrate a seasonal behaviour of precipitation (wet winter season and drier summer months) and a regular fluctuation of annual temperature cycle.*

The main statistics of the precipitation and temperature series for the period of years 1977-2000 are provided in *Table 3-3.* The statistics were derived from daily data and characterize the entire period as a whole in a generalized manner.

Table 3-3. *Statistics of the mean daily and mean monthly precipitation and temperature series.*

	Mean	Standard Deviation	Median	Minimum	Maximum	Skewness	Kurtosis
Mean daily precipitation series	4.92 mm	9.54 mm	0.40 mm	0 mm	153 mm	3.80	57.08
Mean monthly precipitation series	4.93 mm	3.52 mm	3.92 mm	0 mm	16 mm	0.97	0.31
Mean daily temperature series	8.49°	4.49°	8.50°	-9.60°	22.10°	-0.23	-0.46
Mean monthly temperature series	8.47°	3.99°	8.04°	-0.13°	15.60°	0.05	-1.18

Both mean daily and mean monthly precipitation data exhibit right-skewed distribution (*Figure 3-8.*). Daily series are heavily right-tailed with numerous outside and far outside values. The distribution of mean daily and mean monthly temperature is close to normal with few outliers occurring in the daily series.



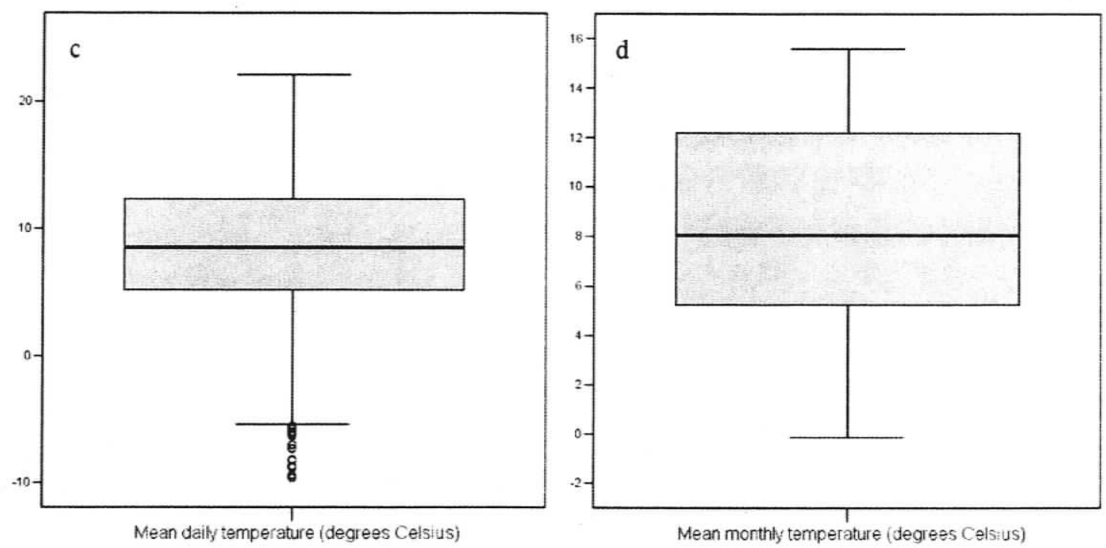


Figure 3-8. *Boxplots of (a) mean daily precipitation, (b) mean monthly precipitation, (c) mean daily temperature, and (d) mean monthly temperature data depicting the median, interquartile range, skewness of the series and the presence of outliers (note: the scale is different for daily and monthly plots).*

The results of spectral analysis in *Table 3-4.* show that the most significant component of both precipitation and temperature data is the periodic component. Over 60 % of the total variance in mean monthly precipitation series is due by annual cycle (frequency of 0.083 cycles per month). Thirty five percent of the variance remains as random residual unexplained by the linear additive decomposition model. As can be seen from the fairly regular mean monthly temperature time series plot (*Figure 3-7.*), the variation in temperature series is almost entirely explained by the annual cycle. Frequencies of 0.069, 0.083 and 0.097 cycles per month, corresponding to periods of 14, 12 and 10 months respectively, appeared to be significant in the temperature spectral analysis plot.

Table 3-4. *Time series components as a percentage of total variance of precipitation and temperature data.*

	Period analyzed	Linear trend	Periodicities	Auto-regression	Resid.	First order linear trend	
						Intercept	Slope
Daily precipitation series	1985 - 2000	0.0	42.7	4.9	52.4	-63.82	0.04
Monthly precipitation series	1977 - 2000	0.0	64.4	0.0	35.4	-80.26	0.04

Daily temperature series	1985 - 2000	0.0	79.5	8.3	12.2	-45.02	0.03
Monthly temperature series	1977 - 2000	0.0	94.0	0.0	6.0	-49.91	0.03

Correlation and regression analyses were run on precipitation and temperature series to investigate a relationship among climate data recorded at several stations in the northern part of Vancouver Island (*Table 3-5.*). Some of the stations recorded data only during the winter season, e.g. Mt. Washington Resort, the others were operational only during certain years within a 1977-2000 period. Nonparametric correlations based on the Spearman's Rho coefficient appeared to be significant at the 0.01 level for all pairs of stations and for both the daily precipitation and the daily temperature series (*Table 3-6.* and *Table 3-7.*, respectively). A very high correlation was found between the Alert Bay station, a station closest to the Tsitika Watershed, and the Port Hardy A station. This suggests that weather conditions at the two stations are similar, and thus the Port Hardy A records might be used for modeling purposes instead of using Alert Bay data.

Table 3-5. *Climate stations included in statistical analysis.*

Climate Station	Latitude	Longitude	Elevation (m a.s.l.)	Precipitation Records	Temperature Records
Alert Bay	50° 35'	126° 56'	59	6232	6235
Sayward	50° 22'	126° 00'	0	4497	1886
Campbell River A	49° 57'	125° 16'	106	8702	8716
Port Hardy A	50° 41'	127° 22'	22	8759	8753
Mt. Washington Resort	49° 45'	125° 17'	1197	2684	3015
Mt. Washington Upper	49° 45'	125° 17'	1450	994	900
Upper Campbell Lake	49° 54'	125° 38'	549	6257	6381

Table 3-6. *Nonparametric correlations (Spearman's rho) of mean daily precipitation (** correlation is significant at the 0.01 level, 2-tailed; lower triangle – number of cases).*

	Alert Bay	Sayward	Campbell River A	Port Hardy A	Mt. Washington Resort	Mt. Washington Upper	Upper Campbell Lake
Alert Bay		0.657 **	0.622 **	0.901 **	0.497 **	0.482 **	0.635 **
Sayward	2016		0.764 **	0.672 **	0.736 **	0.686 **	0.780 **
Campbell River A	6193	4434		0.635 **	0.816 **	0.751 **	0.826 **

Port Hardy A	6231	4491	8695		0.517 **	0.471 **	0.651 **
Mt. Washington Resort	1851	1141	2679	2679		0.870 **	0.810 **
Mt. Washington Upper	403	624	990	991	944		0.766 **
Upper Campbell Lake	4852	2132	6252	6252	2146	701	

Table 3-7. *Nonparametric correlations (Spearman's rho) of mean daily temperature (** correlation is significant at the 0.01 level, 2-tailed; lower triangle – number of cases).*

	Alert Bay	**Sayward**	**Campbell River A**	**Port Hardy A**	**Mt. Washington Resort**	**Mt. Washington Upper**	**Upper Campbell Lake**
Alert Bay		0.957 **	0.946 **	0.979 **	0.805 **	0.758 **	0.940 **
Sayward	1865		0.965 **	0.942 **	0.843 **	-	0.949 **
Campbell River A	6197	1839		0.941 **	0.741 **	0.636 **	0.962 **
Port Hardy A	6234	1885	8703		0.761 **	0.683 **	0.918 **
Mt. Washington Resort	2157	456	3012	3005		0.929 **	0.817 **
Mt. Washington Upper	246	0	898	893	852		0.747 **
Upper Campbell Lake	4947	608	6378	6372	2485	634	

Latitude, longitude, elevation data, mean monthly precipitation and mean monthly temperature data for meteorological stations were subjected to regression analysis. The purpose was to find out how the climate data are affected by the spatial location of the stations and whether a regression model based on the variables characterizing geographical location can be built to adjust the precipitation and temperature series for the Tsitika River Watershed.

As a first step, regression equations were obtained with latitude, longitude and elevation included in the models as explanatory variables. However, the values of the multicollinearity statistics – namely the tolerance and the variance inflation factor – indicated high correlation among variables, especially in the case of latitude and longitude. Multicollinearity in explanatory variables was detected for both precipitation and temperature regression models. As a second step, regression models for mean monthly precipitation and temperature were derived by the stepwise regression method. Individual variables were entered and/or removed with respect to a specified statistical criterion (*Table 3-8.* and *Table 3-9.*). The results show that only one variable was selected as a contributing factor in each one of the models, thus eliminating the multicollinearity problem. The representation of independent variables in regression models derived was rather fair. Although the regression coefficients for precipitation models were high, the plots of mean monthly precipitation levels for stations considered suggest that neither latitude, nor longitude or elevation had a single dominant influence on precipitation (*Figure 3-9.*). Precipitation seems to be more affected by local microclimate conditions, extent and duration of particular meteorological events in specific months. Mean monthly temperature shows a much more regular pattern with respect to latitude, longitude and elevation (*Table 3-9.*). With an exception of Mt. Washington Upper station, temperature increases with an increasing latitude (which is probably caused by a closer distance to the ocean waters), and clearly decreases with an ascending elevation of a climate station for most of the cases (*Figure 3-10.*).

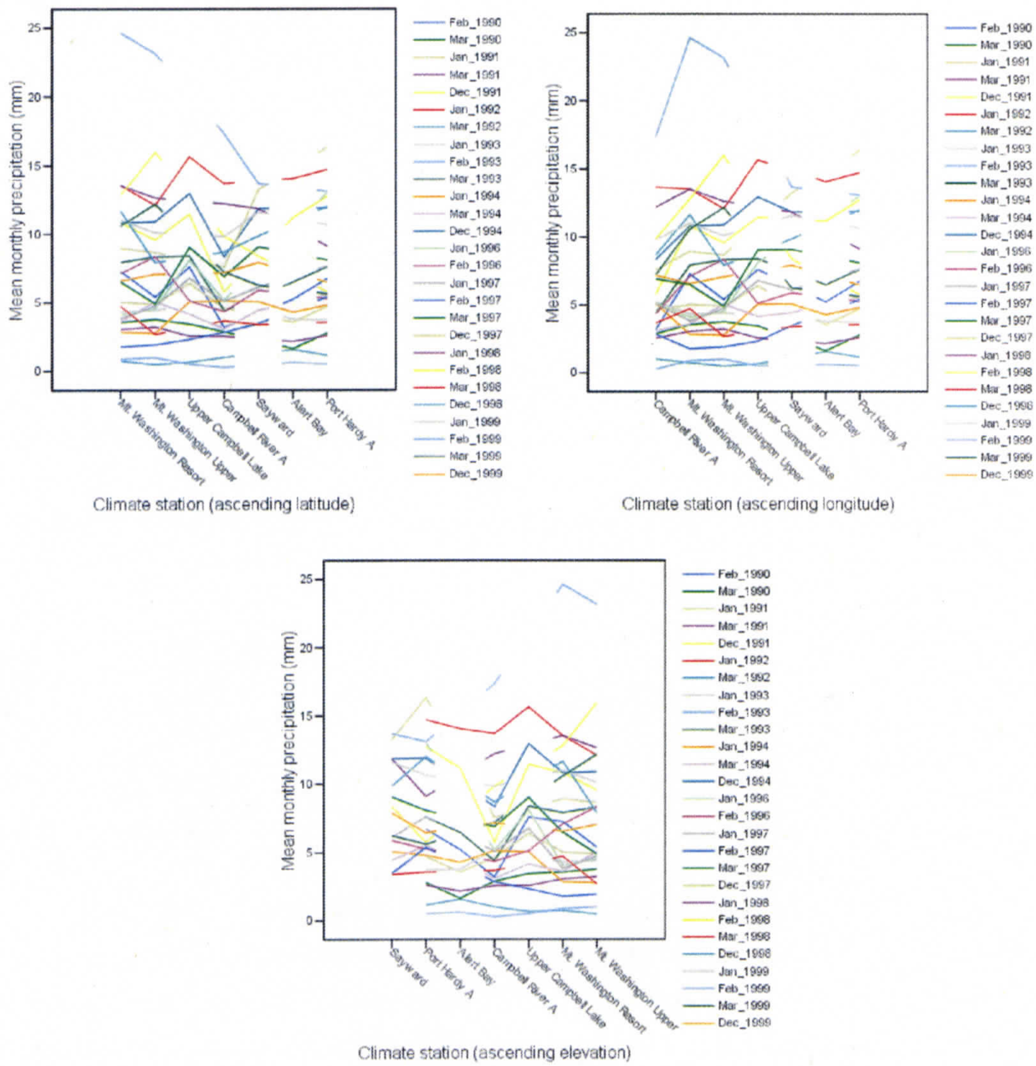


Figure 3-9. *Mean monthly precipitation at seven climate stations for the months used in the regression analysis. The figures graphically illustrate the relationship between the amount of observed precipitation and the spatial location of climate stations. The stations are sorted on x-axis by ascending latitude, longitude and elevation, respectively. Note: the x-axis is not proportional to the particular scale.*

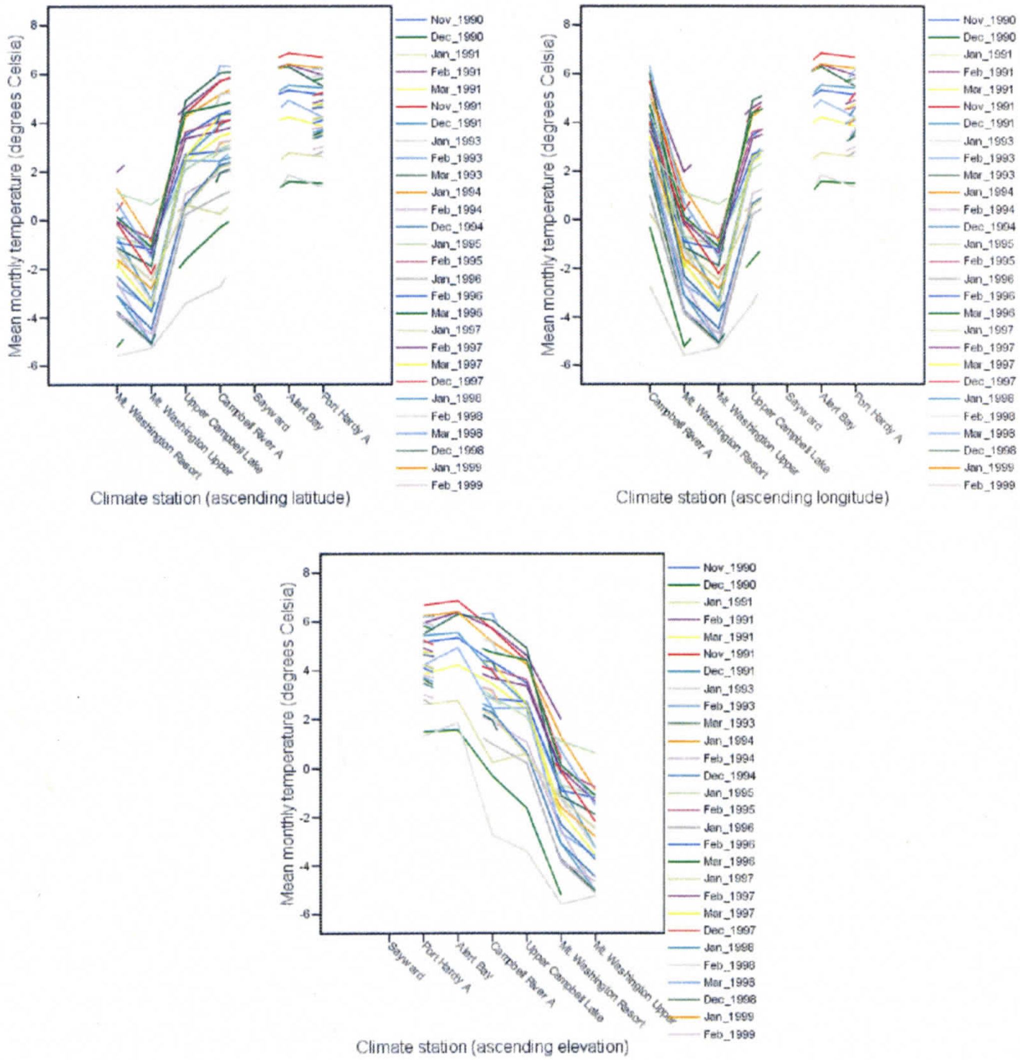


Figure 3-10. *Mean monthly temperature at seven climate stations for the months used in the regression analysis. The figures graphically illustrate the relationship between the values of observed temperature and the spatial location of climate stations. The stations are sorted on x-axis by ascending latitude, longitude and elevation, respectively. Note: the x-axis is not proportional to the particular scale.*

Table 3-8. *Stepwise regression analysis of mean monthly precipitation (criteria to enter/remove an independent variable: probability of F to enter variable ≤ 0.05, probability of F to remove variable ≥ 0.10.*

Month -Year	Cases	Variables Entered			R	R Sq.	ANOVA	Constant			Latitude				Longitude				Elevation			
		Lat.	Long.	Elev.			Sign.	Unst. β	St. Error	Sign.	Unst. β	St. Error	St. β	Sign.	Unst. β	St. Error	St. β	Sign.	Unst β	St. Error	St β	Sign.
Mar-90	6	*			0.811	0.658	0.050	83.79	29.088	0.045	-1.611	0.580	-0.811	0.050								
Mar-91	6			*	0.902	0.813	0.014	2.43	0.101	0									0.001	0	0.902	0.014
Mar-92	6	*			0.850	0.722	0.032	-41.889	13.289	0.034	0.854	0.265	0.850	0.032								
Jan-94	7			*	0.885	0.783	0.008	5.033	0.265	0									-0.002	0	-0.885	0.008
Jan-96	5		*		0.963	0.927	0.009	-517.554	85.134	0.009					4.164	0.676	0.963	0.009				
Feb-96	6			*	0.866	0.750	0.026	5	0.445	0									0.002	0.001	0.866	0.026
Jan-97	6		*		0.821	0.674	0.0045	-162.27	583473	0.050					1.334	0.464	0.821	0.045				
Feb-97	6	*			0.984	0.968	0	-165.706	15.39	0	3.364	0.307	0.984	0								
Dec-97	5		*		0.950	0.903	0.013	-505.998	97.857	0.014					4.104	0.777	0.95	0.013				
Jan-98	5		*		0.955	0.911	0.012	245.623	42.103	0.010					-1.856	0.334	-0.955	0.012				
Feb-98	5			*	0.926	0.858	0.024	7.638	1.035	0.005									0.006	0.001	0.926	0.024
Feb-99	5			*	0.941	0.885	0.017	14.364	1.251	0.001									0.008	0.002	0.941	0.017
Mar-99	5			*	0.985	0.970	0.002	6.107	0.343	0									0.005	0	0.985	0.002

Table 3-9. *Stepwise regression analysis of mean monthly temperature (criteria to enter/remove an independent variable: probability of F to enter variable ≤ 0.05, probability of F to remove variable ≥ 0.10.*

Month -Year	Cases	Variables Entered			R	R Sq.	ANOVA Sign.	Constant			Latitude				Longitude				Elevation			
		Lat.	Long.	Elev.				Unst. β	St. Error	Sign.	Unst. β	St. Error	St. β	Sign.	Unst. β	St. Error	St. β	Sign.	Unst β	St. Error	St β	Sign.
Nov-90	5			*	0.982	0.964	0.003	5.407	0.298	0									-0.004	0	-0.982	0.003
Dec-90	5			*	0.976	0.952	0.004	1.373	0.424	0.048									-0.005	0.001	-0.976	0.004
Jan-91	5	*			0.929	0.863	0.022	-224.346	51.817	0.023	4.492	1.034	0.929	0.022								
Feb-91	5			*	0.989	0.978	0.001	6.336	0.182	0									-0.003	0	-0.989	0.001
Mar-91	5			*	0.980	0.961	0.003	4.381	0.347	0.001									-0.004	0	-0.980	0.003
Nov-91	5			*	0.988	0.979	0.002	6.909	0.284	0									-0.004	0	-0.988	0.002
Dec-91	6			*	0.985	0.971	0	5.055	0.366	0									-0.006	0	-0.985	0
Jan-93	6	*			0.980	0.960	0.001	-404.391	40.837	0.001	8.020	0.815	0.980	0.001								
Feb-93	6			*	0.968	0.938	0.001	4.064	0.543	0.002									-0.006	0.001	-0.968	0.001
Mar-93	6			*	0.973	0.946	0.001	6.217	0.530	0									-0.006	0.001	-0.973	0.001
Jan-94	6			*	0.985	0.970	0	6.059	0.308	0									-0.005	0	-0.985	0
Feb-94	5			*	0.980	0.961	0.003	2.331	0.461	0.015									-0.005	0.001	-0.980	0.003
Dec-94	5			*	0.996	0.992	0	2.496	0.218	0.001									-0.006	0	-0.996	0
Jan-95	5			*	0.973	0.946	0.005	3.533	0.399	0.003									-0.004	0.001	-0.973	0.005
Feb-95	5			*	0.979	0.959	0.004	4.274	0.356	0.001									-0.004	0	-0.979	0.004
Jan-96	5			*	0.984	0.968	0.002	1.661	0.417	0.028									-0.005	0.001	-0.984	0.002
Feb-96	5			*	0.969	0.940	0.006	3.375	0.410	0.004									-0.004	0.001	-0.969	0.006
Mar-96	5			*	0.977	0.955	0.004	5.213	0.452	0.001									-0.005	0.001	-0.977	0.004
Jan-97	5			*	0.983	0.967	0.003	2.433	-0.310	0.004									-0.004	0	-0.983	0.003
Feb-97	5			*	0.978	0.957	0.004	4.213	0.384	0.002									-0.004	0.001	-0.978	0.004
Dec-97	4			*	0.989	0.978	0.011	4.485	0.425	0.009									-0.006	0.001	-0.989	0.011
Jan-98	4			*	0.996	0.992	0.004	2.882	0.325	0.012									-0.007	0	-0.996	0.004
Feb-98	4			*	0.999	0.998	0.001	5.338	0.185	0.010									-0.008	0	-0.999	0.001
Dec-98	4			*	0.993	0.986	0.007	2.576	0.419	0.025									-0.007	0.001	-0.993	0.007
Jan-99	4			*	0.997	0.994	0.003	3.525	0.233	0.004									-0.006	0	-0.997	0.003
Feb-99	4			*	0.998	0.996	0.002	3.226	0.241	0.006									-0.007	0	-0.998	0.002
Dec-99	4			*	0.951	0.905	0.049	3.459	0.426	0.015									-0.003	0.001	-0.951	0.049

The estimates of potential evapotranspiration were calculated by a Thornthwaite-type water-balance equation model (Dingman, 2002). Mean monthly precipitation and temperature values from the Port Hardy A climate station were adjusted to account for elevation zones in the Tsitika River Watershed and then were utilized as input into the water-balance equation model. Subsequently, monthly estimates of potential evapotranspiration were retrieved and used as input into the rainfall-runoff model. *Figure 3-11.* gives an example of Thornthwaite-type water-balance model application for the Port Hardy A climate station. It shows an annual cycle of precipitation, soil and snowpack storage, evapotranspiration, and water available for surface runoff. The values shown in *Figure 3-11.* were calculated from original records at the Port Hardy A station and are based on monthly averages for years 1977-2000.

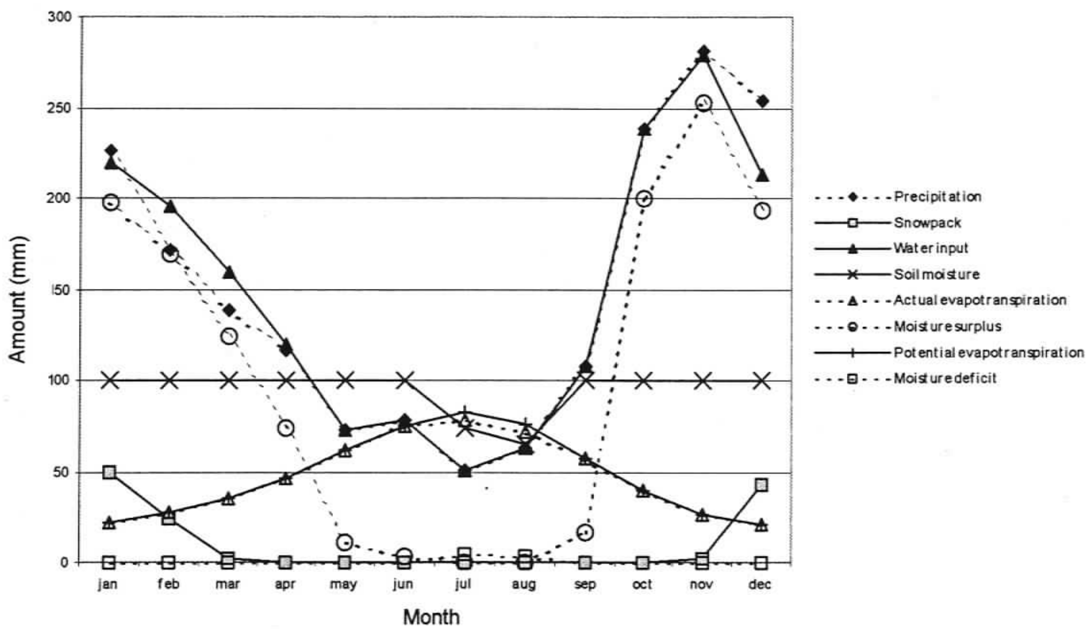


Figure 3-11. *Annual cycle of water-balance components as calculated by the Thornthwaite-type monthly water-balance model for the Port Hardy A climate station. Based on monthly averages for years 1977-2000 (Modified after Dingman, 2002).*

3.2.3. Topographic and elevation data

Planimetric positional data and gridded digital elevation model (DEM) were obtained from the Ministry of Sustainable Resource Management. Planimetric data were originally collected for the Terrain Resource Information Management (1:20 000 TRIM) program. The data were transformed from the standard Spatial Archive and Interchange Format (SAIF) into ESRI format using the FME Universal Translator package. Vector layers of rivers and lakes were checked and corrected for errors related to mapsheets edgematching and dangling/not connected arcs.

Digital elevation model with the resolution of 25 m x 25 m provided the basis for watershed delineation. Terrain Analysis Using Digital Elevation Models (TauDEM) software (Tarboton, 2002) was used to derive the boundaries of the watershed located upstream of the hydrometric station 08HF004 Tsitika River below Catherine Creek. The program is based on Jenson and Domingue (1988) and Tarboton (1997) methods for extracting topographic structures from digital elevation data. The procedure of watershed delineation involved generation of the following data sets:

- Grid of elevation values with pits filled.
- Grid of stream network rasterized from the TRIM data.
- Elevation grid with "burned-in" streams. The burning-in streams process was necessary to perform as without it the watershed was not delineated properly. A small subwatershed in south-eastern part was missing when compared with the B.C Watershed Atlas map (Fisheries, 1999).
- Grid giving direction of flow by the D8 method with enforced stream flow directions.
- Point vector file containing the outlet (hydrometric station) location.
- D8 contributing area grid where each cell was assigned a value equal to the number of cells that flow into it.
- Grid giving the Strahler stream order for each flow path.
- Stream aster grid with cell values of 1 on streams and 0 off streams.
- Vector network produced from the stream raster grid.
- Grid demarcating a single watershed draining to the outlet specified by the location of hydrometric station.
- Polygon watershed layer translated from the grid representation.

An output watershed used in this study is shown in *Figure 3-12*.

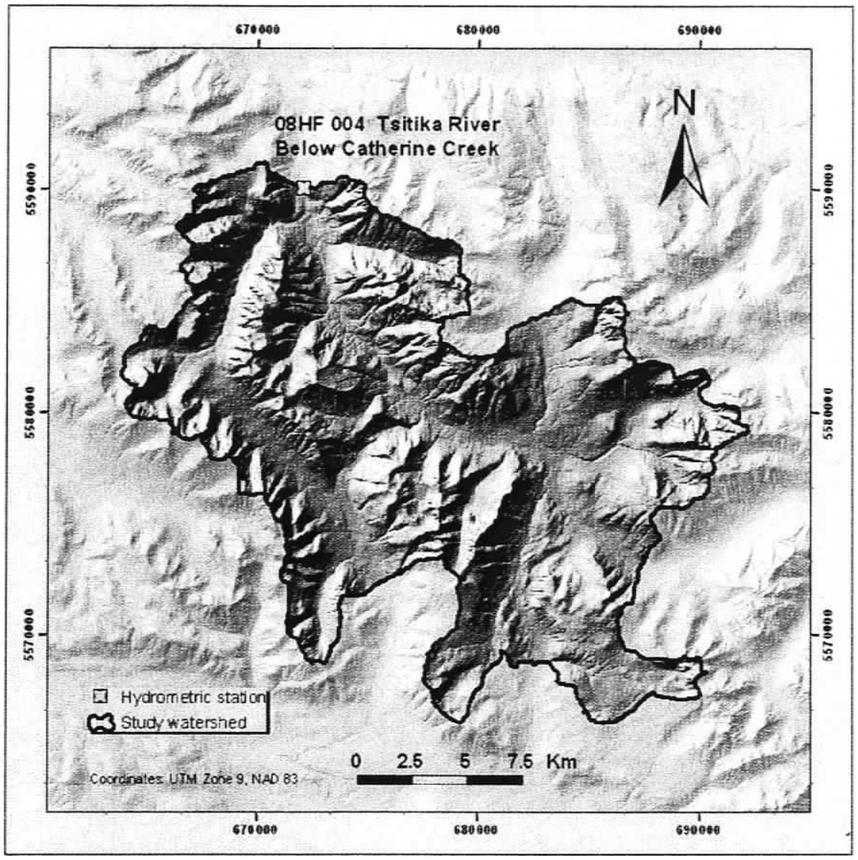


Figure 3-12. *Delineated boundaries of the study watershed as derived from digital elevation data.*

3.2.4. Land cover and vegetation

Information on temporal and spatial distribution of land cover was obtained from the Landsat 5 TM and Landsat 7 ETM+ imagery. Four Landsat scenes (path: 50, row: 25) were available for analysis: Landsat 5 TM images acquired on June 10, 1985, on June 11, 1989 and on August 01, 1990, and Landsat 7 ETM+ image acquired on August 02, 1999. Subsets of the Landsat scenes were reprojected to a common datum and coordinate system – UTM Zone 9, NAD83, were classified to provide a basis for assessment of land use/land cover changes over time, and finally were resampled so that the pixel size matched the pixel element of grid elevation data (25m x 25m).

A supervised classification method was applied to extract different land cover categories from satellite data. Training sites were defined interactively in the screen based on the uniform color, i.e. homogeneity, of the samples. Training areas were collected on the false color composite created by the combination of bands 1, 4 and 5. Band 1 was useful in differentiating barren soil from vegetation, band 4 helped to distinguish different stages of vegetation and to delineate water bodies, and band 5 was especially useful in discriminating between clouds and snow. The classification was performed on 7 multispectral bands with a maximum likelihood classifier. A mode filter with a kernel size of 3x3 pixels was applied to classified images to reduce the "salt and pepper" effect, i.e. to replace a small "islands" of misclassified pixels by their larger, surrounding theme classes. Land cover thematic layers were exported into ArcGIS program, converted to a vector format, and a percent proportion of each land cover class within a study watershed was calculated (*Table 3-10.*)

Table 3-10. *Land cover classes selected for the classification and percentage of each class within a study watershed as derived from Landsat imagery for years 1985, 1989, 1990 and 1999.*

Thematic Class	**Percentage of Watershed**			
	1985	**1989**	**1990**	**1999**
Water	0.17	0.30	0.27	0.18
Clouds	16.71	2.75	0.03	0
Snow	1.64	3.96	0.17	3.76
Barren Land	12.04	19.06	13.16	30.12
Young and Low Vegetation	0.94	4.15	10.28	3.03
Forest	68.50	69.78	76.09	62.91

4. MODELING PROTOCOL

Modeling protocol is a procedure that describes a sequence of steps involved in the application of hydrologic models (Refsgaard, 1996). The protocol presented in the thesis was inspired by modeling protocols suggested and applied by Refsgaard (1996), Refsgaard and Knudsen (1996), and Refsgaard and Henriksen (2004), and has been modified for the purposes of this research project. Different steps included in hydrologic modeling of the Tsitika River Watershed are described in Sections 4.1. – 4.11.

4.1. Purpose of the model application

The overall objective of the case study is to present and discuss the methodology for the construction, calibration and validation of a hydrologic model at the medium scale. Special attention is given to the formulation and analysis of an automatic calibration strategy for a rainfall-runoff model and to the validation of a model applied to the gauged catchment subject to non-stationary land cover conditions. In this respect, the purpose of the model is to simulate the overall hydrologic regime in the Tsitika River Watershed and especially the dynamics of river discharges.

4.2. Modeling code selection and structure

A hydrologic modeling code used in this study is the NAM rainfall-runoff system that forms a part of the MIKE 11 river-modeling package (DHI, 2004). The NAM (Nedbør-Afstrømnings-Model) was originally developed at the Technical University of Denmark (Nielsen and Hansen, 1973) and has been modified and used in a number of projects dealing with simulations of rainfall-runoff processes in catchments and subcatchments (DHI, 2004; Madsen, 2000).

Several reasons supported the selection of the NAM modeling system:

- The model simulates hydrologic processes that affect the generation and routing of runoff in the Tsitika River Watershed.
- The model provides continuous simulation of water flows, i.e. is designed to reproduce hydrologic behaviour of a watershed over longer periods of time, including low-flow periods between rainfall events.

- The model can operate on daily time steps that correspond to the temporal resolution of meteorological and river discharge data.
- Model documentation including user's and reference manuals is readily available.
- The model has been previously used in rainfall-runoff modeling studies.

The NAM is a deterministic, lumped, conceptual modeling code that simulates various components of catchment runoff as a function of the moisture content in four mutually interrelated storages (DHI, 2004; Madsen, 2000). These represent different physical elements of the catchment and are denoted as snow storage, surface storage, lower zone (root zone) storage and groundwater storage. A schematic view of the structure of the NAM model is given in *Figure 4-1.*

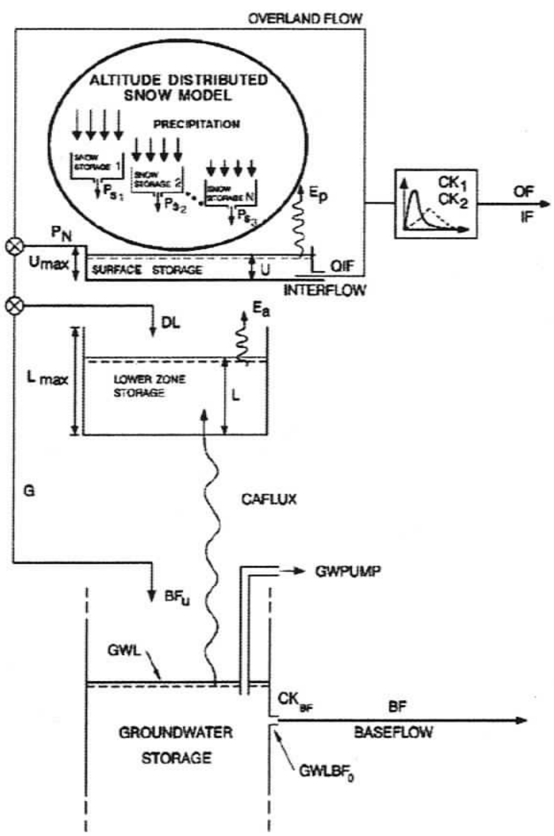


Figure 4-1. *Structure of the NAM modeling code with extended snow module (After DHI, 2004).*

A hydrologic model based on the NAM code requires input data of precipitation, potential evapotranspiration, and temperature (in case the snow modeling is included). It also allows modeling of man-made interventions in the hydrologic cycle such as irrigation and groundwater pumping. Based on this, catchment runoff and groundwater level values are produced as main results. The soil moisture content and the groundwater recharge are also calculated. Conceptually, the resulting catchment runoff is split into overland flow, interflow and baseflow components that represent fast, intermediate and slow response modes of the hydrograph respectively (DHI, 2004; Madsen et al., 2002). The parameters and variables for the model represent average values for catchment or subcatchment. Some of them can be based on physical catchment data. However, the final parameter estimation is performed by calibration against observed discharge data. The automatic calibration module allows calibration of the nine structural model parameters (DHI, 2004).

4.3. Modeling components and model parameters

The following modeling components – the description is based on DHI (2004) – were used in this study:

- Surface storage – moisture intercepted on the vegetation as well as water trapped in depressions and in the uppermost, cultivated part of the ground.
- Lower zone or root zone storage – the soil moisture in the root zone, a soil layer below the surface from which the vegetation can draw water for transpiration.
- Evapotranspiration - evapotranspiration demands are first met at the potential rate from the surface storage. If the moisture content U in the surface storage is less than these requirements ($U < E_p$), the remaining fraction is assumed to be withdrawn by root activity from the lower zone storage at an actual rate E_a. E_a is proportional to the potential evapotranspiration and varies linearly with the relative soil moisture content of the lower zone storage.
- Overland flow – when the amount of water in the surface storage exceeds the upper limit U_{max}, the excess water P_N gives rise to overland flow as well as to infiltration. The amount of water contributing to overland flow is proportional to P_N and varies linearly with the relative soil moisture content of the lower zone storage. The portion of the excess water that does not run off as overland flow infiltrates into the lower zone storage and increases the moisture content L in this storage. The remaining amount of infiltrating moisture is assumed to percolate deeper and recharge the groundwater storage.
- Interflow - the interflow contribution is assumed to be proportional to the moisture content in the surface storage U and to vary linearly with the relative moisture content of the lower zone storage.
- Groundwater recharge – accounts for the amount of water G infiltrating into the groundwater storage.

- Soil moisture content – the lower zone storage represents the water content within the root zone.
- Baseflow - the baseflow *BF* from the groundwater storage is calculated as the outflow from a linear reservoir with time constant CK_{BF}.
- Accumulation and melting of snow – during cold periods precipitation is retained in the snow storage from which it is melted in warmer periods. The snowmelt is calculated using a degree-day approach.

Table 4-1. gives a brief description of the nine structural model parameters and their physical interpretation. These are to be determined by model calibration.

Table 4-1. *NAM structural model parameters (After DHI, 2004; Madsen et al., 2002)*.

Parameter	Units	Description
U_{max}	mm	Maximum water content in the surface storage. This storage is interpreted as including the water content in the interception storage, in surface depression storages, and in the uppermost few cm's of the ground.
L_{max}	mm	Maximum water content in the lower zone storage. L_{max} can be interpreted as the maximum soil moisture content in the root zone available for the vegetative transpiration.
CQOF	-	Overland flow runoff coefficient. *CQOF* determines the distribution of excess rainfall into overland flow and infiltration.
TOF	-	Threshold value for overland flow. Overland flow is only generated if the relative moisture content in the lower zone storage, L/L_{max}, is larger than *TOF*.
TIF	-	Threshold value for interflow. Interflow is only generated if the relative moisture content in the lower zone storage, L/L_{max}, is larger than *TIF*.
TG	-	Threshold value for groundwater recharge. Recharge to the groundwater storage is only generated if the relative moisture content in the lower zone storage, L/L_{max}, is larger than *TG*.
CK_{IF}	H	Time constant for interflow from the surface storage. CK_{IF} determines together with U_{max} the amount of interflow. $(CK_{IF})^{-1}$ is the quantity of the surface water content *U* that is drained to interflow every hour. It is the dominant routing parameter of the interflow because $CK_{IF} >> CK_{12}$.
CK_{12}	H	Time constant for overland flow and interflow routing. CK_{12} determines the shape of hydrograph peaks. The value of CK_{12} depends on the size of the catchment and how fast it responds to rainfall.
CK_{BF}	H	Baseflow time constant. CK_{BF} determines the shape of the simulated hydrograph in dry periods. According to the linear reservoir description the discharge in such periods is given by an exponential decay.

4.4. Selection of modeling periods

The selection of reference and test modeling periods was based on a visual inspection of hydrograph, knowledge about the land cover changes in the watershed, statistical testing for a step-change, and an application of general guidelines for the selection of modeling periods as described in Lørup et al. (1998). To minimize the influence of erroneous set-up of initial conditions and estimation of water content in different storage components, all simulation periods were set to start in August. In the northeast Vancouver Island, August is one of the two months with lowest precipitation amounts in a year and coincides with the end of a drier summer period.

A split-sample testing procedure for model calibration and validation (in the terminology of Klemeš, 1986b) was applied in the case study. It involves selecting a reference period for model calibration and validation. Data records for the reference period are split into two segments, usually two halves. A hydrologic model is calibrated on the first part of the measured data and then validated against the data from the second part of the reference period. According to the reference manual for the NAM modeling system (DHI, 2004), "satisfactory calibrations over a full range of flows usually require continuous observations of runoff for a period of 3-5 years". To account for this and also for the range of available observed data (1977-2000), as well as for the changes in land cover the watershed was subjected to, the periods of three-years duration were selected for model calibration, validation and testing simulations. The reference period of August 1983-July 1989 was chosen for initial model calibration and validation in the present study. The model was set up and calibrated on data from the first part of the reference period – August 1983 to July 1986, and subsequently validated against data from August 1986 to July 1989. Land cover changes were rather limited during the reference period, especially when compared to later periods. The model was then used to simulate runoff for the two test periods using the same parameters as were found optimal for the reference period. The first test period of August 1990-July 1993 covered the years of more extensive timber harvesting in the watershed. In addition, the hydrograph inspection revealed more frequent occurrence of high flows and higher cumulative runoff that might have been possibly induced by clear-cut practices. The second test period of August 1997-July 2000 was chosen to be as late as possible with respect to available data and modeling consistency. As can be seen on Landsat satellite images, this period corresponds to the most intensive logging in the watershed.

A statistical test for step-change was carried out for precipitation and runoff to quantitatively compare the modeling periods. A nonparametric Mann-Whitney test (equivalent to the Wilcoxon Rank-Sum test, Lørup et al., 1998) was used to look for differences between the means of variables. The tests were carried out as a classical hypothesis-testing of hydrologic time series with a null hypothesis H_0 implying that there was no change in the mean of a series, and an alternative hypothesis H_1 being that a change existed in either direction (two-sided test), i.e. the mean was either increasing or decreasing over time (Kundzewicz and Robson, 2004; Lørup et al., 1998). The results of tests for step-change in means are presented in *Table 4-2.* It appears that the means of precipitation and runoff for the reference and the first test period are not significantly different. The significance level for runoff is much lower than it is for precipitation, suggesting that the runoff process might be affected by other factors such as land cover changes. However, it is not easy to distinguish between the impacts of human practices and the effects of weather and climate regime on a hydrologic cycle in a particular year (Lørup et al., 1998), especially when the changes are weak and do not last long (Radziejewski and Kundzewicz, 2004).

Table 4-2. *Results from the statistical Mann-Whitney test for the shift in means of variables (a=0.05).*

Ref. period	Test period	Precipitation (mm/day)					Runoff (mm/day)				
		Mean		Std. Dev.		Sign.	Mean		Std. Dev.		Sign.
		Ref. per.	Test per.	Ref. per.	Test per.		Ref. per.	Test per.	Ref. per.	Test per.	
08/83 –07/89	08/90 –07/93	4.88	4.99	9.26	10.13	0.446	4.64	6.47	5.92	12.06	0.202
08/83 –07/89	08/97 –07/00	4.88	5.50	9.26	9.30	0.000	4.64	6.07	5.92	6.24	0.000

When precipitation and runoff for the second test period are examined, it can be seen that for both variables the means are significantly larger for the second test period than they are for the reference period. Thus the change in precipitation regime (among other factors) is also reflected in the change of runoff behaviour.

4.5. Model construction and parameterization

Model set-up involves the development of model with respect to the spatial representation of the watershed, setting up initial conditions, making preliminary selection of parameter values, and providing ranges of expected values. The estimates of initial parameter values are usually based on data from previous fieldwork, previous modeling experience, or published literature. However, because most parameters are empirical and conceptual, their final values are determined from calibration against hydrologic time series (DHI, 2004). In the NAM-based rainfall-runoff model, most variables and parameters represent average values for the entire watershed.

Meteorological time series of precipitation and temperature (daily data) were extracted from the original database of Environment Canada. Monthly estimates of potential evapotranspiration were determined by Thornthwaite-type water-balance equation model (Dingman, 2002). All time series were transformed into a format readable by the modeling package and prepared as a set of input data files for the modeling system.

Input variables of precipitation and temperature were adjusted for the simulation of accumulation and melting of snow. The snow module allows user to define several elevation zones, for which the temperature and precipitation are calculated separately. A distributed degree-day approach (taking into account altitude zones instead of using one adjustment coefficient for the whole watershed) has been applied, with snowmelt parameters, precipitation and temperature input adapted for the four elevation zones. The selection of four altitude zones was based on the hypsometric curve obtained for the watershed and on information about the biogeoclimatic zones occurring in the region (NISG, 1975; TPC, 1978). The average elevation and area of each zone was determined from the DEM data. The precipitation lapse rate of 0.33 mm/100 m was derived from the results of the regression analysis (*Table 3-8.*). It was calculated as an average slope gradient from the regression models where elevation was an explanatory variable. It represents an increase in precipitation amount corresponding to the elevation increment of 100 m. The dry and wet temperature lapse rates were specified according to the published literature (Dingman, 2002; Smith, 1993) and the results of the regression analysis (*Table 3-9.*) using the same logic as applied for the precipitation lapse rate . The snow module parameters for the four altitude zones used in the study are shown in *Figure 4-2.* The degree-day coefficient C_{snow} was assumed to vary over a year. Monthly values of C_{snow} as applied during simulations are given in *Figure 4-3.*

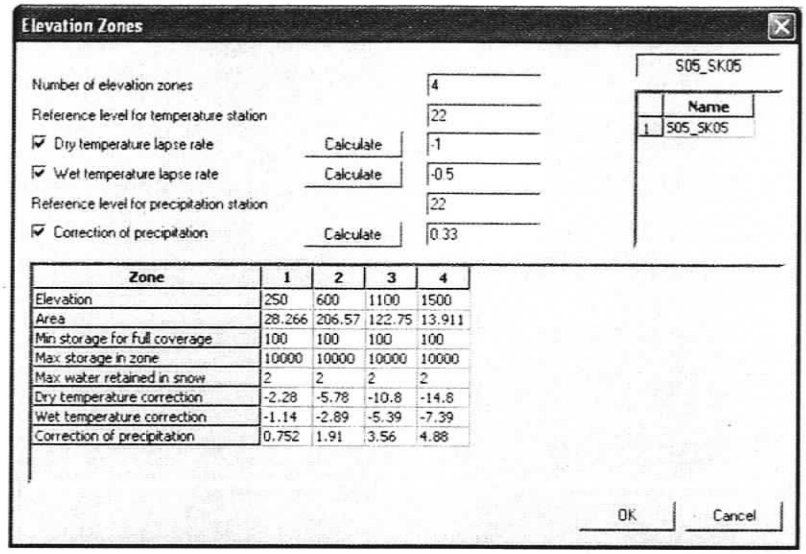


Figure 4-2. *Snow module parameters used in model simulations.*

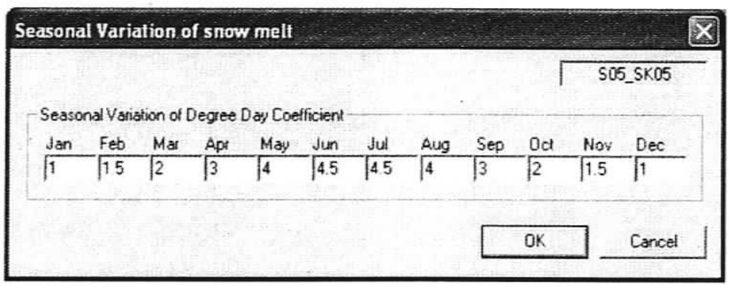


Figure 4-3. *Seasonal variation of the degree-day coefficient (mm/°C/day). The degree-day coefficient determines the rate of snow melting caused by the seasonal variation of the incoming short wave radiation and the albedo of the snow surface.*

The set-up of initial conditions for the model requires specifying the initial water contents in the surface and root zone storages and providing the initial values of overland flow, interflow, and baseflow. Following the recommendations of modeling software manual (DHI, 2004), all initial values except of the water content in the root zone and the baseflow values were set to zero. This has been found sufficient when a simulation starts at the end of a dry period (DHI, 2004), which is the case of this study. The water content in the root zone was set to 30% of the capacity and the baseflow was given a value slightly smaller than the observed discharge. To minimize the influence of erroneous initial conditions, a one-year "warm-up" period of August 1982-July 1983 was applied before model calibration. Model results for this period were not used for the calculation of the objective functions, but helped to improve the estimates of the initial parameter values for the model calibration period.

4.6. Model performance criteria

To measure the model performance for each calibration and validation test, a standard set of criteria has been defined. In this study, a combination of two graphical and two numerical performance measures (*Table 4-3.*) were selected to evaluate how closely the simulated series of daily flows correspond to the measured series. These were:

- Joint plots of the simulated and observed hydrographs.
- Joint plots of the simulated and observed accumulated runoffs.
- Overall water balance error (DHI, 2004) measuring the difference between the average observed and simulated runoff volumes.
- The Nash and Sutcliffe coefficient of efficiency, R^2 (DHI, 2004; Nash and Sutcliffe, 1970) measuring the overall agreement of the shape of the hydrograph.

Table 4-3. *Numerical measures of model performance.*

Performance Measure	Formula	Description	Reference
Overall water balance error (Overall runoff volume error)	$F_{WB} = \left\| \frac{1}{N} \sum_{i=1}^{N} \left(Q_{obs,i} - Q_{sim,i} \right) \right\|$	A measure of the agreement between the average simulated and observed runoff volumes	(DHI, 2004)
Nash and Sutcliffe coefficient of efficiency	$R^2 = 1 - \frac{\sum_{i=1}^{N} \left(Q_{obs,i} - Q_{sim,i} \right)^2}{\sum_{i=1}^{N} \left(Q_{obs,i} - \overline{Q}_{obs} \right)^2}$	A measure of the overall agreement of the shape of the hydrograph The coefficient is a transformed and normalized (with respect to the variance of the observed hydrograph) measure of the overall root mean square error	(Nash and Sutcliffe, 1970) (DHI, 2004)

Where: $Q_{obs,i}$ is the observed discharge at time i, $Q_{sim,i}$ is the simulated discharge at time i, $\overline{Q}_{obs}$ is the average observed discharge, N is the number of time steps in the simulation period.

4.7. Model calibration

The model calibration involves an automatic and/or manual selection of parameters so that the model simulates the hydrologic behaviour of a watershed as closely as possible. Different objectives can be taken into account in the calibration, for example (DHI, 2004):

- A good agreement between the average simulated and observed catchment runoff (i.e. a good water balance).
- A good overall agreement of the shape of the hydrograph.

- A good agreement of the peak flows with respect to timing, rate, and volume.
- A good agreement of the low flows.

In automatic calibration, parameters are adjusted by automatic routines for optimization of an objective function. Different calibration objectives are translated into a formulation of different numerical measures of the goodness of fit of the calibrated model. In the NAM-based model the optimization is performed using the Shuffled Complex Evolution (SCE) algorithm developed by Duan et al. (1992).

An automatic calibration routine has been applied for the calibration of the Tsitika River Watershed model. The model was calibrated against the series of measured daily river flows for the period of August 01, 1983–July 31, 1986 with a model initialization (warm-up) period set to August 01, 1982–July 31, 1983. The autocalibration module allows the adjustment of nine structural model parameters or any subset of them. As no specific information about the watershed was available for constraining the upper and lower limits of model parameters, the default values defining the feasible parameter ranges, i.e. the hypercube search space, were kept and used (*Figure 4-4.*). A modeling code user is given a choice of specifying the priorities with respect to the objectives of model simulation. One or any combination of the following four objective functions can be chosen for optimization: overall water balance, overall RMSE, peak flow RMSE, and low flow RMSE. For the purpose of this study peak flows were defined as periods with flow above a 46.4 m^3/s threshold value and low flows were defined as periods with flow below 3.0 m^3/s threshold. The values correspond to the long-term 90^{th} and 10^{th} percentiles, respectively (as derived from available discharge data for a period of 1977-2000). A maximum number of 2000 model evaluations were employed as a stopping criterion for simulations. This is, in general, sufficient for efficient calibration and for reaching the global optimum (DHI, 2004; Madsen, 2000).

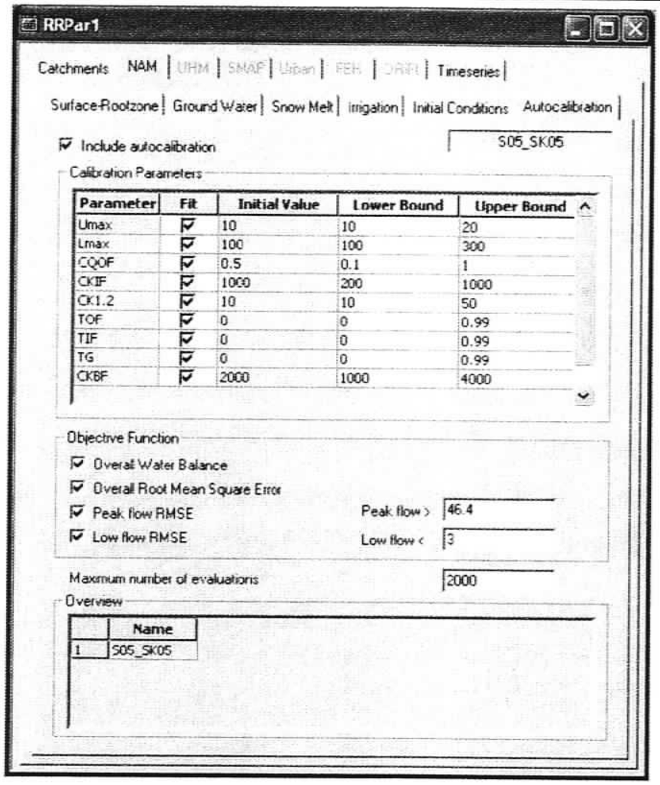


Figure 4-4. *Model parameters to be optimized by calibration and their feasible parameter ranges (hypercube search space).*

To analyze the trade-offs among solutions for various calibration objectives, several calibration runs were conducted. The calibration tests were carried out as follows:

- Single-objective calibration for the overall water balance (volume error) – calWB.
- Single-objective calibration for the overall RMSE – calRMSE.
- Single-objective calibration for the peak flow RMSE – calPeak.
- Single-objective calibration for the low flow RMSE – calLow.
- Multi-objective calibration on two objectives for the overall RMSE and the overall water balance – calRMSE&WB.
- Multi-objective calibration on two objectives for the overall RMSE and the peak flow RMSE – calRMSE&Peak.
- Multi-objective calibration on four objectives for the overall RMSE, the water balance, the peak flow RMSE, and the low flow RMSE – calAll.

The optimum parameter sets derived for seven combinations of different calibration objectives and performance statistics obtained for simulations are presented in *Table 4-4.* The variation of parameters for optimal solutions is illustrated in *Figure 4-5.* The parameter values are normalized with respect to the upper and lower limits as given in *Figure 4-4.* so that the feasible range of all parameters is between 0 and 1. The variation of parameter combinations obtained by different calibration runs is also reflected in a variability of simulated hydrographs as shown in *Figure 4-6.* and in a variability of accumulated runoffs as illustrated in *Figure 4-7.*

Table 4-4. *Optimal parameter sets and performance statistics obtained for different calibration objectives.*

Calibration objective	U_{max}	L_{max}	CQOF	CK_{IF}	CK_{12}	TOF	TIF	TG	CK_{BF}	R^2	WB
calWB	10.4	103	0.987	217.4	48.4	0.010	0.369	0.976	3959	0.483	18.6
calRMSE	10.1	123	0.754	683.7	24.5	0.770	0.052	0.980	1003	0.593	20.6
calPeak	10.6	131	0.951	883.2	23.3	0.559	0.652	0.987	3774	0.552	19.5
calLow	20	152	0.836	344.4	49.7	0.623	0.948	0.976	3429	0.463	20.4
calRMSE&WB	10.2	109	0.78	206.9	24.8	0.428	0.223	0.960	1020	0.592	20.3
calRMSE&Peak	10	145	0.885	837.7	24.2	0.603	0.358	0.984	3869	0.576	20.1
calAll	10.1	100	0.886	249.9	23.6	0.444	0.453	0.988	3757	0.579	19.6

Abbreviations denote parameters as explained in Table 4-1. R^2 - Nash and Sutcliffe coefficient of efficiency, WB – water balance (% difference between observed and simulated runoff volumes).

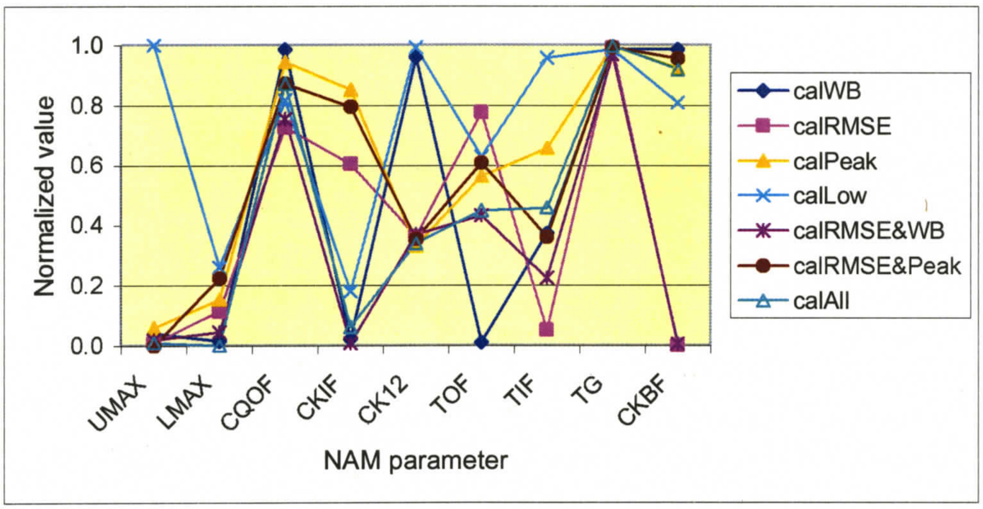


Figure 4-5. *Normalized parameters estimated for optimization of different calibration objectives. The values are standardized with respect to the lower (assigned 0) and upper (assigned 1) limits of the feasible parameter ranges as specified in Figure 4-4.*

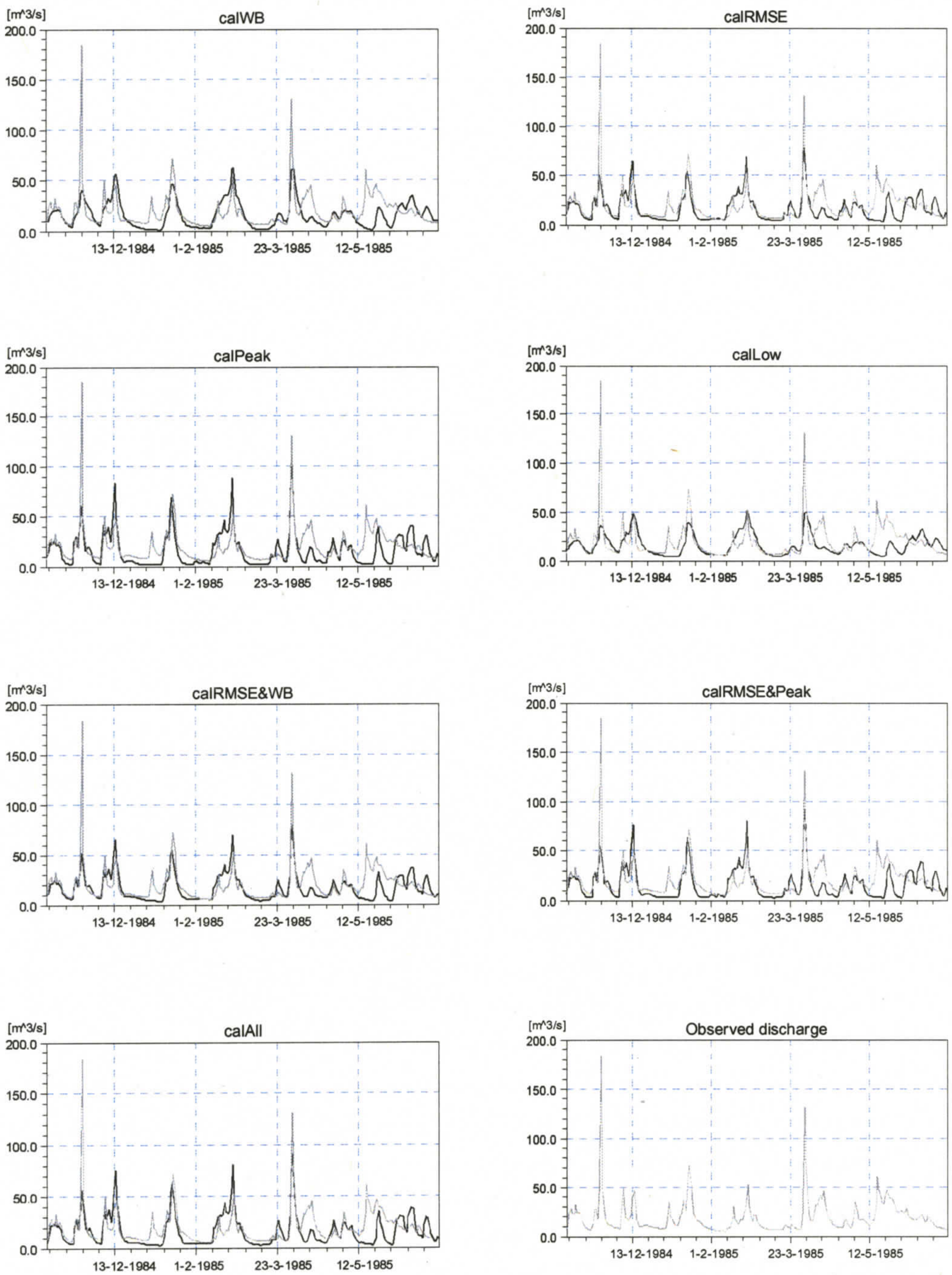


Figure 4-6. *Simulated hydrographs obtained with the parameter sets listed in Table 4-4. compared with the observed hydrograph (gray line – observed discharge, black line – simulated discharge; selected period of November 1984-June 1985).*

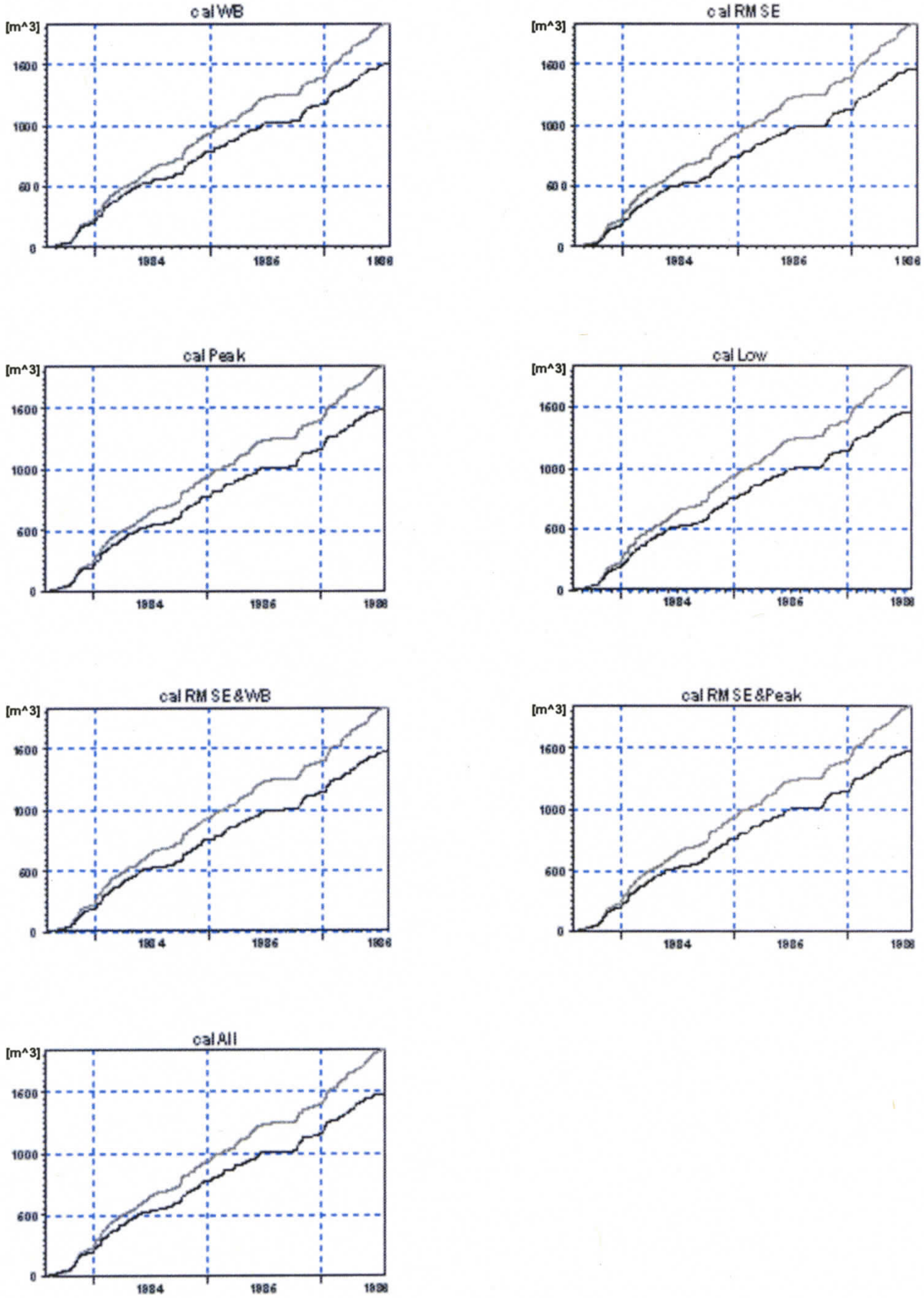


Figure 4-7. *Simulated (black line) and observed (gray line) accumulated runoffs corresponding to the simulations optimized for different calibration objectives as listed in Table 4-4.*

As indicated in *Table 4-4.*, the simulated runoff volumes were underestimated by 18.6-20.4 % when compared with observed data for different calibration runs. The coefficient of efficiency characterizing the overall agreement of the shape of the hydrograph ranged between 0.463 and 0.593. Generally, the overall flow pattern was captured relatively well with an exception of the late spring periods. Apparent deficiencies occurred during the months of April, May, June and July, which correspond to the snowmelt season. The flow dynamics is more poorly simulated and the discharges are mostly underestimated. This could be due to the model structure error, i.e. the snow routine was not able to track the melting season adequately. The underprediction of snowmelt events may also be caused by erroneous inputs of precipitation and evapotranspiration, which may not be representative of the conditions throughout the watershed.

Visual inspection of simulated and observed hydrographs reveals that the most significant trade-offs occur between the optimization of peak flows and the optimization of low flows. An improvement of peak flows simulation during the calPeak calibration is obtained at the expense of a poorer reproduction of low flows. Similarly, the calLow calibration captured well the low flow periods but the simulated and observed peak hydrographs exhibited larger discrepancies. Certain parameters - notably U_{max}, CK_{IF}, CK_{12}, and TIF - have considerably different values for the two objectives. These are the parameters that play a key role in determining the shape of the hydrograph, which then explains the dissimilarities between the simulation outputs.

A balanced aggregated objective function, which puts equal weights to the four different objectives - namely the overall water balance, the overall RMSE, the RMSE of peak flows and the RMSE of low flows - seems to provide a good compromise solution for an optimal parameter set. Therefore, the parameter values as derived by the calAll calibration (*Table 4-4.*) were used for the model validation simulations.

To investigate the effect of a problematic season on calibration period, three more calibration tests were conducted for the periods of August 1983 – March 1984 (cal8384All), August 1984 – March 1985 (cal8485All), and August 1985 – March 1986 (cal8586All). In this case the months covering the snowmelt period, i.e. April-July, were excluded from model simulations. The calibration runs were optimized for the four objectives, i.e. the overall water balance, the overall RMSE, the RMSE of peak flows, and the RMSE of low flows. The parameter sets obtained and model performances achieved are listed in *Table 4-5*. The variation of standardized parameter values is illustrated in *Figure 4-8.*

Table 4-5. Optimal parameter sets and performance statistics for the periods with the snowmelt season excluded.

Calibration objective	U_{max}	L_{max}	CQOF	CK_{IF}	CK_{12}	TOF	TIF	TG	CK_{BF}	R^2	WB
cal8384All	17	280	0.994	210.2	23.5	0.020	0.241	0.153	3834	0.587	12.8
cal8485All	18.9	114	1.000	325.4	24.5	0.980	0.763	0.973	3337	0.714	5.6
cal8586All	12.8	130	0.996	862.8	19.3	0.507	0.965	0.601	1516	0.782	17.1

Abbreviations denote parameters as explained in Table 4-1. R^2 - Nash and Sutcliffe coefficient of efficiency, WB – water balance (% difference between observed and simulated runoff volumes).

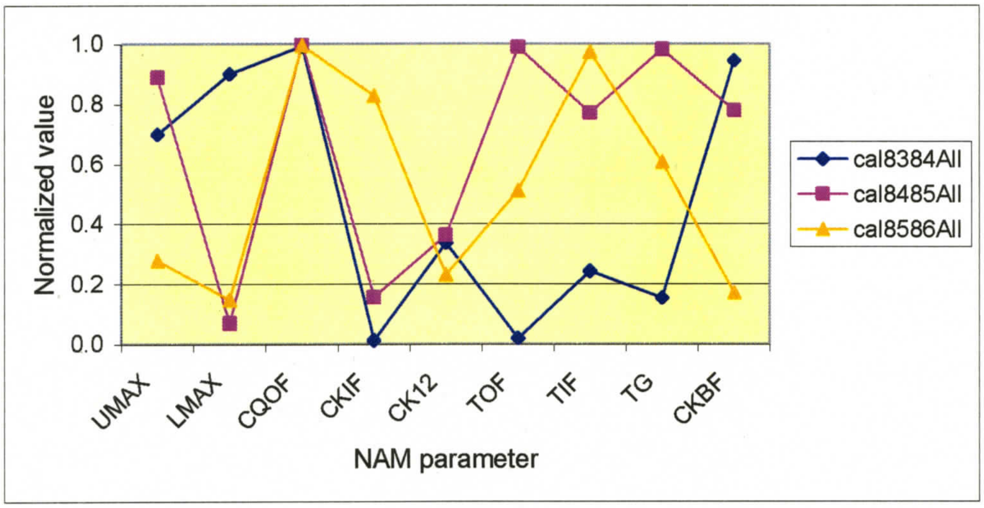


Figure 4-8. Normalized parameters estimated for the periods with the snowmelt season excluded. The values are standardized with respect to the lower (assigned 0) and upper (assigned 1) limits of the feasible parameter range as specified in Figure 4-4.

An improvement of the representation of monthly flows, as indicated by higher R^2 values, has been achieved, especially for the cal8485All and cal8586All calibration runs when R^2 equals to 0.714 and 0.782, respectively. The model performance with respect to the runoff volumes has also improved, with very good water balance simulation obtained for the cal8485All calibration (5.6 % difference in runoff volumes). However, as can be seen in *Figure 4-8.*, the spread of parameter values has also increased, especially for the U_{max}, L_{max}, and TG parameters.

4.8. Model validation

Following the calibration procedure, the hydrologic model for the Tsitika River Watershed was validated against the data for the second half of the reference period (August

1986–July 1989). Simulations were also run for the two testing periods (August 1990–July 1993, August 1997–July 2000). Model parameter values as obtained by calibration optimized for the all four calibration objectives, i.e. the overall water balance, the overall RMSE, the RMSE of peak flows, and the RMSE of low flows (*Table 4-4.*), were used for all validation simulations. In addition to the simulation runs covering the entire years, the model performance for selected periods excluding the snowmelt season was also examined. The results obtained are summarized in *Table 4-6. Figure 4-9.* shows the observed and simulated discharges for the validation and the testing periods.

Table 4-6. *Summary of the model validation performance.*

Validation/testing period	R^2	WB	Total precipitation
August 1986 – July 1989	0.616	11.0	5697
August 1990 – July 1993	0.548	38.0	5472
August 1997 – July 2000	0.601	24.9	6029
August 1986 – March 1987	0.792	6.6	1651
August 1987 – March 1988	0.775	-11.5	1597
August 1988 – March 1989	0.538	-5.7	1449
August 1990 – March 1991	0.502	35.5	1685
August 1991 – March 1992	0.488	46.5	1623
August 1992 – March 1993	0.702	25.8	1293
August 1997 – March 1998	0.820	17.2	1999
August 1998 – March 1999	0.682	10.9	1852
August 1999 – March 2000	0.489	20.5	1232

R^2 - Nash and Sutcliffe coefficient of efficiency, WB – water balance (% difference between observed and simulated runoff volumes).

The model maintains the moderately good performances for the entire validation and testing periods. Generally, a worse model performance would be expected for the model validation when compared with the calibration. However, the results for the validation period are even slightly better than the results obtained during the calibration of the model (R^2 = 0.579, WB = 19.6 % obtained for the calibration period compared to R^2 = 0.616, WB = 11 % achieved for the validation period). The simulation for the first testing period represents one of the poorest performances both in terms of monthly runoffs and the overall water balance. This period coincides with the beginning of more extensive logging in a watershed. More frequent occurrence of extreme peak flows was also found during these years. This could suggest that the model with parameters as optimized during the calibration is not able to reproduce the hydrologic behaviour under changed land cover conditions very well. However, a comparison of the R^2 values and the runoff volume error between the calibration and the second testing period indicates that there is a comparable performance between the two simulations despite the significant changes in land cover conditions (R^2 = 0.579, WB = 19.6 % and R^2 = 0.601, WB = 24.9 % for the calibration period and the second testing period, respectively). Thus the change in land cover is probably not the solely most important factor affecting the model performance through the values of effective parameters.

When the snowmelt season was excluded from the calculation of performance statistics, the correspondence between observed and simulated monthly runoffs has improved. The improvements were achieved especially for the years with higher precipitation inputs although this was not a strict rule. For the years covering the validation period the difference between the simulated and observed water balance ranged between 5.7 and 11.5 %. The coefficient of efficiency ranged between 0.538 and 0.792. Worse simulations of runoff volumes were obtained for the three years corresponding to the first testing period (water balance differences of 35.5 %, 46.5 % and 25.8 %, and the values of the coefficient of efficiency of 0.502, 0.488 and 0.702). Simulated runoffs were considerably underestimated. The model shows, in general, relatively good performance for the snow-season-excluded subperiods of the second testing period (the water balance in the range of 10.9-20.5%, the coefficient of efficiency ranging from 0.489 to 0.820).

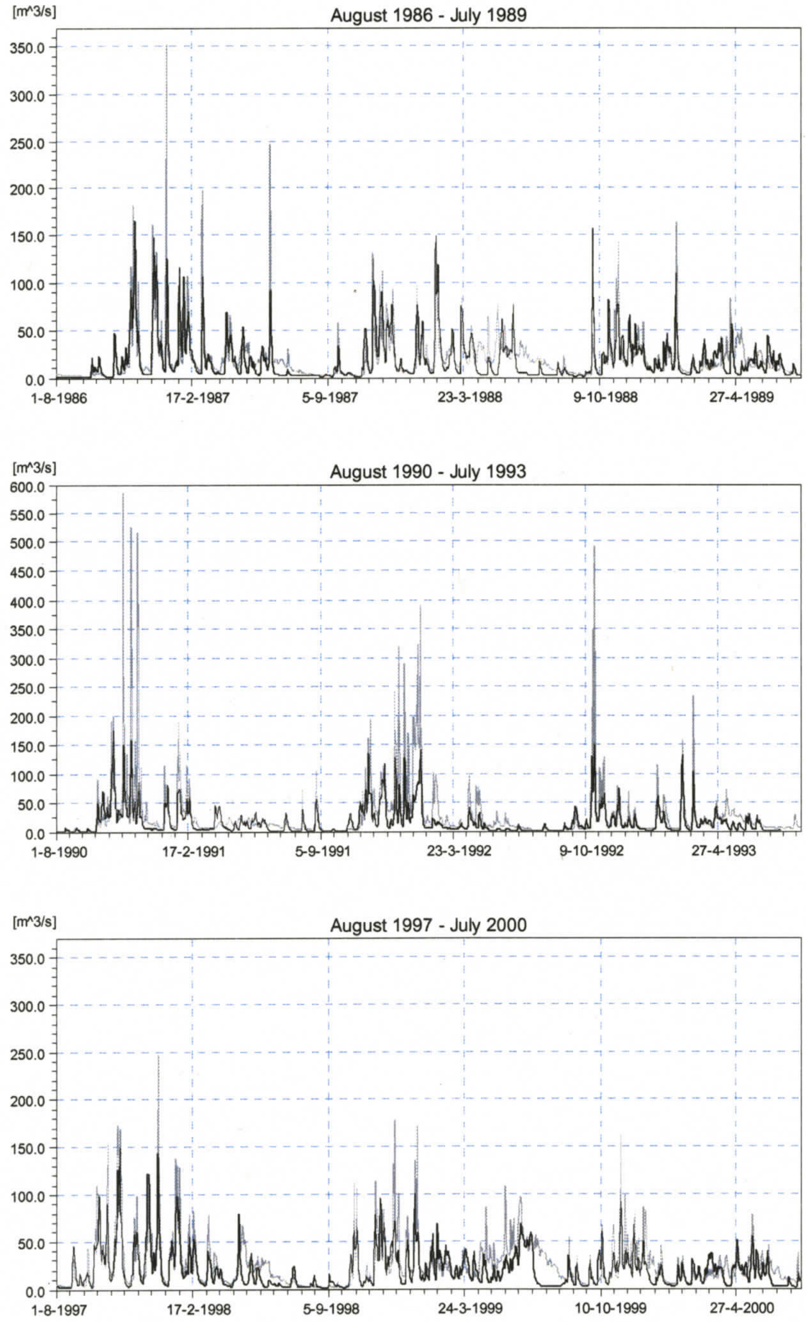


Figure 4-9. *Simulated (black line) and observed (gray line) river discharges for the validation (August 1986-July 1989) and the two testing periods (August 1990-July 1993, August 1997-July 2000).*

4.9. Parameter uncertainty

The wide spread of most parameter values as illustrated in *Figure 4-5.* and *Figure 4-8.* indicates their large uncertainty. The soundness of model parameter values was examined by comparing the values calibrated for the August 1983–July 1986 period with the values calibrated for the August 1986–July 1989 period. In this analysis, calibrations were optimized for all four calibration objectives as explained and used previously in Section 4.7. Calibrated parameter values for the two periods have been plotted against each other. The scatterplots of values corresponding to the 1436 model evaluations (after which the calibration optimum was reached) are shown in *Figure 4-10.* The rationale behind the scatterplots is as follows (Merz and Blöschl, 2004): if the parameters for the two evaluated periods are similar, then they would be clustered around 1:1 lines, and hence the uncertainty can be regarded as small. Large scatter of parameter values implies large uncertainties.

When examining the uncertainty by looking at the scatterplots in *Figure 4-10.* and optimal parameter sets illustrated in *Figure 4-5.* and *Figure 4-8.*, it appears that the parameters with the smallest uncertainty are the overland flow runoff coefficient CQOF and the time constant for overland flow and interflow routing CK_{12}. The time constant CK_{12} is the dominant parameter that affects the peak flow recession. The CQOF coefficient determines mainly the volume of peak flows. Hence the higher credibility of these two parameters is also reflected in relatively good simulations of the high flow hydrograph shapes. The most uncertain parameters seem to be the threshold value for the interflow TIF, the time constant for interflow from the surface storage CK_{IF}, and the time constant for baseflow CK_{BF}. These parameters control the recession of intermediate and low flows, which were found to be more problematic to reproduce during simulations. The U_{max} and L_{max} parameters, which represent the storage capacities of the surface and the lower zone storage, respectively, also exhibit considerable uncertainty. These parameters affect the overall water balance.

The results of uncertainty assessment were compared to those obtained in a study of Madsen (2000). The author applied Mike 11/NAM model to the Danish Tryggevaelde catchment to present an automatic multi-objective calibration strategy for a conceptual rainfall-runoff model. The parameters with most uncertainties associated with them were TG, U_{max}, and L_{max}. The smallest uncertainties were found for the CK_{12} and CQOF parameters. This is similar to the results obtained for the Tsitika River Watershed.

To explore the correlation between different parameters, all calibrated parameters obtained for the August 1983–July 1986 period were plotted against each other (*Figure 4-11.*). If obvious interdependences were found between the parameters, it would suggest overparameterization of the model and a need for the model restructuring and/or the reduction of the number of free model parameters that are to be calibrated (Madsen et al., 2002; Merz and Blöschl, 2004). The ranges of parameter values were standardized according to the a priori defined parameter ranges as specified in *Figure 4-4.*

Overall, the correlations are very weak and almost not present. It can be inferred that the number of model parameters subjected to calibration cannot be reduced easily. Therefore, the possible modeling errors caused by interdependences between the parameters are believed to be minimal.

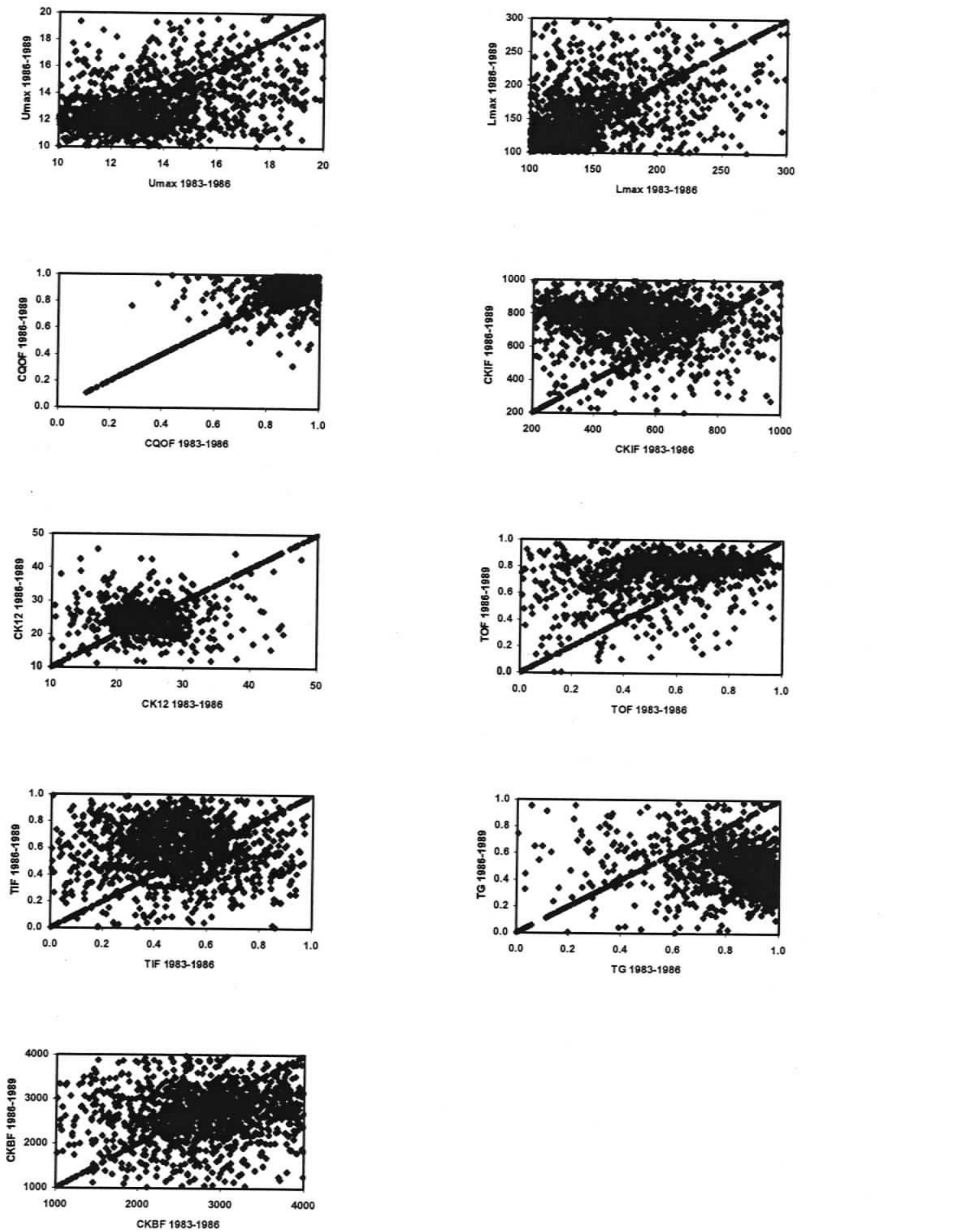


Figure 4-10. *Assessment of parameter uncertainty. Parameter values calibrated on the period of August 1983-July 1986 are plotted against parameter values calibrated on the period of August 1986-July 1989. Large scatter of values implies large parameter uncertainty.*

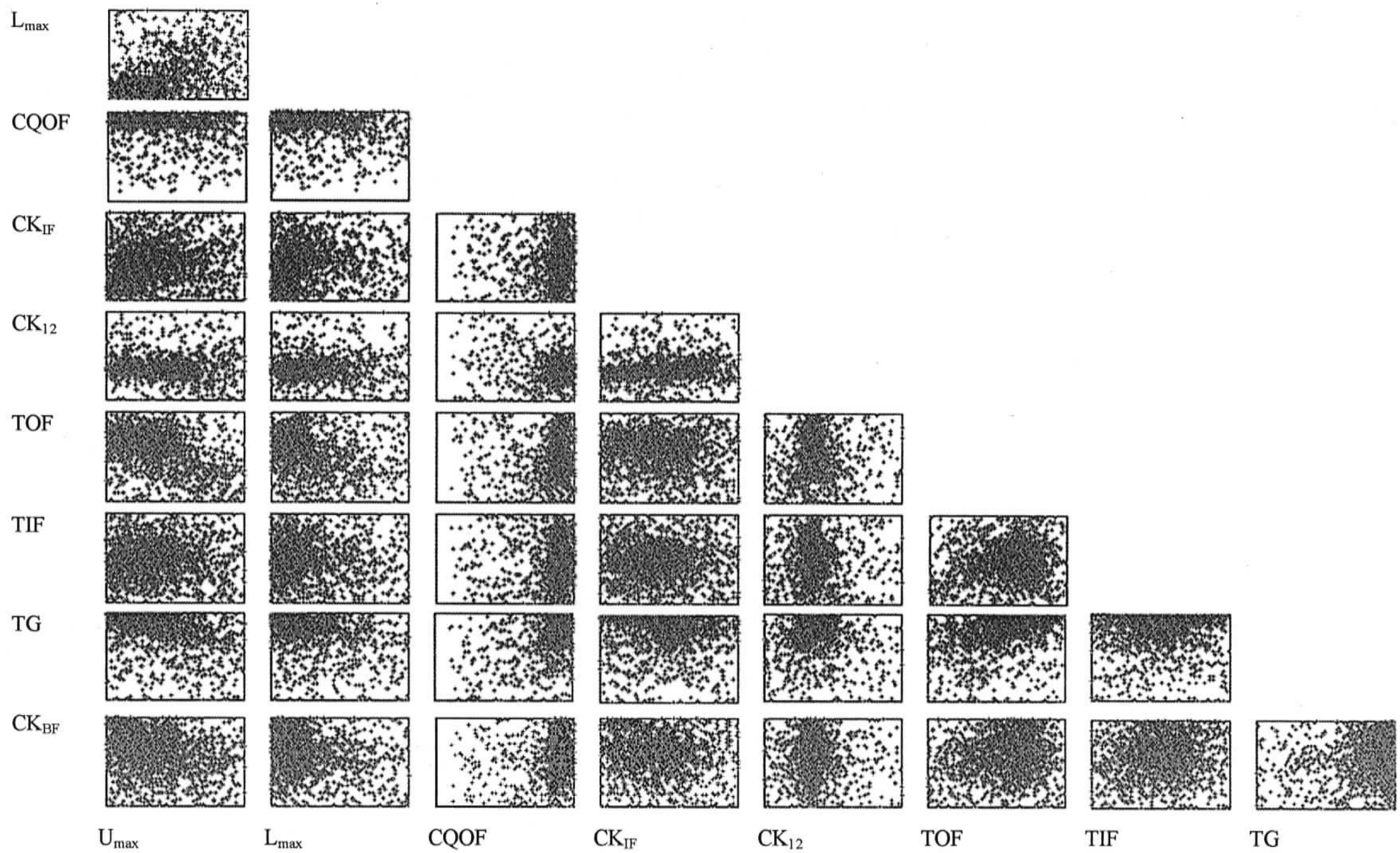


Figure 4-11. *Interdependence of calibrated model parameters. Parameter ranges are normalized with respect to the upper and lower value limits as given in Figure 4-4. Large scatter of values implies weak correlations between the corresponding parameters.*

4.10. Sensitivity analysis

As was shown in Sections 4.7. and 4.8., most discrepancies between the observed and simulated hydrographs occurred during the snowmelt season. To explore the variability in simulated model response produced by uncertainty in parameter values, three snow module parameters were subjected to sensitivity analysis. These were: the dry temperature lapse rate, the wet temperature lapse rate, and the precipitation lapse rate. In the approach adopted here, for each simulation run a single parameter was varied at a time from its value as used during the validation and testing simulations described in previous sections. Also tested was the scenario with no adjustment for altitude zones employed, i.e. the case when the watershed was not divided into the elevation zones and the model output was calculated in a simple lumped approach for the entire area as whole. The effect on the simulated hydrograph was assessed quantitatively by the Nash-Sutcliffe coefficient of efficiency, R^2 and the percent difference between the observed and simulated runoff volumes. The snow module parameter values used in the sensitivity analysis as well as performance statistics obtained are presented in *Table 4-7.* Comparing the graphical plots of simulated and observed hydrographs made qualitative assessment of the sensitivity to each examined parameter. *Figure 4-12.* and *Figure 4-13.* illustrate the measured hydrograph, hydrograph obtained by the calAll calibration run, and the hydrographs resulting from the sensitivity tests.

Table 4-7. *Results of the sensitivity analysis for the calibration period of August 1983-July 1986.*

Parameter	Parameter value	Performance statistics	
		R^2	WB
Dry temperature lapse rate (deg. C/100m)	0.8	0.595	19.6
Dry temperature lapse rate (deg. C/100m)	0.9	0.587	19.5
Dry temperature lapse rate (deg. C/100m)	1.0	0.579	19.6
Wet temperature lapse rate (deg. C/100m)	0.4	0.581	21.2
Wet temperature lapse rate (deg. C/100m)	0.5	0.579	19.6
Wet temperature lapse rate (deg. C/100m)	0.6	0.595	18.3
Wet temperature lapse rate (deg. C/100m)	0.7	0.522	17.7
Precipitation lapse rate (mm/100m)	0.1	0.578	21.2
Precipitation lapse rate (mm/100m)	0.33	0.579	19.6
Precipitation lapse rate (mm/100m)	0.5	0.579	18.3
Precipitation lapse rate (mm/100m)	1.0	0.577	14.7
Precipitation lapse rate (mm/100m)	2.0	0.559	7.4

Precipitation lapse rate (mm/100m)	3.0	0.524	0.1
Precipitation lapse rate (mm/100m)	3.6	0.493	-4.2
Precipitation lapse rate (mm/100m)	4.0	0.470	-7.1
No altitude zones adjustment applied		0.495	25.1

R2 - Nash and Sutcliffe coefficient of efficiency, WB – water balance (% difference between observed and simulated runoff volumes).

Three values of the dry temperature lapse rate, which were close to the standard adiabatic lapse rate of 0.98 °C/100 m, were tested for their effects on model response. The hydrographs obtained had almost identical shape with an exception of the end of the snow melting period when higher lapse rates yielded higher discharge values. The performance statistics for all three simulations were also similar.

Much more variation in model output was found for altered values of the wet temperature lapse rate. This might be expected, as the wet temperature lapse rate is also more variable in natural systems. It can change values for specific meteorological events and for specific locations. The wet temperature lapse rate of 0.4 °C/100 m did not reproduce the hydrograph during the snowmelt season correctly. The discharges were much underestimated and the dynamics of the hydrograph was not captured properly. On the contrary, the use of the lapse rates of 0.6 and 0.7 °C/100 m resulted in exaggeration of the peak flows and shifted timing, especially during the final periods of the snowmelt season. The lapse rate of 0.5 °C/100 m seemed to provide the hydrograph with the closest match to the observed river discharges. Overall, the model is most sensitive to the values of the wet temperature lapse rate in terms of proper timing and volume of peak flows and simulating the runoff behaviour during the melt of snowpack.

As can be seen in *Figure 4-13.*, the different values of the precipitation lapse rate affect mainly the volume of peak flows and the dynamics of hydrograph during the late snowmelt period. The model performance statistics (*Table 4-7.*) show that higher precipitation correction factor can yield a better simulation of water balance. However, this is achieved at the expense of worse representation of the overall shape of the hydrograph as assessed numerically by the lower values of the coefficient of efficiency R^2. The precipitation lapse rate of 0.33 mm/100 m derived from regression analysis provided a good compromise choice for the precipitation correction and was therefore used for model validation simulations.

To evaluate the contribution of the elevation zones adjustment for snow accumulation and snow melt simulations, a model run was carried out with no altitude zones taken into account, i.e. the whole watershed was treated as one unit with the same temperature and precipitation input. A simplified model exaggerated some of the peak flows and was not able to capture the dynamics of the runoff behaviour during the snowmelt season. Almost not runoff was produced suggesting the need for a model set-up where the spatial discretization for vertical zones would be accounted for.

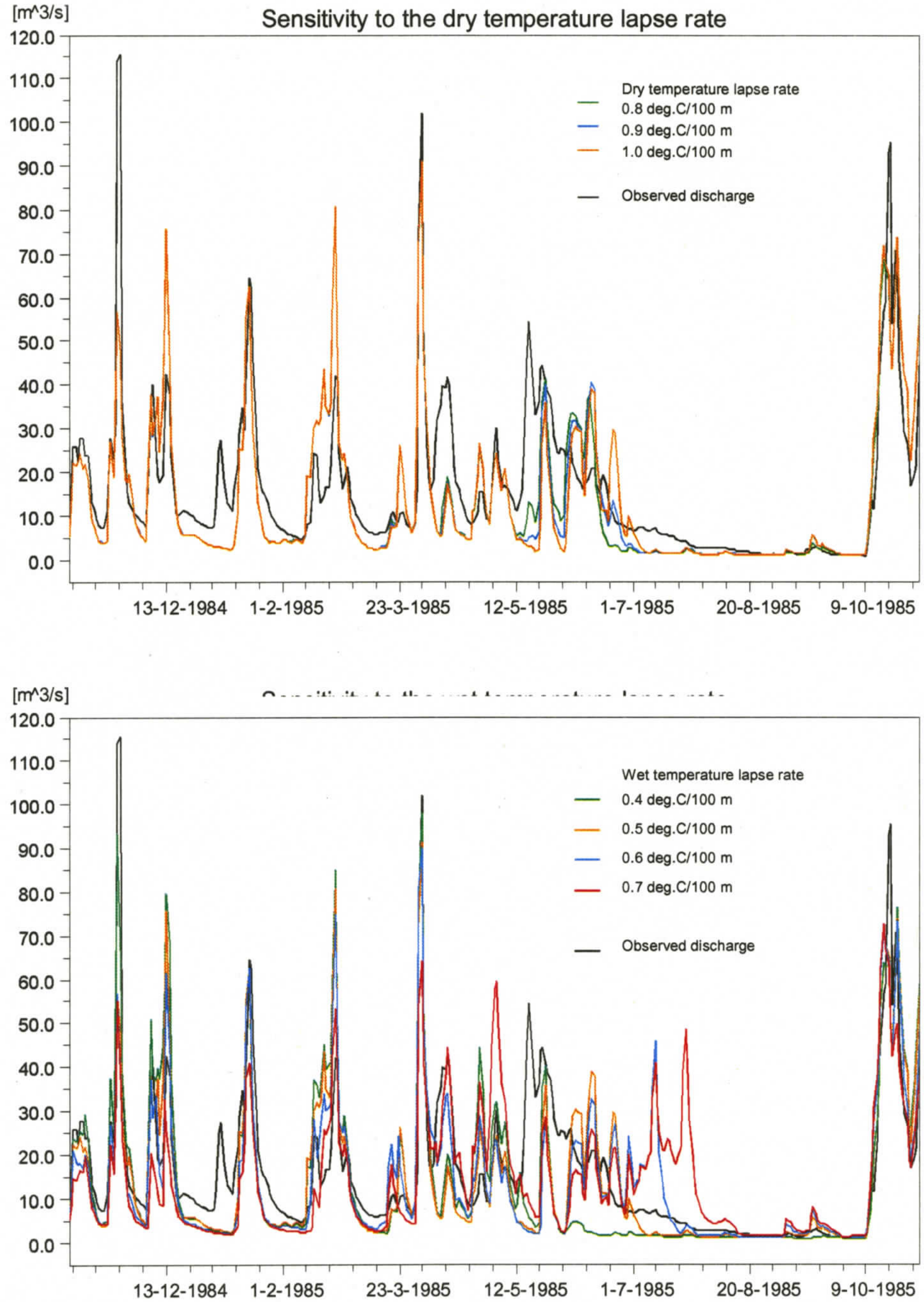
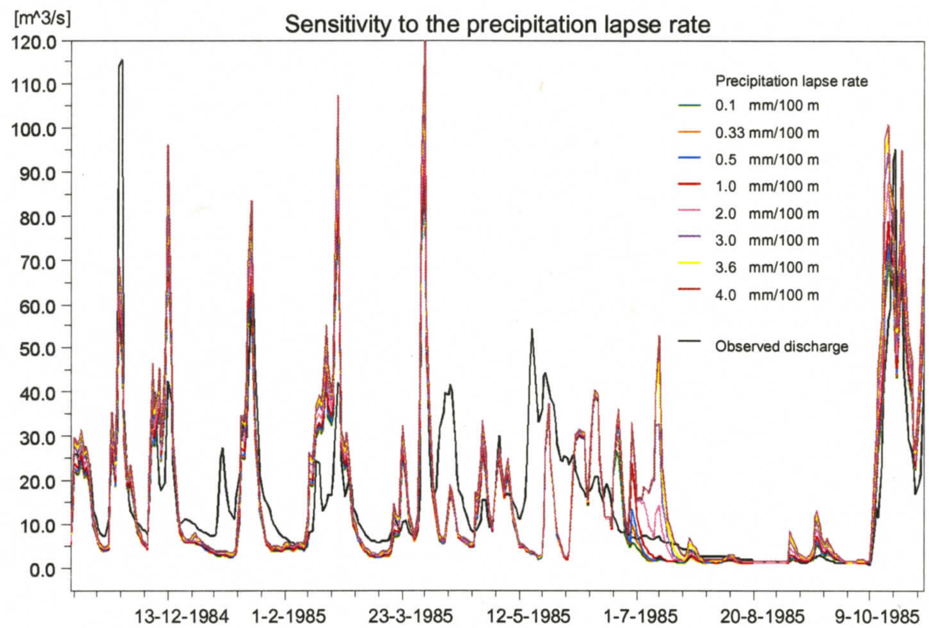


Figure 4-12. *Test of sensitivity to the dry and wet temperature lapse rates – comparison of observed and test hydrographs.*



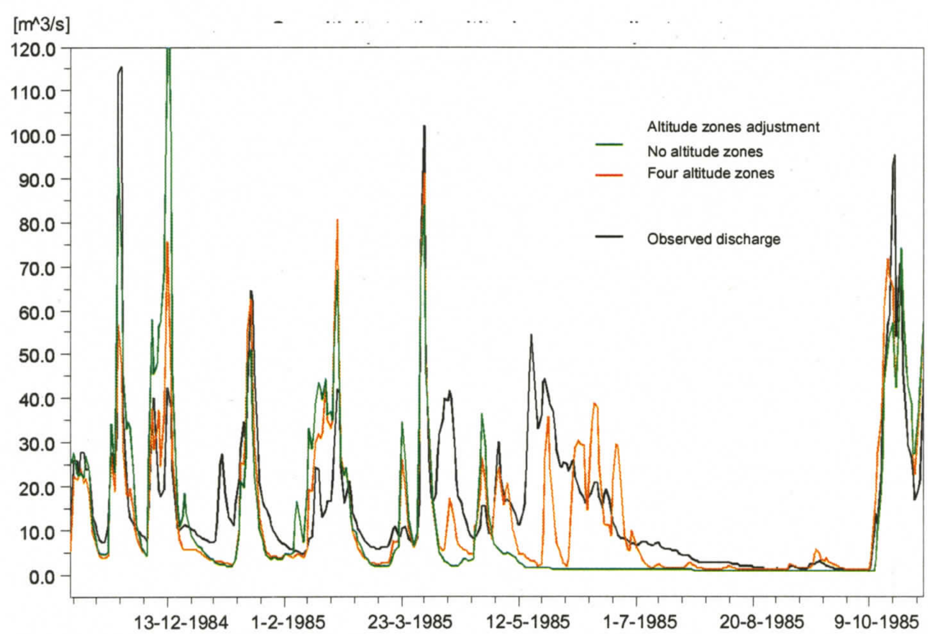


Figure 4-13. *Test of sensitivity to the precipitation lapse rate and to the altitude zones adjustment – comparison of observed and test hydrographs.*

4.11. Discussion

The thesis project applied a systematic procedure for a construction, calibration, and validation of a lumped hydrologic model and illustrated some of the problems involved. With only conventional data being available for the modeling exercise, i.e. not expanded by a specific fieldwork program, and rather limited knowledge about particular conditions in the watershed, the model produced moderately good simulation results when parameters had been calibrated against recorded discharge data. In general, the differences between observed data and simulated model output can be caused by several sources of error (Melching, 1995; Refsgaard, 1996), most of which possibly also apply to the present study:

- Errors in meteorological input data, for example precipitation, temperature, evaporation, representing temporal and spatial input conditions over the watershed.
- Errors in recorded data, for example river discharge or groundwater heads, that are used for comparison with the simulated model response.
- Errors inherent in the model structure resulting from a simplified, incomplete, or biased model set-up.
- Random temporal and spatial fluctuations inherent in natural processes of runoff generation.

The quality of input precipitation and temperature data is crucial for obtaining good model performance. Since there is no meteorological station within the watershed area that would provide long-term precipitation, temperature, and/or other useful data, the recordings from the Port Hardy A station were used for the modeling. Precipitation and temperature series had to be adjusted for the four elevation zones based on the results of regression analysis. However, these adjustments might not adequately reflect a real situation in the river basin. Due to the inadequate network of climate stations established in the north-east Vancouver Island, relatively large watershed area and substantial topographic variations not captured by the model, the weather conditions were not represented sufficiently, thus introducing errors in model simulations. The temperature lapse rates used in the modeling were based on the values published in the literature and derived from the regression analysis. It is recognized that these values might differ for specific catchments and also for specific meteorological conditions. Therefore, generalization of the lapse rate parameters also contributed to the modeling uncertainties.

As a part of preliminary analysis, the spatial variations of precipitation over the Tsitika River Watershed and Port Hardy A station were explored using the gridded dataset of monthly precipitation developed for the Climate Research Brand of the Meteorological Service of Canada

(Seglenieks and Soulis, 2000). The dataset contains monthly mean maximum and minimum precipitation values for the whole Canada with a spatial resolution of 50km by 50km. When accumulated annual values for the highest elevations over the watershed were examined, they seemed to be very high (over 4400 mm/year). As the precipitation dataset "is very much a research dataset and will continue to evolve and be modified as additional data are included and improved procedures implemented" (Skinner, 2001) and the precipitation for top altitudes was thought to be unrealistically overestimated, the precipitation lapse rate used for the simulations was not based on this dataset.

Several experimental precipitation correction coefficients were analyzed during the modeling exercise. It was found that a much better water balance estimates could be achieved when a correction factor of about 3.0 mm/100 m was used (on average 5% difference between the observed and simulated runoff volumes). However, the inspection of a hydrograph revealed that underestimation of water flows in certain periods (especially during the snow-melt season) was counterbalanced by exaggeration of flows during other periods. Hence the errors in input data and model structure were compensated for by model parameter estimation during model calibration. Although the water balance improved, the preference was given to the use of lapse rates as derived by regression analysis as those seemed to be more reliable and provided a closer match between the simulated and observed hydrographs. A sensitivity analysis of the model response to the to the dry and wet temperature lapse rates showed that the model behaviour was particularly affected by the values of the saturated adiabatic lapse rate. This suggests a need for gathering more local temperature data to represent the conditions in the watershed and to improve the simulation outputs.

Mean monthly estimates of potential evapotranspiration were calculated by Thornthwaite-type water balance model using precipitation and temperature values as input variables. This is a very approximate estimate that could not be verified by ancillary data due to the lack of direct local observations. In addition, any errors present in meteorological data cascade further through the modeling procedure and affect the reliability of evapotranspiration estimates and consequently the modeling performance. Since both precipitation and temperature are important and sensitive input data, it is recommended that these variables should be given priority when the improvement of the quality of hydrologic simulations is sought.

Only river discharge measurements were available for the comparison with the simulated model output. No apparent irregularities in the discharge series, which might have indicated for example a change of a hydrometric station location or a method of measurements, were observed.

It is unknown to what level these data might be erroneous or error-free and to what degree the uncertainties associated with them might affect the calibration procedure and simulation results.

Conceptually, the NAM-based hydrologic model of the Tsitika River Watershed represents several components of the rainfall-runoff process. Based on the meteorological input data it produces watershed runoff that is split into overland flow, interflow, and baseflow. This is done by continuously accounting for the water content in four interconnected storages, namely the snow storage, surface storage, lower zone (root zone) storage, and groundwater storage.

The snow component was included in the modeling because the accumulation and melt of snow occurs in the Tsitika River Watershed. Precipitation is retained in the snow storage during cold periods and subsequently the snow is melted during warmer parts of the year. The Tsitika River model does have troubles with the proper simulation of the snowmelt season. The model's inability to track the meltwater might be caused by: (1) generalizations associated with the degree-day approach, which was taken to calculate the snowmelt, (2) insufficient discretization of a watershed into altitude zones, (3) the use of inappropriate snow parameter values, and (4) insufficient depiction of the effects of forest removal and regrowth on the snowpack dynamics. In general, the conversion of ice/snow into water is a complicated process. Many factors, which are not adequately accounted for in the simplified lumped hydrologic model, affect the snowmelt. In particular, the following factors are usually involved (USACE, 1998):

- Short-wave radiation – solar radiation providing the most important source of energy available to the snowpack. The amount of usable energy depends on latitude, aspect of the surface slope, season, time of day, cloud cover conditions, forest cover, the reflectivity of the snow (albedo).
- Long-wave radiation – energy radiated from the snowpack to the atmosphere.
- Turbulent exchange of energy between the atmosphere and snowpack through the processes of convection (transfer of sensible heat from warm air advected over the snow surfaces) and condensation (exchange of latent heat when water vapour from the atmosphere is condensed on the snow).
- Heat entering the snowpack by solid conduction from the ground.
- Heat convected from the snow by rainfall.
- Changes in the character of the snow crystals – "ripening" of the snowpack.
- Changes in the snow temperature, depth, and density of the snowpack.
- Movement of meltwater through the snowpack.
- The occurrence of frozen soil mantle and frozen ground.

- The presence of glaciers.

Detailed, comprehensive physical models could be utilized to properly simulate the changes in snow conditions. The use of such a model might possibly improve the computation of water balance and the calculation of a hydrograph during the snow accumulation/melt season. However, the requirements for input data would increase dramatically and would most likely not be met by the present availability of local observations. Due to the data restrictions only a simple degree-day method could have been applied in the present project although this approach was found to be insufficient for reproducing the hydrologic behaviour of the study watershed.

The model does not explicitly take into account the effects of forest canopy removal and regrowth on the build-up and melting of snowpack. Forest openings have more snow accumulation than surrounding forests because less tree canopy blocks snow from reaching the ground surface. The snowmelt is faster in canopy gaps due to the higher rates of convection and condensation over the snow surfaces in open areas. Greater snow accumulation and snowmelt generate large inputs of water to the soil and increase runoff, especially during rain-on-snow events. The rainfall combined with the rapid melting of the snow results in peak flow discharges of greater magnitude. The underestimation of some of the simulated peak flows in the modeling of snowmelt season might suggest insufficient handling of rain-on-snow events in the Tsitika River Watershed model.

Modeling results might also be affected by structural simplifications of the surface and root zone model components and by not accounting for the spatial representation of land cover changes. For example, the removal and regrowth of forest affect evapotranspiration and cloud/fog water interception and hence influence the surface, intermediate and low flows. Removal of trees reduces transpiration demands, evaporation from the canopy and the storage of water in the canopy. Therefore, increased water delivery to the soil and reduced evapotranspiration will increase runoff. In the Tsitika River Watershed evapotranspiration is an important factor controlling the soil moisture and affecting the runoff, especially in early fall when temperatures are optimal for transpiration by vegetation, water is taken up from the soil, soil moisture is relatively low after dry summer and rainfall input is also low (*Figure 3-11.*). Forest removal also reduces the cloud/fog water interception resulting in decreased throughfall and hence reduced soil moisture and runoff. The cloud water interception affects intermediate flows, low flows and consequently the runoff mainly in summer and early fall when air temperatures are relatively high, soil moisture content low and precipitation events scarce (Jones, 2000; Pike and Scherer, 2003). The difficulties associated with the simulation of intermediate and low flows might also be attributed to the simplifications of model structure associated with the modeling of evapotranspiration and cloud water interception processes.

In the modeling exercise it was assumed that hydrogeological boundaries of the watershed coincide with the topographic division although in reality this might not be exactly so. Local geological conditions may generate the drainage to or from neighbouring watersheds. Although the NAM modeling code allows user to specify the proportion of the groundwater recharge that is drained to or from adjacent catchments this option was not used in the study.

In case of either manual or automatic calibration, it is attempted to specify the values of model parameters in such a way that the model response closely matches the historical input-output data. The errors caused by the usage of non-optimal parameter values should be minimized by model calibration. It is important to consider various sources of uncertainty because model calibration may compensate for other sources of errors. The modeller should also have in mind the fact that model calibration might not yield a single "best" set of parameter values applicable to all purposes of the model usage. As the calibration example in Section 4.7. showed, the trade-offs exist between the fitting of different objectives of a hydrologic system. Multiple parameter combinations may result in comparable modeling performance. An identification of the most suitable parameter set is thus strongly dependant on different goals of a hydrologic model application and on the selection of performance criteria.

Every watershed is a unique physical system with many complex processes involved in the generation of runoff and routing of water. Similarly, every meteorological event is site-specific and unique. Such topographically diverse system as is the Tsitika River Watershed is more likely to exhibit large variations of physical processes both in time and space. Therefore, errors resulting from inevitable simplifications (and ultimately impossibility of perfect reproduction) of temporal and spatial characteristics of the behaviour of a natural system also influence and deteriorate the quality of modeling output.

Overall, it can be concluded that the construction of a hydrologic model is not an easy and straightforward task. The many uncertainties associated with the modeling process influence the quality of simulation output. In this project, the greatest restrictions were related to the (un)availability of reliable data for model set-up and validation. However, it is believed that a more experienced modeller could possibly build a better-structured model yielding a more credible performance results.

5. SUMMARY AND CONCLUSIONS

There has been a considerable interest in the use of hydrologic models for both research purposes and for operational practice. Many different modeling systems have been developed aiming at different purposes of their application. The present thesis documented a systematic procedure for using a MIKE 11/NAM-based rainfall-runoff model to simulate the watershed runoff and illustrated some of the problems involved. The study described the steps required for the model construction and parameterization, paid a special attention to automatic calibration emphasizing different calibration objectives, presented the split-sample testing scheme for model validation, and explored the uncertainties associated with several model parameters.

5.1. The usefulness of conventional data for model construction

Data collection formed an important part of the overall modeling project. It was attempted to gather as much conventional data as possible. Topographic data, Landsat imagery and river discharge measurements were available for the Tsitika River Watershed. As there was no long-term climate station operational in the study area, the temperature and precipitation series had to be extracted and modified from observations made at the nearest climate station having a record of meteorological data suitable for modeling exercise. The temperature and precipitation measurements acquired at the Port Hardy A station were used and adjustments made based on the observations made at other climate stations on northern Vancouver Island. Due to the lack of satisfactory observations in the watershed area itself, it could not be verified how well the adjusted series depicted the real situation in the watershed and how much was the quality of modeling results affected by the usage of adjusted input meteorological variables. However, if a better and more reliable simulation output is sought, it is suggested that a much finer spatial resolution and preferably even more types of climate data are obtained for the Tsitika River Watershed to provide adequate description of spatial and temporal characteristics of meteorological events.

The series of mean daily river discharge at the watershed outlet were sufficient for continuous simulations at daily time step. Nevertheless, any future availability of discharge measurements at several stations within the watershed area might offer a good opportunity to split the watershed into subunits and make internal, i.e. within the watershed area, validation of modeling simulations. Landsat imagery is a useful data source for deriving information about the land cover and changes in land cover over time, provided the cloud-free imagery can be obtained for the area and period of interest.

5.2. Limitations in model performance and the effects of land cover changes

An automatic calibration procedure based on the Shuffled Complex Evolution algorithm was applied to determine the values of the nine structural model parameters. The optimization of parameter values was performed by calibration against time series of river discharge at watershed outlet. Several combinations of the four objectives usually considered in the calibration process were explored. The objectives included: (1) a good agreement of the overall shape of the hydrograph, (2) a good agreement of the overall water balance, (3) a good agreement of the peak flows with respect to timing, rate and volume, and (4) a good agreement of the low flows. It was shown that trade-offs existed between the different calibration objectives. It was found that no single set of parameter values was able to optimize all objectives concurrently, thus illustrating the problem of non-uniqueness in model calibration. However, the model might produce useful simulation outputs when calibrated and used for specific purposes, for example if the user is mainly interested in simulations of peak flows. It is therefore suggested to calibrate the values of structural model parameters for a particular calibration objective and to utilize them for corresponding model applications. Similarly, if the simulation of low flows is required, the model might offer satisfactory outputs, provided it has been calibrated for this specific purpose and a more deficient simulation of peak flows is not of a serious concern.

The calibrated model was subjected to validation based on the split-sample testing procedure. The model performance was evaluated for one 3-year validation period and its subperiods excluding the snowmelt season and for the two testing periods with corresponding subperiods. Overall, the model produced results comparable to those obtained during the calibration period, although the simulation of water balance during the first testing period was worse than during other simulation runs. The first testing period corresponds to the onset of more extensive logging in the watershed. This might suggest that the generation and routing of runoff was affected by land cover/land use changes. However, it is hard to quantify the effects or to differentiate between the contributions of different factors such as the changes in land cover or the particular meteorological conditions occurring during the concerned period. In general, the model yielded moderately good simulations of watershed runoff with most problems arising during the snowmelt periods. The model did not reproduce the accumulation and melting of snow correctly, which can be explained by shortcomings in meteorological data, insufficient representation of input temporal and spatial conditions over the watershed, and by errors inherent in the model structure resulting from a simplified model set-up that does not account for many complex processes associated with the accumulation of snow, the changes in the snowpack character, and with the melting of snowpack.

Future work might help to improve simulation results by incorporating a more sophisticated snow module that would take into account the processes of snow accumulation and snow melt in a more complex way. Another possibility for future research is to explore the usefulness of applying a more spatially distributed approach, i.e. to divide the watershed into subunits based on topography and land cover characteristics and then to evaluate simulations results. Also interesting might be a comparison of simulation outputs produced by the model based on the MIKE 11/NAM modeling code with those obtained from model simulations using other rainfall-runoff modeling packages.

5.3. Parameter uncertainty

The comparison of model parameters calibrated on two different 3-year periods showed that all nine structural parameters that were subjected to calibration were associated with some uncertainty. The most uncertain parameters were the threshold value for the interflow TIF, the time constant for interflow from the surface storage CK_{IF}, and the time constant for baseflow CK_{BF}. These parameters regulate the recession of intermediate and low flows, which were more problematic to reproduce during simulations. The parameters with the smallest uncertainty were the overland flow runoff coefficient CQOF and the time constant for overland flow and interflow routing CK_{12}, the parameters that control the peak flow recession and the volume of peak flows. These findings correspond to those obtained by other researchers, for example in the study of Madsen (2000). The movement of water through the subsurface environment is a complicated process and it is therefore not surprising that effective values of parameters controlling the intermediate and low flows exhibit larger uncertainties. The examination of the correlation between different parameters revealed weak interdependencies, thus implying that the number of these structural parameters cannot be easily reduced.

A sensitivity of the model output to several of the snow module parameters was also examined. The vertical discretization of the watershed into the four elevation zones significantly improved the simulations during the snowmelt period when compared with the model run performed for the study area as a whole. The model response was found to be sensitive especially to the values of the wet temperature lapse rate and to the precipitation lapse rate. These parameters are also more variable – both spatially and over time – in natural systems and they significantly affect hydrologic processes in river basins. It is therefore assumed that a better spatial coverage of temperature and precipitation observations might help to derive more reliable values and to reduce the error caused by uncertainties associated with these parameters.

5.4. Final conclusion

The thesis provided insight into the capabilities and limitations of a lumped hydrologic model for simulations of watershed runoff in a medium-sized watershed when only conventional data were available for the model set-up and validation. Hydrologic models, such as the one presented in the thesis, might be useful tools for conceptualizing our knowledge and testing the hypothesis about processes active in a particular watershed or can assist hydrologists in practical applications provided the restrictions in data availability, data quality, purpose of model usage, modeling experiences, and simplifications inherent in the model structure are carefully taken into account.

6. REFERENCES

Abbott, M.B., Bathurst, J.C., Cunge, J.A., O'Connell, P.E. and Rasmussen, J., 1986. An introduction to the European Hydrological System - Systeme Hydrologique Europeen, 'SHE', 1: History and philosophie of a physically-based, distributed modelling system. Journal of Hydrology, 87: 45-59.

Alila, Y. and Beckers, J., 2001. Using numerical modelling to address hydrologic forest management issues in British Columbia. Hydrological Processes, 15(18): 3371-3387.

Anderton, S., Latron, J. and Gallart, F., 2002. Sensitivity analysis and multi-response, multi-criteria evaluation of a physically based distributed model. Hydrological Processes, 16(2): 333-353.

Andréassian, V., Perrin, C. and Michel, C., 2004. Impact of imperfect potential evapotranspiration knowledge on the efficiency and parameters of watershed models. Journal of Hydrology, 286(1-4): 19-35.

Bathurst, J.C., 1986. Sensitivity analysis of the Systeme Hydrologique Europeen for an upland catchment. Journal of Hydrology, 87(1-2): 103-123.

Bathurst, J.C., Ewen, J., Parkin, G., O'Connell, P.E. and Cooper, J.D., 2004. Validation of catchment models for predicting land-use and climate change impacts. 3. Blind validation for internal and outlet responses. Journal of Hydrology, 287(1-4): 74-94.

BCMF, 1990. B.C. Forest Service review of Tsitika Watershed. Updated technical background, British Columbia Ministry of Forests, Victoria, BC.

Beven, K.J., 1989. Changing ideas in hydrology - The case of physically-based models. Journal of Hydrology, 105(1-2): 157-172.

Beven, K.J., 2001a. How far can we go in distributed hydrological modelling? Hydrology and Earth System Sciences, 5(1): 1-12.

Beven, K.J., 2001b. Rainfall-runoff modelling: The primer. John Wiley & Sons Ltd., Chichester, UK, 360 pp.

Beven, K.J., 2002. Towards an alternative blueprint for a physically based digitally simulated hydrologic response modelling system. Hydrological Processes, 16(2): 189-206.

Beven, K.J. and Binley, A.M., 1992. The future of distributed models: model calibration and uncertainity prediction. Hydrological Processes, 6(3): 279-298.

Beven, K.J. and Fisher, J., 1996. Remote sensing and scaling in hydrology. In: J.B. Stewart, E.T. Engman, R.A. Feddes and Y. Kerr (Editors), Scaling up in Hydrology using Remote Sensing. John Wiley & Sons Ltd., pp. 1-18.

Biftu, G.F. and Gan, T.Y., 2001. Semi-distributed, physically based, hydrologic modeling of the Paddle River Basin, Alberta, using remotely sensed data. Journal of Hydrology, 244(3-4): 137-156.

Boegh, E. et al., 2004. Incorporating remote sensing data in physically based distributed agro-hydrological modelling. Journal of Hydrology, 287(1-4): 279-299.

Bosh, J.M. and Hewlett, J.D., 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. Journal of Hydrology, 55(1-4): 3-23.

Bowling, L.C., Storck, P. and Lettenmaier, D.P., 2000. Hydrologic effects of logging in western Washington, United States. Water Resources Research, 36(11): 3223-3240.

Bronstert, A., Niehoff, D. and Bürger, G., 2002. Effects of climate and land-use change on storm runoff generation: present knowledge and modelling capabilities. Hydrological Processes, 16(2): 509-529.

Bultot, F., Dupriez, G.L. and Gellens, D., 1990. Simulation of land use changes and impacts on the water balance - A case study for Belgium. Journal of Hydrology, 114(3-4): 327-348.

Calder, I.R., 1993. Hydrologic effects of land-use change. In: D.R. Maidment (Editor), Handbook of hydrology. McGraw-Hill, Inc., pp. 13.1-13.50.

Canada, E., 2000. HYDAT - National Water Data Archive. Environment Canada.

Christiaens, K. and Feyen, J., 2002. Constraining soil hydraulic parameter and output uncertainty of the distributed hydrological MIKE SHE model using the GLUE framework. Hydrological Processes, 16(2): 373-391.

Clarke, R.T., 1973. A review of some mathematical models used in hydrology, with observations on their calibration and use. Journal of Hydrology, 19(1): 1-10.

DHI, 2003a. MIKE 11 - Reference Manual. Danish Hydraulic Institute, 460 pp.

DHI, 2003b. MIKE SHE - Reference Manual. Danish Hydraulic Institute, 174 pp.

DHI, 2004. MIKE 11 - Reference Manual. DHI Software.

Dingman, S.L., 2002. Physical Hydrology. Prentice Hall, 646 pp.

Downer, C.W. et al., 2003. The case for physically-based distributed hydrologic modeling approaches for the U.S. Army Corps of Engineers civil works projects. In: U.S.A.C.o. Engineers (Editor), Watershed System Conference 2003, Portland, OR.

Duan, Q., Sorooshian, S. and Gupta, V.K., 1992. Effective and efficient global optimization for conceptual rainfall-runoff models. Water Resources Research, 28(4): 1015-1031.

Eckhardt, K., Breuer, L. and Frede, H.-G., 2003. Parameter uncertainty and the significance of simulated land use change effects. Journal of Hydrology, 273(1-4): 164-176.

Engman, E.T., 1995. Recent advances in remote sensing in hydrology. Reviews of Geophysics, 33 Supplement: 967-975.

Ewen, J. and Parkin, G., 1996. Validation of catchment models for predicting land-use and climate change impacts. 1. Method. Journal of Hydrology, 175(1-4): 583-594.

Fisheries, M.o., 1999. B.C. Watershed Atlas Tsitika River Group. Ministry of Fisheries, Fisheries Inventory Section, Victoria, BC.

Fortin, J.-P. et al., 2001. A distributed watershed model compatible with remote sensing and GIS data. II: Application to Chaudière watershed. Journal of Hydrologic Engineering, 6(2): 100-108.

Franchini, M. and Pacciani, M., 1991. Comparative analysis of several conceptual rainfall-runoff models. Journal of Hydrology, 122(1-4): 161-219.

Gan, T.Y. and Biftu, G.F., 1996. Automatic calibration of conceptual rainfall-runoff models: Optimization algorithms, catchment conditions, and model structure. Water Resources Research, 32(12): 3513-3524.

Grayson, R.B., Moore, I.D. and McMahon, T.A., 1992. Physically based hydrologic modeling, 2. Is the concept realistic? Water Resources Research, 28(10): 2659-2666.

Guthrie, R.H., 1997. The characterization and dating of landslides in the Tsitika River and Schmidt Creek Watersheds, Northern Vancouver Island, British Columbia, University of Victoria, Victoria, BC.

Hudson, R., 2001. Comparative analysis of sediment production in two partially harvested watersheds in coastal British Columbia. Forest Research Technical Report TR-010 Hydrology, Nanaimo, BC.

Hydrocomp, 2001. Hydrologic simulation models: An overview. http://www.hydrocomp.com/ simoverview.html, Accessed: February 17, 2004.

Jenson, S.K. and Domingue, J.O., 1988. Extracting topographic structure from digital elevation data for geographic information system analysis. Photogrammetric Engineering and Remote Sensing, 54(11): 1593-1600.

Jones, J.A., 2000. Hydrologic processes and peak discharge response to forest removal, regrowth, and roads in ten small experimental basins. Water Resources Research, 36(9): 2621-2642.

Khu, S.T. and Madsen, H., 2005. Multiobjective calibration with Pareto preference ordering: An application to rainfall-runoff model calibration. Water Resources Research, 41: W03004.

Kite, G.W., 1989. Use of time series analysis to detect climatic change. Journal of Hydrology, 111(1-4): 259-279.

Kite, G.W., 1991. Time series analysis, Hydrologic Applications : Computer Programs for Water Resources Engineering. Water Resources Publications, pp. 120-136.

Kite, G.W. and Kouwen, N., 1992. Watershed modeling using land classifications. Water Resources Research, 28(12): 3193-3200.

Kite, G.W. and Pietroniro, A., 1996. Remote sensing applications in hydrological modelling. Hydrological Sciences Journal, 41(4): 563-592.

Klemeš, V., 1983. Conceptualization and scale in hydrology. Journal of Hydrology, 65(1-3): 1-23.

Klemeš, V., 1986a. Dilettantism in hydrology: Transition or destiny? Water Resources Research, 22(9): 177S-188S.

Klemeš, V., 1986b. Operational testing of hydrological simulation models. Hydrological Sciences Journal, 31(1): 13-24.

Kokkonen, T.S. and Jakeman, A.J., 2001. A comparison of metric and conceptual approaches in rainfall-runoff modeling and its implications. Water Resources Research, 37(9): 2345-2352.

Koren, M., 1995. The world of spatial information. Geoinfo, 2(1): 25-29 (In Slovak).

Koster, R.D., Houser, P.R. and Engman, E.T., 1999. Remote sensing may provide unprecedented hydrological data. EOS, Transactions, American Geophysical Union, 80(156).

Kuczera, G., Raper, g.P., Brash, N.S. and Jayasuriya, M.D., 1993. Modelling yield changes after strip thinning in a mountain ash catchment: an exercise in catchment model validation. Journal of Hydrology, 150(2-4): 433-457.

Kundzewicz, Z.W. and Robson, A.J., 2004. Change detection in hydrological records—a review of the methodology. Hydrological Sciences Journal, 49(1): 7-19.

Kuo, W.-L. et al., 1999. Effect of grid size on runoff and soil moisture for a variable-source-area hydrology model. Water Resources Research, 35(11): 3419-3428.

Loague, K.M. and Freeze, R.A., 1985. A comparison of rainfall-runoff modeling techniques on small upland catchments. Water Resources Research, 21(2): 229-248.

Lørup, J.K., Refsgaard, J.C. and Mazvimavi, D., 1998. Assessing the effect of land use change on catchment runoff by combined use of statistical tests and hydrological modelling: Case studies from Zimbabwe. Journal of Hydrology, 205(3-4): 147-163.

Madsen, H., 2000. Automatic calibration of a conceptual rainfall-runoff model using multiple objectives. Journal of Hydrology, 235(3-4): 276-288.

Madsen, H., Wilson, G. and Ammentorp, H.C., 2002. Comparison of different automated strategies for calibration of rainfall-runoff models. Journal of Hydrology, 261(1-4): 48-59.

Martinec, J. and Rango, A., 1989. Merits of statistical criteria for the performance of hydrological models. Water Resources Bulletin, 25(2): 421-432.

Melching, C.S., 1995. Reliability estimation. In: V.P. Singh (Editor), Computer models of watershed hydrology. Water Resources Publications, Highlands Ranch, Colorado, pp. 69-118.

Merz, R. and Blöschl, G., 2004. Regionalisation of catchment model parameters. Journal of Hydrology, 287(1-4): 95-123.

Michaud, J. and Sorooshian, S., 1994. Comparison of simple versus complex distributed runoff models on a midsized semiarid watershed. Water Resources Research, 30(3): 593-606.

Nash, J.E. and Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part I - A discussion of principles. Journal of Hydrology, 10(3): 282-290.

Nielsen, S.A. and Hansen, E., 1973. Numerical simulation of the rainfall-runoff process on a daily basis. Nordic Hydrology, 4: 171-190.

NISG, 1975. Tsitika-Schoen resources study. Volume II: Appendices, North Island Study Group.

O'Callaghan, J.F. and Mark, D.M., 1984. The extraction of drainage networks from digital elevation data. Computer Vision, Graphics and Image Processing, 28: 323-344.

Onstad, C.A. and Jamieson, D.G., 1970. Modelling the effects of land use modifications on runoff. Water Resources Research, 6(5): 1287-1295.

Parkin, G. et al., 1996. Validation of catchment models for predicting land-use and climate change impacts. 2. Case study for a Mediterranean catchment. Journal of Hydrology, 175(1-4): 595-613.

Pike, R.G. and Scherer, R., 2003. Overview of the potential effects of forest management on low flows in snowmelt-dominated hydrologic regimes. BC Journal of Ecosystems and Management, 3(1): 1-17.

Radziejewski, M. and Kundzewicz, Z.W., 2004. Detectability of changes in hydrological records. Hydrological Sciences Journal, 49(1): 39-51.

Rawls, W.J., Brakensiek, D.L. and Miller, N., 1983. Green-Ampt infiltration parameters from soil data. Journal of Hydraulic Engineering, 109(1): 62-70.

Refsgaard, J.C., 1996. Terminology, modelling protocol and classification of hydrological model codes. In: M.B. Abbott and J.C. Refsgaard (Editors), Distributed Hydrological Modelling. Kluwer Academic Publishers, pp. 17-39.

Refsgaard, J.C. and Henriksen, H.J., 2004. Modelling guidelines - terminology and guiding principles. Advances in Water Resources, 27(1): 71-82.

Refsgaard, J.C. and Knudsen, J., 1996. Operational validation and intercomparison of different types of hydrological models. Water Resources Research, 32(7): 2189-2202.

Sandholt, I. et al., 2003. Integration of earth observation data in distributed hydrological models: the Senegal River basin. Canadian Journal of Remote Sensing, 29(6): 701-710.

Schultz, G.A., 1988. Remote sensing in hydrology. Journal of Hydrology, 100(1-3): 239-265.

Schultz, G.A., 1997. Integration of remote sensing information: Digital elevation models and digital maps within a GIS to generate new spatial environmental data sets for water management purposes. In: N.B. Harmancioglu, M.N. Alpaslan, S.D. Ozkul and V.P. Singh (Editors), Integrated Approach to Environmental Data Management Systems. NATO Science Partnership Sub-series: 2. Kluwer Academic Publishers, pp. 153-170.

Schultz, G.A. and Engman, E.T. (Editors), 2000. Remote Sensing in Hydrology and Water Management. Springer Verlag, 473 pp.

Seglenieks, F. and Soulis, R., 2000. Generation of square grid normals for Canada - Phase 1, Meteorological Service of Canada, Downsview.

Shih, S.F., 1996. Integration of remote sensing and GIS for hydrologic studies. In: V.P. Singh and M. Fiorentino (Editors), Geographical Information Systems in Hydrology. Kluwer Academic Publishers, pp. 15-42.

Singh, V.P., 1995. Watershed modeling. In: V.P. Singh (Editor), Computer models of watershed hydrology. Water Resources Publications, Highlands Ranch, Colorado, pp. 1-22.

Skinner, W., 2001. Rehabilitated gridded Canadian historical air temperature and precipitation database. In: M.M. Burgess, Riseborough, D.W. and Smith, S.L. (Editor), Permafrost and glaciers/icecaps monitoring networks workshop - January 28-29, 2000. Report on the permafrost sessions. Geological Survey of Canada, Ottawa.

Smith, J.A., 1993. Precipitation. In: D.R. Maidment (Editor), Handbook of Hydrology. McGraw-Hill, pp. 3.2-3.3.

Smith, R.E., Goodrich, D.R., Woolhiser, D.A. and Simanton, J.R., 1994. Comment on "Physically based hydrologic modeling, 2, Is the concept realistic?" by R. B. Grayson, I. D. Moore, and T. A. McMahon. Water Resources Research, 30(3): 851-854.

Song, Z. and James, L.D., 1992. An objective test for hydrologic scale. Water Resources Bulletin, 28(5): 833-844.

Sorooshian, S. and Gupta, V.K., 1995. Model calibration. In: V.P. Singh (Editor), Computer models of watershed hydrology. Water Resources Publications, Highlands Ranch, Colorado, pp. 23-68.

Stewart, J.B. and Finch, J.W., 1993. Application of remote sensing to forest hydrology. Journal of Hydrology, 150(2-4): 701-716.

Tarboton, D.G., 1997. A new method for the determination of flow directions and upslope areas in grid digital elevation models. Water Resources Research, 33(2): 309-319.

Tarboton, D.G., 2002. Terrain Analysis Using Digital Elevation Models (TauDEM). Utah State University.

Todini, E., 1988. Rainfall-runoff modeling - Past, present and future. Journal of Hydrology, 100(1-3): 341-352.

TPC, 1978. Tsitika watershed integrated resource plan. Summary Report, Volume II., Tsitika Planning Committee, Victoria, BC.

USACE, 1998. Runoff from snowmelt, Engineer Manual 1110-2-1406. U.S. Army Corps of Engineers, Department of the Army.

Vázquez, R.F., Feyen, L., Feyen, J. and Refsgaard, J.C., 2002. Effect of grid size on effective parameters and model performance of the MIKE-SHE code. Hydrological Processes, 16(2): 355-372.

Vieux, B.E., 2001. Distributed Hydrologic Modeling Using GIS. Water Science and Technology Library, 38. Kluwer Academic Publishers, 312 pp.

Wilcox, B.P., Rawls, W.J., Brakensiek, D.L. and Wight, J.R., 1990. Predicting runoff from rangeland catchments: A comparison of two models. Water Resources Research, 26(10): 2401-2410.

Wood, E.F., Sivapalan, M., Beven, K.J. and Band, L., 1988. Effects of spatial variability and scale with implications to hydrologic modeling. Journal of Hydrology, 102(1-4): 29-47.

Yapo, P.O., Gupta, H.V. and Sorooshian, S., 1998. Multi-objective global optimization for hydrologic models. Journal of Hydrology, 204(1-4): 83-97.