STREAMFLOW MODELLING IN THE TOBIQUE BASIN

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ABSTRACT

Flow simulations of spring runoff periods in the Tobique Basin, New Brunswick, were recently undertaken using remotely sensed inputs and parameters - land-cover statistics, snow-cover extent and snowpack water equivalent - to assess the resulting improvements in flow forecasting precision with the SSARR model. The remotely sensed data along with the appropriate analysis techniques are described, the model calibration is discussed and the resulting flow comparisons with and without utilizing remote sensing are given. Finally, recommended modelling modifications, such as considering snowpack water by elevation bands and using a distributed watershed model, are described.

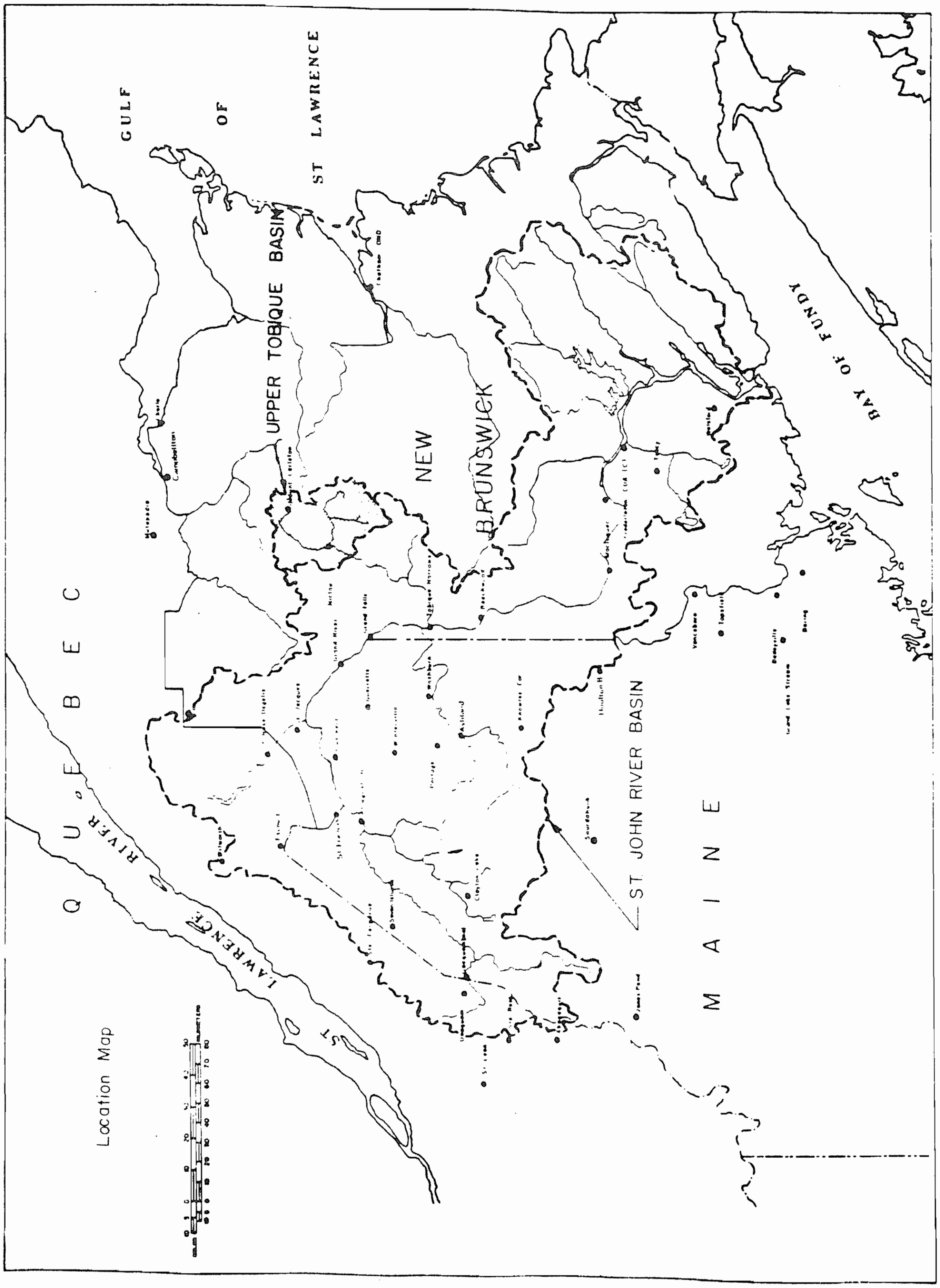
INTRODUCTION

In the following sections, the various aspects of applying remote sensed inputs to an operational SSARR model in order to determine the increased accuracies of flow forecastings are covered. The remotely sensed inputs are basin land-cover statistics, snow cover extents and snowpack water equivalents. The improvements in forecast accuracies were verified by means of flow simulations of a subbasin of the Tobique River watershed, a left basin tributary of the Saint John River. Various techniques were used to analyze the remotely sensed data, which were described in the following text, and the resulting flow simulations were compared with observed flows as well as flows forecasted during actual flow periods by the New Brunswick River Forecast Centre over two spring runoff periods. Finally, recommendations are given on types of models that are best suited to take advantage of the remotely sensed inputs, on the various remotely sensed parameters that can be utilized in these models, and on the kind of techniques that should be used to integrate the remotely sensed data with the model structures.

STUDY BASIN

The location of the Upper Tobique Basin within the boundaries of the Saint John Basin is given in Figure 1. The overall Tobique Basin has a drainage area of 4356 sq. km. and enters the main branch upstream of Perth/Andower. The actual basin modelled in this study is the drainage area upstream of the Riley Brook hydrometric station where the drainage area is 2230 km^2 and the drainage system is provided by two tributaries: one is the Little Tobique and the other is the Campbell River.

Most of the study basin is underlain by highly folded sedimentary rocks with the northern portion consisting predominantly of intrusive and extrusive igneous and flat lying sedimentary rocks. There are unconsolidated deposits on the valley floors. The predominantly land-cover types are coniferous and deciduous forests which make up 43 and 40 percent of drainage area, respectively. The remainder consists of lakes and


Location Map
QUEBEC
GULF OF ST LAWRENCE
UPPER TOBIQUE BASIN
NEW BRUNSWICK
ST. JOHN RIVER BASIN
MAINE
BAY OF FUNDY
ST LAWRENCE RIVER

agricultural lands. Flows have been recorded at the Riley Brook hydrometric station since 1954. There are two climatological recording stations within the study basin: one is at Nictau where precipitation and temperatures are recorded; the other is on Mount Carleton where, in addition to the above-stated two parameters, wind, hours of sunshine and evaporation are measured. There are an additional five stations within the close proximity of the basin which were used also to calculate basin wide averages.

In order to determine snow statistics data from six snow courses, data is collected and analyzed six times a year by the New Brunswick Electric Power Commission. The survey dates are January 31st, February 28th, March 15th, March 31st, April 15th and 30th. Recently, gamma ray flight surveys have been conducted along prescribed lines once a year in order to measure the snowpack water equivalents.

In the headwaters of the Tobique River Basin there are four storage reservoirs which provide storage for the 20 MW run-of-the-river hydro plant situated near the confluence with the Saint John River. The reservoirs are: Sisson, Trousers Lake, Long Lake and Serpentine Lake. The combined storage volumes exceed 192 mcm, and the Sission has a hydroelectric plant with 10 MW capacity.

SIMULATION MODEL

A conceptual, multi-basin hydrologic model known as SSARR was used in the study. This basin model consists of two major components - a generalized basin model which takes into account rainfall, snowmelt, interception, evapotranspiration, soil moisture, infiltration, runoff routing and snowpack cold content, liquid water content as well as snow conditioning. The other model component accounts for the hydraulics of the river system and reservoir operations.

The reasons for selecting this model were: it is the most common forecasting model currently used in Canada for flow forecasts for hydroelectric generation purposes and, the forecasting undertaken by the New Brunswick River Forecast Centre for all the modelled Saint John River tributaries use this model. The data on the Tobique River calibrations and previous forecasts was also provided by that organization.

REMOTELY SENSED DATA

Three SSARR inputs and parameters that can be remotely sensed on an operational basis are land cover, snow cover extent and snowpack water equivalent. The techniques of processing data on these characteristics and then integration into the SSARR model will be covered next.

Land-cover categories are conventionally derived from topographic maps, which are based on aerial surveys. A second method to determine land cover is the use of satellite imagery. The operational satellite that currently gives the best resolution and the highest accuracy is Landsat, in particular the Thematic Mappers (TM) of Landsat 4 and 5, which gives a pixel resolution of 30 meters.

During the melt season only coniferous forests would provide canopy cover and any significant evapotranspiration. An estimate of areas covered by softwoods would provide a representative springtime canopy cover for use in the SSARR model. In order to satisfy the input requirements of the model, an estimate of percent softwood is required as a single value over the entire sub-basin.

There are two main techniques of analysis for land cover classification using remotely sensed data. They are: 1) projection techniques and 2) computer assisted digital techniques.

The projection technique use remotely sensed images in a photographic positive format. They can be aerial photographs or preprocessed satellite imagery. These positives are inserted into a specialized projector where their images can be stretched, rotated and enlarged before being projected onto standard topographic maps. The land-cover classifications are subsequently delineated then planimetered from the image projected on topographic maps.

The second group of analysis techniques are computer assisted digital techniques and can be classified as supervised or unsupervised analyses. Unsupervised analyses are automatically completed by the computer system once the operator has "trained" the computer to recognize the different land-cover types. Using this method, a digital imagery is then automatically scanned to obtain the land-cover statistics. With supervised analyses the operator has control of the classification process and can interactively delineate the different land-cover statistics.

Another computer-assisted digital methodology was used for this application which combined the advantages of both techniques. This methodology couples full colour video digitized remotely-sensed images with a Geographic Information System (GIS). Lower cost preprocessed Landsat images in transparency or hard copy format are digitized by video techniques and analysed by GIS software routines residing on a microcomputer based system. The costs of applying this technique are lower than those for the projection technique while the degree of accuracy is comparable to full digital techniques since much of the analysis is performed by the computer.

Landsat TM images were chosen over Landsat Multispectral scanner (MSS) images primarily because of the higher resolution, but also because of the larger colour separation between forest types. Landsat MSS images require greater efforts to delineate coniferous and deciduous forests since the two types are subtle variations of one colour in this system.

Forestry inventory maps (1:20,000) were used to provide ground truth data and used as a basis for comparison. The comparisons of the analysis results with the ground truth data were used as a measure of accuracy.

Landsat TM images used for this study were obtained from the Canadian Centre for Remote Sensing (CCRS). Two Landsat TM images were required to cover the Riley Brook subbasin. Quadrants A and C of path 11, row 27 (Landsat Index Map) scheme provided adequate ground coverage. Recent TM images, dated July 1, 1985 were used for analysis.

Unlike conventional natural colour aerial photographs, Landsat TM images are false colour representations; therefore, ground features cannot be readily identified. The images colour spectrum must be cross referenced, or ground truthed, to the features of interest before any classification can proceed. The procedure of ground truthing the Landsat TM images involved gathering land-cover statistics from the video-digitized images within an area where data could be readily obtained from forestry inventory maps. The statistics from both data sources are compared and land-cover classification associated with intermediate colours on the video-digitized image are adjusted to best reflect the classifications on the forestry inventory maps. By comparing the location of the intermediate green areas on the video digitized image with the same location on the forestry inventory maps, a land-cover classification associated with the intermediate green is established.

The analysis was redone in a supervised environment. Table 1 shows the results of the classification and initially it was found that a large percentage of areas classified as softwoods should have been classified as hardwoods. Corrections were made and the results of the final classification are also shown in this table.
The GIS software was used to overlay the boundary of the Riley Brook sub-basin on to the video digitized images. Elevation bands were delineated and used as computational

RESULTS OF LAND COVER CLASSIFICATION ANALYSIS

	Initial Classification			Final Classification		
	S	H	N	S	H	N
Land Cover Classification in Area 1	68.8%	25.2%	6.0%	56.5%	41.0%	2.5%
Difference From Forest Inventory Area 1 (%)	9.3%	-11.1%	1.8%	-3.0%	4.7%	-1.7%
Land Cover Classification in Area 2	63.3%	11.0%	25.7%	65.7%	25.3%	9.0%
Difference From Forest Inventory Area 2 (%)	-1.0%	-15.3%	16.3%	1.4%	-1.0%	-0.4%

Note: S=Softwood, H=Hardwood, N=Nonforest

Table I

polygons. Table 2 shows the analysis results using the final classification.

SNOW COVER EXTENT

The analysis techniques currently used in assessing the snow covered areas fall into four main groups: 1) projection techniques, 2) density slicing techniques, 3) computer-assisted digital techniques, and 4) grid techniques. The scope of work allowed the assessment of only density slicing and digital techniques.

The SSARR model utilizes the snow cover data as aerial averages over a given sub-basin or elevation band. As a result of the particular application, the snow cover analysis methodology was tailored to achieve SSARR input requirements.

Monochromatic satellite images are displayed on a computer graphics terminal in various grey scales and a threshold grey level selected as the boundary snow-covered areas and bare ground. The computer system then counts the snow classified pixels within boundaries of interest. Both NOAA's polar orbiting and GOES satellite imagery data can be utilized. Table 3 summarizes the findings by elevation bands.

During the past six years, techniques for determining snow water equivalent have advanced significantly. Snow water-equivalents can be determined by active as well as passive microwave and by gamma ray surveys. The microwave techniques are still considered to be experimental and require either sensors with superior resolution or operational radar, such as the one scheduled to be mounted in the planned Radarsat, before they become operational. Airborne gamma-ray surveys has become operational during the past few years, and the data obtained have been used to some degree in operational hydrologic forecasting models. This technique is based on the measurable difference of the natural terrestrial gamma radiation attenuation between no snow cover and a snow cover. Gamma-ray surveys can provide accurate snow water equivalent in areas where the snow water equivalent in areas where the snow water equivalent is less than 300 mm; hence this technique can be used in most regions of Canada including the Tobique Basin.

In order to satisfy the input requirements of the selected snowmelt model options used in the SSARR modelling, an estimate of snow water equivalent is required not only as a single value over the entire sub-basin but also by elevation bands within the sub-basin. Three methods by which spatial snowpack water equivalent statistics can be calculated are the Trend Surface Analysis, the Correlation Area Method and the Conventional Method. Trend surface analysis incorporate physiographic and climatic characteristics of the area of interest to derive weighted snow water equivalent averages. Parameters, such as percent water area, percent wet land area, percent forest area, average elevation and average slope are used in deriving regressional relations which are subsequently applied to estimate snowpack water equivalent.

The correlation area method utilizes areal weighted data from many measurement technologies to determine a basin average of snowpack-water equivalent. Associated with each technology is a correlation factor. This factor is a measure of certainty on the accuracy of the data for a particular technology at its source location. The data is spatially represented in one of three ways. It is represented as either a point source, line source or as an aerial source. The rate at which the correlation factor decreases is known as the decay factor.

The conventional method of determining snowpack water equivalents makes use of snow course surveys. Each snow course survey is treated as a point source. A Thiessen polygon network is then created. The area of each polygon is determined and is used to weight the enclosed point sources data. A basin snowpack water equivalent is then determined based on a weighted average of all the point sources.

Summary of Land Cover
for Riley Brook Sub-basin

Classification	Sub-basin Lumped	---------- Elevation Bands ---------- <300m	300m-450m	450m-600m	>600m
S	43.2%	43%	39.8%	48.7%	74.8%
H	39.5%	39.6%	42.8%	31.9%	19.2%
N	17.3%	17.4%	17.4%	19.4%	6.0%
Est. Area of Cover km2	1650	600	775	225	50

Note: S=softwoods, H=hardwoods, N=nonforest

Table 2

Snow Cover Analysis Results
for Different Elevation Bands

Date	All Areas Average	Snow Cover in Percent- ----------Elevation Band (m)--------- <300	300 to 450	450 to 600	>600
84/04/29	54	46	49	66	82
84/05/07	31	24	25	42	57
85/04/23	54	32	56	85	87
85/04/24	67	46	70	88	61

Note: Results based on digital analysis of NOAA images for all sub-basins

Table 3

There are six snow course survey stations and four gamma ray flight survey lines within the Tobique Basin. These were used in the final snowpack water equivalent analyses. Table IV shows a comparison of snowpack water equivalents determined by the three methods for four dates.

SIMULATION RESULTS

The merits of determining hydrological parameters by remotely sensed means for snowmelt analysis has been addressed previously. The current New Brunswick Forecast Center (RFC) modelling was used as a base from which improvements in streamflow forecasting could be studied.

The modelling evaluation program adopted the following format which involved comparing long-term continuous forecasts and short-term forecasts with the corresponding observed flow series. For the study, the short-term simulations were defined to encompass spring events and vary from five to nine days. The long-term simulations cover the melt period and extend for two months or more to include the entire spring freshet.

The RFC operation of the SSARR model is a different application than the simulations performed in this modelling application. The RFC operation is a short-term forecast using forecasted meteorological data which are updated each day as initial conditions for the subsequent five-day forecasting period. The simulations used observed temperature and precipitation data, and comparisons were made with the observed flow series for the simulations period - either short- or long-term.

The snow cover depletion (SCD) approach uses the temperature index approach to quantify the melt processes. The SCD option only depletes the snowcovered area as a function of percent seasonal accumulated runoff as shown in Figure 1. The main drawback with this option is that the technique does not have a direct method to account for any snow accumulation during the snowmelt period. The snow cover depletion evaluation process concentrated on the data integration and potential improvements to the modelling obtained with the remotely-sensed snow cover extent information as also shown in Figure 1.

Figure 2 shows the results of improved short-term modelling with the remotely sensed data. The elevation band approach provides an accounting procedure by monitoring the snow water equivalent of the snowpack. This accounting procedure also makes adjustments for any snow accumulation which may occur during the melt period. The elevation band option was used with the Generalized Snowmelt Equation (GSE) which satisfies the energy balance of the snowpack. This equation allows for a more direct response to changes in meteorological data.

Two parameters for the elevation band option with the GSE were obtained by remotely sensed means; the snow water equivalent and the forest canopy cover. Initially, the entire basin is modelled as one elevation band with a distribution of elevation versus basin drainage area. This information was readily available as a product of the land cover analysed. To use this option with the GSE requires a considerably larger amount of data. In addition to previous data requirements for the SCD option, the following information is required: widespread, radiation, albedo, dewpoint, forest canopy cover and snow water equivalent.

Figure 3 shows a simulated and observed hydrographs for a nine-day simulation during the 1984 snowmelt runoff period. The impact of the forest canopy estimate on the simulation results can be noticed. Figure 4 shows a long-term simulation result using remotely sensed snowpack water equivalent.

Summary of Snowpack Water Equivalent
By Method of Analysis

	Method		
Date	**Trend**	**CAM**	**Conventional**
84/03/31	271(SC) 220(GF)	285.3(SC+GF) 273.4(GF)	295.5(SC)
85/03/31	156(SC)	-	161.2(SC)
85/04/07	110(GF)	116(GF)	-
85/04/15	167(SC)	-	133.5(SC)

Note: SC=Snow Course Survey, GF=Gamma-Ray Flight Survey

Table 4

COMPARISON OF PERCENT SNOW COVERED AREA VERSUS PERCENT RUNOFF

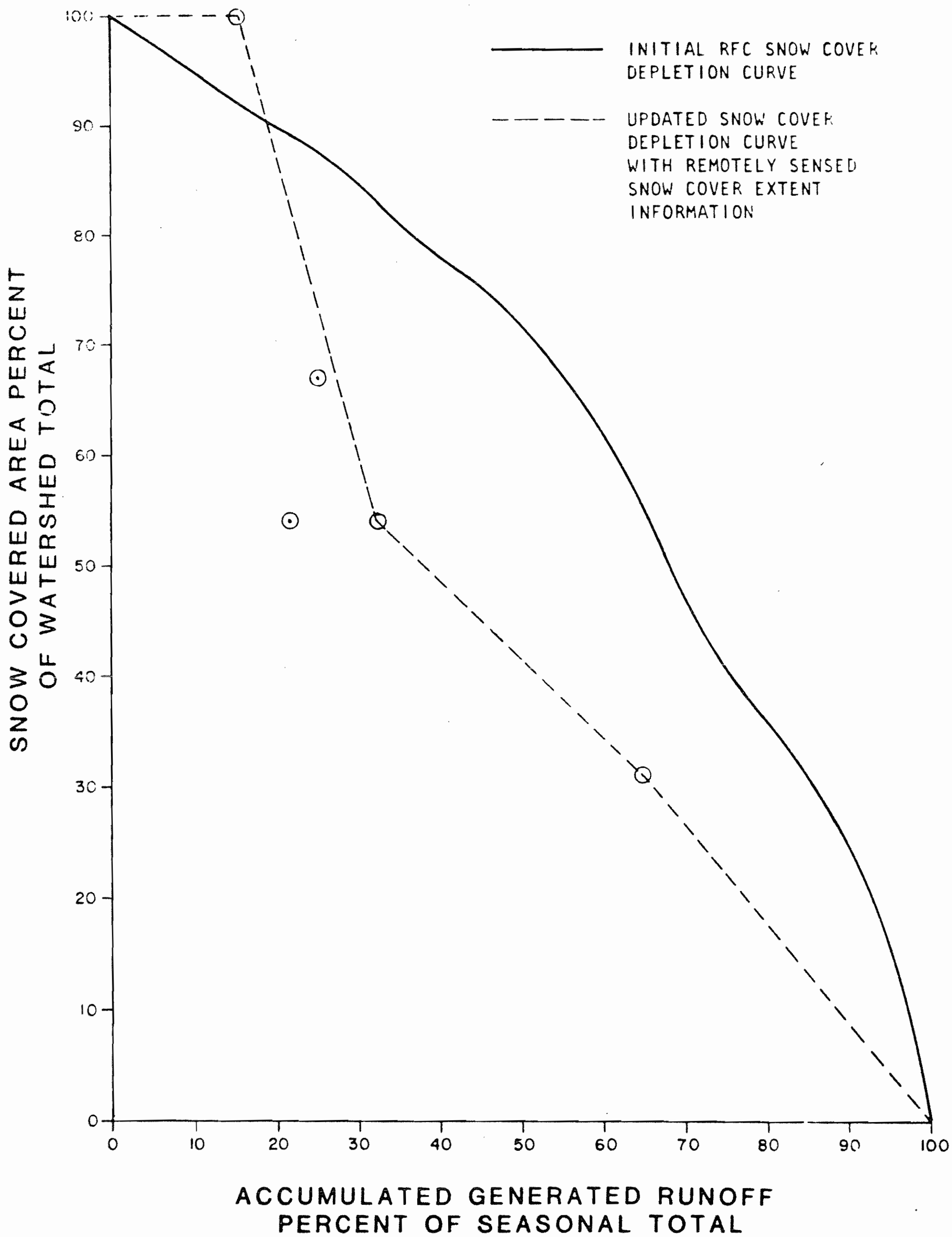


Figure: 1

Figure 2:

SHORT TERM FORECASTS

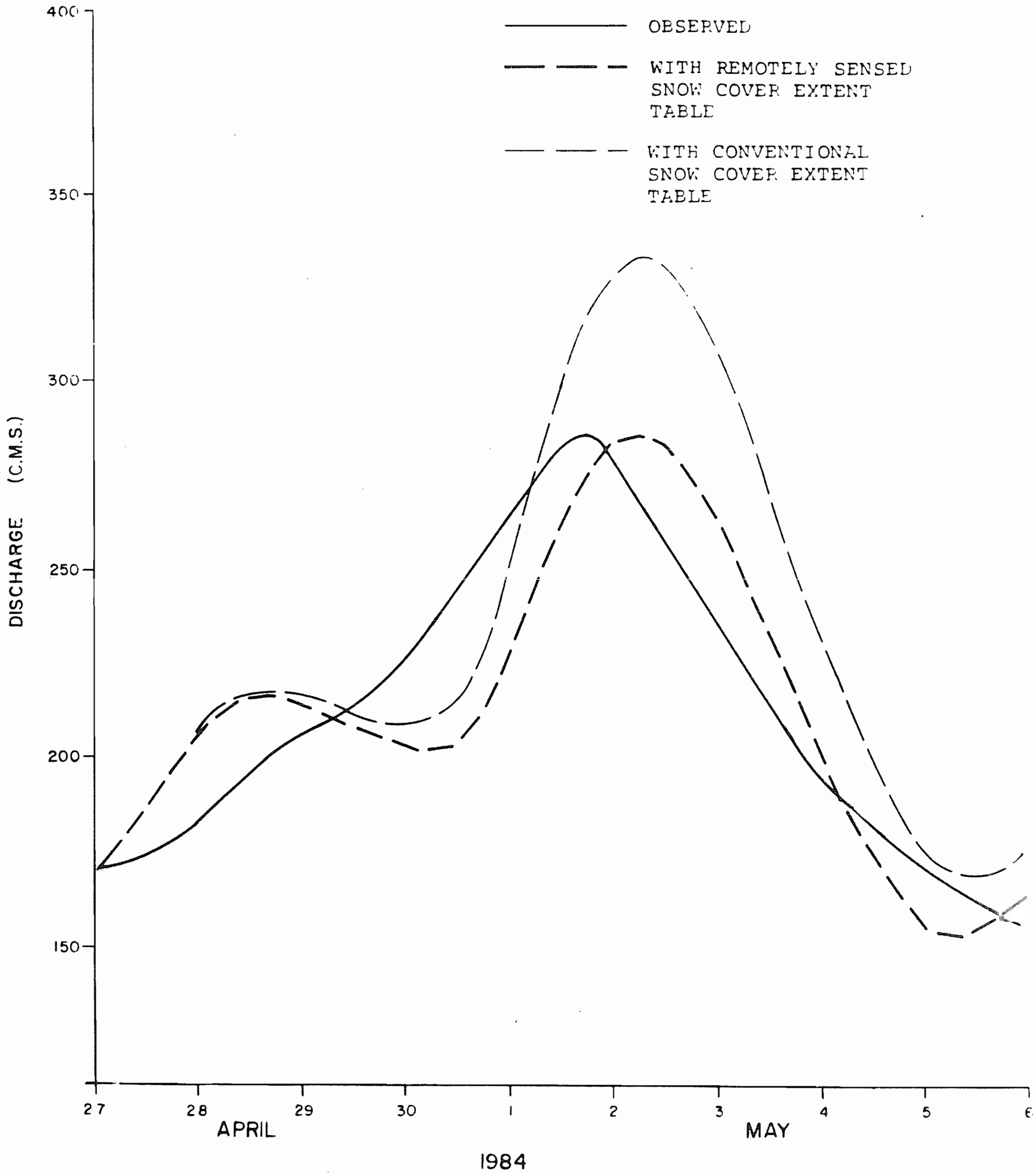


Figure 3: SHORT TERM FORECASTS SINGLE-BAND OPTION GSE APPROACH

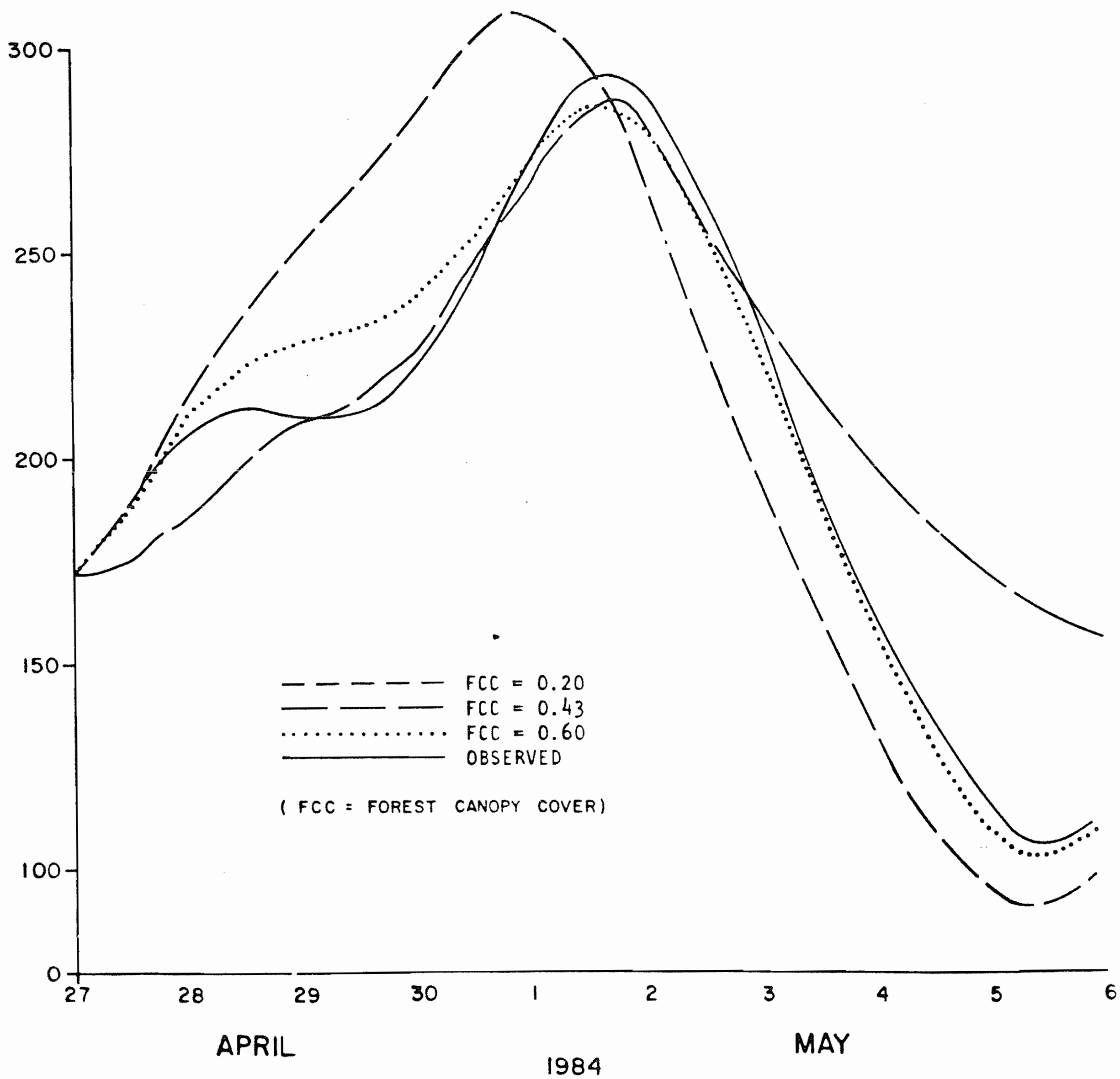
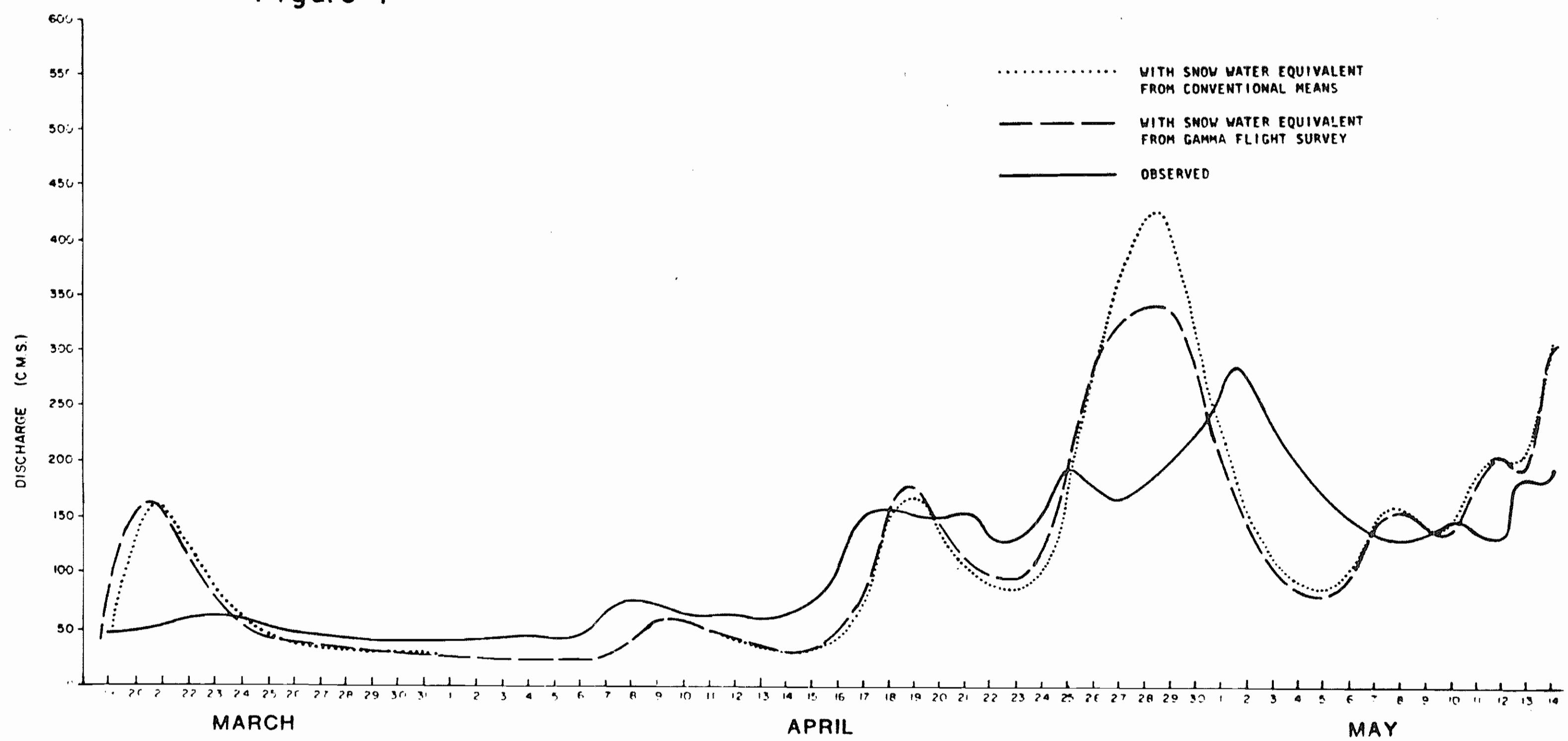


Figure 4



Elevation Band Option - Generalized Snowmelt Equation -1984 Long-Term Simulation

The multi-band approach is an extension of the single band option with a series of data and equations for each elevation band. As previously mentioned, the basin was divided into four elevation bands for these simulations. Each elevation band has its own forest canopy cover factor and snow water equivalent determined by remotely sensed means. The purpose of modelling with the multi-band option was to attempt to model with SSARR the resolution capabilities of remotely sensed data. All previous options used point representations of forest canopy cover and snow water equivalent. This option attempted to give a more distributed representation of these point averaged parameters.

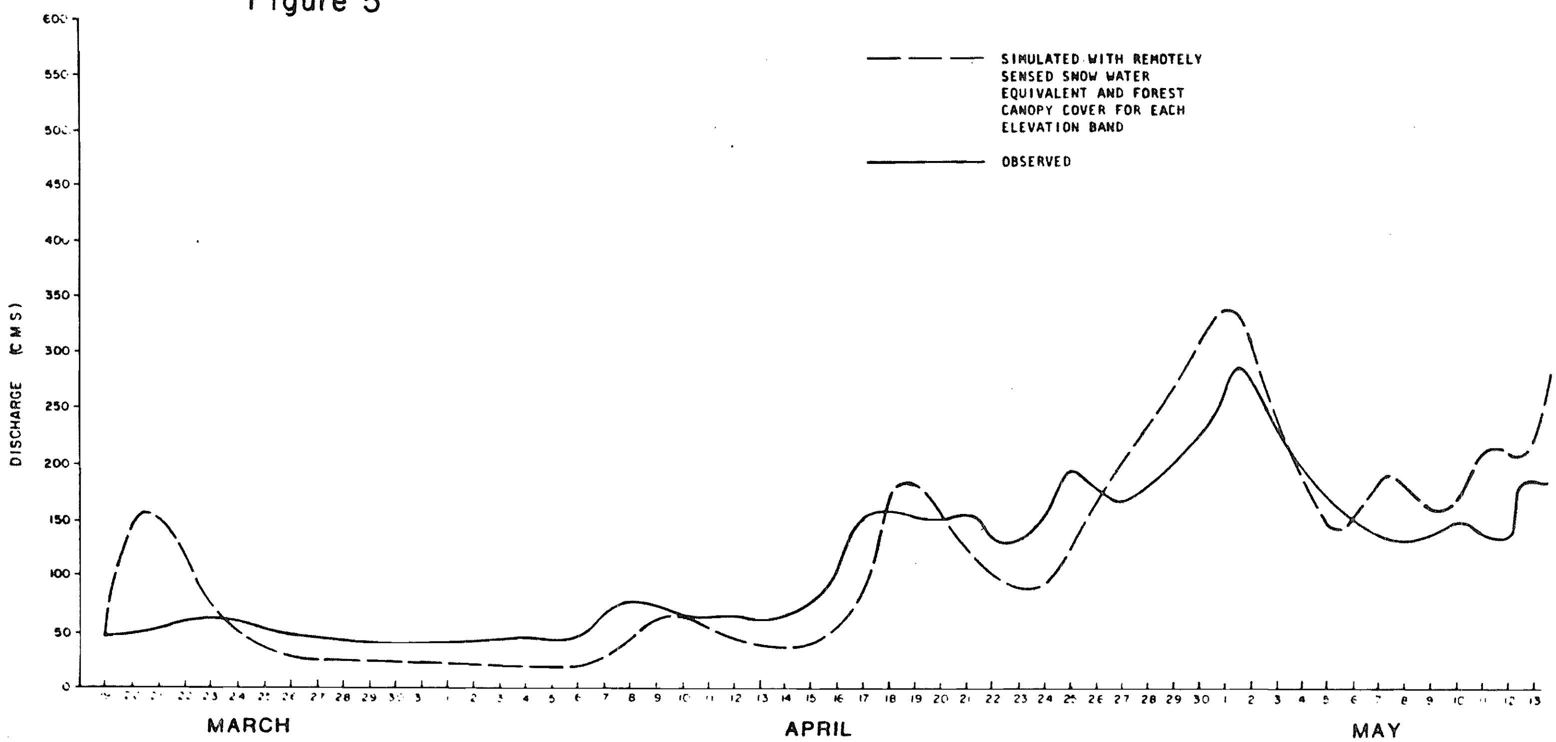
Figure 5 shows a long-term simulation period using the multi-band approach for three remotely sensed parameters.

The accuracy criteria used to evaluate the simulated flow series are those presently used by the RFC. The accuracy results of short term simulations are outlined in Table 5. Each accuracy criterion listed in Table 5 measures a different aspect of the calibration with the exception of the composite criterion (C_f) which accounts for all aspects. The Nash criterion (C_n) is a general accuracy indicator equally weighting high and low flows while the peak criterion (C_p) measures calibration accuracy for high flows. The volume criterion (C_v) measures water balance throughout the simulation period; therefore, it gives an indication of the model runoff simulation accuracies.

Perfect values for the various criterion are Cn = 1.0, Cp = 0.0, Cv = 0.0 and, Cf = 0.0. The RFC uses the following upper limits for modelling results acceptability; Cn = 0.8, Cp = 0.5, Cv = 0.5, Cf = 1.25.

Table 5 shows the relative improvement in accuracy obtained using improved knowledge of basin parameters with data obtained by remote sensing.

Figure 5



1984 Melt Season with Multi-Band Option - GSE Approach

Accuracy of Short-Term Simulations

Modelling Approach	**Accuracy Criterion** Nash (C_n)	Peak (C_p)	Volume (C_v)	**Composite** (C_f)
A. Snow Cover Depletion With Conventional Depletion Curve	-0.918	0.179	0.030	2.307
B. Snow Cover Depletion With Remote Sensing Data	-0.820	0.173	0.027	2.181
C. Single Band With Generalized Snowmelt Equation (Canopy Cover = 43%)	0.106	0.102	0.006	1.104
Accuracy Standards				
Perfect	1.000	0.000	0.000	0.000
Objective	8.090	0.020	0.002	0.050
Acceptable Upper Limit	0.080	0.050	0.005	1.025

Table 5

CONCLUSIONS AND RECOMMENDATIONS

This study demonstrated a streamflow forecasting application on a Canadian watershed integrating remotely sensed data. Data was obtained for snow cover extent, snow water equivalent and land cover. These hydrological parameters were subsequently integrated for use with the SSARR streamflow model and applied to the Upper Tobique Basin. The underlying goals of this application was to demonstrate the improvements in forecasting accuracies.

The land-cover analysis utilized in this application used video digitized Landsat TM colour composite images. This approach, using readily available GIS software running on a micro-computer, permitted consistency of assessment in a cost-effective manner. The land-cover classification of canopy cover was completed for the study area by dividing the cover types into three categories: hardwood, softwood and non-forest. Sub-basin statistics were compiled on an elevation band basis and aggregated for the total basin. The snow-cover extent analyses were completed using digital techniques. NOAA-7 AVHRR images were selected for analysis. The comparisons between the density slicing and the digital analysis results showed large discrepancies. The small number of images and absence of ground truthing makes drawing definite conclusions difficult; however, the digital analysis technique is deemed superior.

The snowpack water equivalent analyses involved calculation of representative spatial averages using two measurement techniques. Existing line data from gamma ray flight surveys and point data from snow course surveys. The Correlation Area Method was used to calculate spatial averages for each sub-basin and each elevation band. Previously calculated snowpack water equivalent averages using a Trend Surface Analysis method were obtained and spatial averages of snowpack water equivalent were calculated for each sub-basin and on an elevation band basis.

During the analysis of the spring 1985 data, the gamma ray flight surveys were completed on a certain week while the snow course surveys were completed the previous and following week. Snowpack melt and snowfall occurred during the two week span, thereby effectively creating three completely separate snow water equivalent datasets. The CAM is easy to apply and can be adopted to run on a micro-computer.

The interfacing, or usage, of remotely sensed data with the hydrological model is dependent on the simulators algorithms. The SSARR model was not a suitable candidate model to test the full resolution capabilities of remotely sensed data. Several approaches were investigated, however, and the potential for improved forecasts using remotely sensed data in the SSARR model shown.

This study evaluated only a few combinations of remotely-sensed data and one hydrological model, however, interfacing of several datasets were preformed to the extent possible, considering the model's limitations.

Recommendations are:

1. To provide additional benefits from the gamma ray flight surveys, accurate navigational information should be collected. With this information elevation based averages could be determined instead of the current lineal average.

2. Gamma ray flight lines should be located in more representative snowpack areas rather than located along the river systems for convenience of navigation. The CAM is the recommended snow cover analysis technique for basins where orographic effects can be neglected or where the data acquisition network has a high density. It is highly recommended when there is both line and point data.

3. Land cover delineations using a computerized zoom transfer scope method is recommended.

4. Gamma ray flight surveys and snow course surveys should be coordinated in order to have one temporal dataset for CAM analysis.

5. The SSARR model and other lumped watershed models are not recommended for further research on integrating remotely sensed data with hydrological models.

6. Future modelling research should be with a fully distributed model to demonstrate the benefits of the full utilization of remote sensing data and hydrological modelling. Consideration of extending the simulation period beyond the snowmelt season using remotely sensed rainfall and evapotranspiration data is also recommended since techniques to remotely sense the latter two parameters are soon to be operational.

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