REVIEW OF OPERATIONAL REMOTE SENSING TECHNIQUES AND STREAMFLOW FORECASTING TECHNIQUES

Phase I of
Study of Methodologies of Streamflow Forecasting Incorporating Remotely Sensed Data

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A TERMS OF REFERENCE

B PAPER: COMPATIBILITY OF PRESENT HYDROLOGIC MODELS WITH REMOTELY SENSED DATA

C EMR MAPPING ACCURACY SPECIFICATIONS

D MODEL ACCURACY CRITERIA

E LIST OF PUBLICATIONS REVIEWED

1.0 SUMMARY

Literature on remote sensing techniques was studied to determine the contemporary suitability of using remotely sensed geophysical and physiographic data with hydrologic forecasting methods to improve the model performance or decrease the forecasting costs. Both airborne and satellite - mounted sensors techniques are considered. Precipitation statistics obtained from weather radar and data collection systems that store as well as transmit data to a central processing centre were assessed along with the conventional remote sensing techniques. The costs, accuracies, time and ease of application of each of these techniques were assessed, taking into account the information available and its applicability to hydrologic forecasting modelling. All available, pertinent statistics were compiled.

The available hydrologic models that are pertinent to flow forecasting in a hydroelectric context were studied, and sixty models - both deterministic and stochastic - were selected. The selected models represent a conglomeration of European, American and Canadian developed models. The criteria given in the terms of reference were applied to reduce the list to twenty-eight models. These models were systematically ranked to determine the most promising models for additional study. This ranking was subjective and took into account seven model characteristics and various model component types. From this ranking the twenty-eight models were divided into three categories - distributed, multi-basin and single-basin models.

The scores assigned to models at the top of each of the three categories are very close to each other making the final selection process a difficult task. Two models were selected for additional study and testing. They are the CEQUEAU model, which ranked the second highest in the distributed model category, and the HSP-F model, which ranked second highest in the multi-basin category. It is suggested that one of these two models be tested

in a Canadian basin for cost, accuracy, time and ease of application by varying the model spatial resolution and using operational remote sensing techniques. These techniques include: land use classification, airborne gamma ray snow water equivalent measurements, snow cover extent and albedo analyses. These four remote sensing technologies were recommended for further study.

A study basin location, where the models are to be tested in Phase II of this study, was considered and two geographical regions were selected.

2.0 INTRODUCTION

2.1 General

Hydroelectric generation is governed not only by the demands for power and energy, but also by the availability of streamflow throughout a year and from year to year. The latter constraint is partially overcome at those hydroelectric developments where storage reservoirs exist. Excess streamflow is stored during periods of above average runoff and utilized later for hydro generation during periods of below average streamflow. Optimum hydroelectric generation is rarely achieved since inaccuracies in flow forecasts to reservoirs and headponds force dam operators to release more flows than would most likely be required.

One means of improving the hydrologic forecasts for hydroelectric generation is to utilize remotely sensed data in existing hydrologic forecasting models. Moreover, in view of recent and ongoing research, it may be possible that data acquired via modern remote sensing techniques - both aerial and satellite-based - can improve the performance of conventional flow forecasting methods at a reasonable cost. Before this statement can be fully evaluated, applicable remote sensing and forecasting techniques must be identified, and the latter must be modified to accept the remotely-sensed inputs.

Recognizing the potential of enhanced hydrologic forecasting using remotely sensed data, Environment Canada has formulated terms of reference for a study that will assess the technical merits and economic advantages.

Based on the statement of work that is given in Appendix A, the objectives of this project are to modify conventional methodologies of short-term and long-term streamflow forecasting by incorporating the use of data acquired via contemporary remote sensing technologies and to apply these methodologies to a pre-selected Canadian basin.

2.2 Economic Benefits of Improved Hydrologic Forecasts

One way of expressing the overall objective of this assignment is to investigate whether or not using remotely sensed data in hydrological forecasting models to aid in conserving water for hydroelectric generation is technically feasible. The results of utilizing remote sensing data and allied techniques can be used either to reduce the costs of current forecasting methods or to increase the forecasting accuracies, by either providing more meaningful and precise data or using different models so that economy will be obtained by generating more hydroelectricity. In order to obtain an appreciation for the benefits of improved hydrological forecasting, the annual statistics of Canadian hydroelectric production were studied.

In 1984, the last year for which statistics are available, Canada's total electric generation amounted to 426 Terawatt hours (Twh) of which 283 Twh or 66.4% was produced by hydroelectric plants (Statistics Canada, 1983 & 1984). The provincial and territorial breakdown of these statistics as well as the 1983 values are given in Table 2-1.

In order to investigate the economics of using remote sensing techniques, one could compare the costs, which will be considered in the study Phase II, of improving hydrological forecasting with the benefits that will be derived. These benefits are provided by more hydroelectric generation through more efficient utilization of headpond and reservoir storages and less generation from thermal (oil and coal), nuclear or other sources of energy, which will result in a saving in fuel and, therefore, in money.

TABLE 2-1: CANADIAN ANNUAL ELECTRIC GENERATION IN TWH

	1983			1984		
	Total	Hydro	%	Total	Hydro	%
Newfoundland	40.0	40.0	100	45.0	44.0	98
Prince Edward Island	11.0	0.0	0	2.0	0.0	0
Nova Scotia	6.2	1.0	16	7.2	1.0	14
New Brunswick	11.6	3.1	27	12.2	3.1	25
Quebec	110.6	100.4	98	122.1	118.5	97
Ontario	117.8	40.5	34	120.6	40.8	33
Manitoba	22.1	21.9	99	21.5	21.2	99
Saskatchewan	10.4	2.2	21	11.5	1.7	15
Alberta	29.0	1.5	5	31.1	1.4	4
British Columbia	47.2	44.9	95	52.4	50.2	96
Yukon	0.2	0.2	100	0.3	0.3	100
Northwest Territories	0.4	0.3	75	0.5	0.3	60
TOTAL	405.7	256.0		426.4	282.5	

Note: % refers to percentage of Total that is Hydro generated.

To take advantage of any water conservation through the use of remote sensing in hydrological forecasting, there must be a demand for the additional energy generated. This could occur by three means: 1) in those provinces that have an appropriate mix of hydro and thermal generating capacities, the increased hydroelectric generation could replace thermal-electric generation (either coal or oil); 2) the hydroelectric generation could replace some of the predicted future additional demands that would otherwise be met by yet-to-be installed generation capacity; and 3) the excess energy could be sold to the United States or other provinces. Each of these alternatives will be considered briefly.

Considering the first case, excess hydroelectric generation could replace thermal or nuclear generation. There would not be any economic benefits to hydroelectricity replacing nuclear generation, since production costs of the latter are mainly capital with relatively low operational as well as maintenance costs. These costs would have to be expended whether a plant was operating or not. In replacing thermal generation, only the cost of fuel would be saved, since the capital as well as maintenance costs would remain the same.

In order to use the increased hydro generation to replace existing or future thermal demands, a province would require a good mix of hydro (neither a very high nor a very low hydro with respect to thermal) and other generation capacities. There are two and possibly four provinces that have such mixes: Nova Scotia, New Brunswick, Ontario and Saskatchewan - New Brunswick and Ontario having the better mixes. The percentage of total generation provided by hydroelectric plants in 1984 in these Provinces are 14, 25, 33 and 15%, respectively.

At present the cost of Canadian thermal generation is about $0.04 per kwh of which about $0.02 per kwh is for fuel. The cost of fuel in Canada depends very much on plant location; however, the

$0.02 per kwh will be used for analysis purposes. Thus, a one percent increase in hydroelectric generation in the four provinces that have suitable hydro/thermal mixes (Nova Scotia, New Brunswick, Ontario and Saskatchewan) would provide benefits of $9 million annually.

Some of the Canadian hydroelectric plants, however, are run-of-the-river and would not have the means of storing and later utilizing the water provided by improved forecasting. Assuming that there is reservoir storage for 80 percent of the water used for hydroelectric generation, the economic benefit of replacing thermal generation by increased hydroelectric generation of one percent through improved hydrologic forecasting is about $75 million per year.

The second option - using additional energy generation from existing hydro plants to satisfy future demands - is difficult to quantify, since there is little specific information on planned electrical demand. Furthermore, the current electric demand is not growing very rapidly.

The third option is selling the excess energy to the United States or other provinces at a price of $0.04/kwh (selling price of hydro-generated energy minus generating cost plus transmission cost associated with it). It is assumed that New Brunswick, Quebec, Ontario, Manitoba and British Columbia have this option. Thus the annual total worth of possible generation at the above rate is $93 million for a one percent increase in water available in the five provinces for generation and 80 percent utilization due to enough reservoir storage being available.

In order to obtain a better appreciation of possible savings from improved forecasts, percentages of annual flow volumes that occur in the spring are applied to the 1984 hydroelectric generation statistics given in Table 2-1. To obtain long-term hydrologic forecasting benefits, a representative value of 55 percent is applied to Eastern Canadian generation data and 69 percent to data in the Rocky Mountains. Moreover, most of the hydroelectric generation in the Prairie Provinces is the result of water that enters the streams on the eastern slopes of the Rocky Mountains; thus the percentage applicable for the mountains will be applied to the Prairie Province generation statistics.

The flow volume producing 133 Twh of electricity could be regulated and conserved using long-term hydrological forecasting techniques. The volumes corresponding to generation of 99 Twh, could benefit from the use of short-term forecasting. Thus the worth of possible increased hydroelectric generation through improved hydrologic forecasting that would increase generation by one percent can be estimated. The results of the calculations are summarized in Table 2-2, below.

TABLE 2-2: ESTIMATE OF WORTH OF CANADIAN HYDROELECTRIC GENERATION

Forecasting Technique	Total (Twh)	Annual Economic Worth (Billion Dollars)	One Percent Annual Saving (Million Dollars)
Long Term	133	6.6	66
Short Term	99	4.6	46
Total	232	11.2	112

The above gives an appreciation of the magnitude of the benefits that can be realized from improved hydrologic forecasting. In order to assess the economy of such improvements, the overall magnitude of improvements including their associated costs must be ascertained. The means by which the improvements in hydrologic forecasting can be obtained by using remote sensing techniques has been studied and is described within this report. Interfacing these techniques with hydrologic modelling and the subsequent evaluation of flow conservation and forecasting cost assessment will be the subject of Phase II of this study. The economy of using remote sensing in hydrologic forecast modelling for improved hydroelectric generation can then be appreciated.

3.0 OBJECTIVES AND SCOPE OF WORK

This chapter outlines the specific study objectives for Phase I, discusses the literature review and information gathering procedures and presents a Canadian perspective on the definition of short- and long-term forecasting periods.

3.1 Phase I Study Objectives

Phase I of the two phase study includes a detailed documentation search and review on modern methodologies of streamflow forecasting which could incorporate the use of data acquired via contemporary remote sensing technologies. According to the Terms of Reference this Phase I report was to include the following tasks.

a) The identification and assessment of proven contemporary remote sensing techniques which may now be considered to be fully operational and which have application to hydrologic forecasting.

b) The identification and assessment of hydrological forecasting models - deterministic and stochastic - applicable to the Canadian conditions, which have been designed for or are adaptable to modern remotely-sensed inputs.

c) The selection of the most promising forecasting methodologies on the basis of (a) and (b) above.

Subsequent to the commencement of the study, a clarification of the term "operational" was made. Operational techniques include those techniques that either are operational or could be made operational (ie. the research and development functions are completed).

Therefore, this report covers the review of proven contemporary remote sensing techniques and of hydrological forecasting methods applicable to Canadian conditions, and recommendations are made on the study basin to be used to test the hydrologic models as well as which models to be tested.

3.2 Literature Review and Information Gathering Procedures

Several libraries, associated with the following institutions, were used in carrying out this study.

1) Atmospheric Environment Service, Downsview, Ontario
2) Canada Centre for Remote Sensing, Ottawa, Ontario
3) Canada Department of the Environment, Hull, Quebec
4) Saint John River Forecast Centre, New Brunswick Department of the Environment, Fredericton, New Brunswick
5) University of Toronto, Toronto, Ontario
6) University of Waterloo, Waterloo, Ontario
7) A.J. Robinson & Associates Inc., Kanata, Ontario
8) Study Members' Personal Libraries.

Seven computer literature searches were undertaken; one at the University of Waterloo library and the others at the Canadian Centre for Remote Sensing library on their Remote Sensing On Line Retrieval System (RESORS).

In addition, visits were made to the following organizations for information:

- Canadian Climate Centre, AES, Downsview
  (Dr. B.E. Goodison)
- Department of Energy, Mines and Resources, Ottawa
  (Mr. J.E. Glynn, Mr. J. MacDonald and Ms. E. Fleming)
- Ontario Hydro, Toronto
  (Dr. G.K. Gupta)

- Saint John River Forecast Centre, Fredericton (Mr. J.G. Lockhart and Mr. P.W. Tang)
- Satellite Hydrology Consultants, Washington, D.C. (Mr. D. R. Wiesnet)
- Shawinigan Consultants Inc., Montreal, Quebec (Mr. D. Creamer)
- Universite du Quebec, Ste. Foy, Quebec (Dr. J.P. Fortin)
- Water Survey of Canada, Environment Canada, Hull (Mr. P.I. Campbell)

Telephone conversations were held with the following individuals:

- Dr. G.L. Austin, McGill University, Montreal, Quebec
- M. J.L. Bisson, Quebec Hydro
- Ms. N. Culter, Atmospheric Environment Service, Regional Office, Toronto
- Mr. R.A. Fox, Streamflow Forecast Centre, Conservation Authorities Branch, MNR, Toronto.
- Mr. R.L. Gauthier, US Corps of Engineers, Detroit, Michigan
- Mr. H. Lamb, AES, Toronto
- Mr. R. Millar, AES, Downsview, Ontario
- Mr. G. Scutton, Shawinigan Consultants Inc., Montreal
- Mr. R. Terza, Water Survey of Canada, Environment Canada
- Mr. R.M. Thompstone, Alcan Smelters and Chemicals Ltd., Jonquière, Quebec
- Mr. A. Warkentin, Manitoba Flood Forecasting Center, Winnipeg, Manitoba
- Mr. K. Wiebe, Water Survey of Canada, Environment Canada, Hull

The following hydroelectric generation organizations were canvassed and provided information on their current flow forecasting techniques.

- Newfoundland and Labrador Hydro

- The New Brunswick Electric Power Commission
- Alcan Smelters and Chemical Limited, Jonquiere, Quebec
- Hydro-Quebec, Montreal, Quebec
- Ontario Hydro, Toronto, Ontario
- Saskatchewan Water Corporation, Regina, Saskatchewan
- Energy Resources Conservation Board, Calgary, Alberta
- B.C. Hydro, Burnaby Mountain, British Columbia
- Northern Canada Power Commission, Edmonton, Alberta

Members of the Water Resources Branch, Canada Department of the Environment, provided technical papers and a RESORS-derived computer listing containing titles of technical papers in remote sensing and hydrologic modelling.

The main search for determining information on costs of remote sensing techniques in the context of hydrometeorological and hydrometric data collection systems was done at the Library of the Canada Centre for Remote Sensing. A computer search was made of all remote sensing papers that have cost effectiveness as a key word. Four hundred and seventy nine were found and listed. Of these twelve were selected for study based on their titles.

3.3 Definition of Short- and Long-Term Forecasting Periods - A Canadian Perspective

Before going further, it may be expedient to discuss what is meant by hydrologic forecasting for hydroelectric production in a Canadian context and its ramifications. Also of concern is the usefulness of the study results in improving hydrologic forecasting for increasing hydroelectric production or decreasing the cost of forecast modelling, or both. The World Meteorological Organization (WMO) defines short-term hydrologic forecasting as one that has a prediction duration of less than ten to fifteen days while long-term forecasting as one that has a prediction duration of between ten to fifteen days and several months (WMO, 1975). These definitions generally reflect the Canadian practices for hydroelectric generation. In Canada, there are two types of hydrologic forecasts used for hydroelectric generation. One forecast type predicts the river flows a few days in advance in order to achieve one or two objectives. These objectives are:

1) to determine the inflow to a reservoir or headpond so that the most economic mix of hydro and other generations may be achieved, considering the electrical system load demand both during and following the forecast period;
2) to know how much and when water should be released from a reservoir in order to prevent flood damages both upstream and downstream.

The other type of hydrologic forecasting is to predict the flows up to a few seasons in advance. For many Canadian basins, in which hydroelectric generation is carried out, typical cases are forecasting in the autumn and throughout the winter to estimate characteristics of the spring flow.

In many parts of southeastern Canada and on the Prairies, the first snowfall that remains on the ground throughout the winter occurs in November and the spring snowmelt runoff occurs in March through May. In British Columbia and at northern Canadian latitudes where hydroelectricity is currently being generated, the first snowfall occurs in September or October and the spring snowmelt occurs in May or June. Hence, Canadian snowmelt forecast periods range from five to ten months. Since most Canadian rivers that are used for hydroelectric generation have most of their annual flow volumes occur during the spring runoff period (usually larger than 60% and in the Rocky Mountains as much as 85%), these long-term forecasts are of significant importance to the economy of hydroelectric generation, and to a less extent, to flood damage reduction programs.

The volume, timing and flow rates of these spring floods depend on many factors. These factors include: the soil moisture content in the autumn; the autumn rain amounts; whether the ground is frozen or not when the first permanent snowfall occurs; the amount of snow accumulation during the winter as well as its water equivalent; the rainfall that occurs over the snowpack during the winter; the amount of sublimation from the snowpack and the meteorological conditions (rainfall, air temperatures, relative humidity, solar radiation and wind statistics) during the snowmelt runoff periods.

Quantifying these factors would entail a forecasting organization monitoring:

i) soil moisture and precipitation conditions during the autumn;
ii) snow pack (extent and water equivalent) and rain on snow during the winter months; and
iii) snow pack ablation, rainfall and other meteorological variables during spring snowmelt periods.

In addition, forecasts are updated periodically during the winter, indicating expected flow conditions during the spring snowmelt runoff period.

The extremities of the possible operating forecast periods should be considered briefly. On small basins or on small portions of intermediate and large basins, weather radar can give a good measure of spatial and temporal statistics of convective storms a few hours or minutes, in advance. On the other hand, basins with a sizeable portion of their annual flow volume derived from melting of glaciers can have forecasts of two or more years using past runoff records, basin size, annual melt rates and long-term average meteorologic conditions. This latter type of hydrologic forecast affects only a few Canadian basins where hydroelectricity is produced and remotely sensed techniques are not applicable.

The Atmospheric Environment Service is presently issuing five-day forecasts of air temperatures and precipitation - giving daily statistics up to and including five days ahead. Although a hydroelectric utility could respond to a forecasted change in meteorologic conditions within an hour, the shortest period such changes would significantly affect reservoir hydraulic input is approximately a day. Hence the forecasting periods considered in this study are from one day to six or ten months - the latter representing the autumn through to spring runoff periods previously described. Forecasts of horizons up to and including seven days are considered to be short-term while others are long-term.

4.0 QUANTIFICATION OF INFORMATION OBTAINED BY REMOTE SENSING METHODS FOR STREAMFLOW MODELLING

This chapter deals with the remote sensing determination of hydrologic, meteorologic and physiographic characteristics that are used, or can be used, in hydrologic forecasting models as either input variables, model parameters or as state variables. The majority of these characteristics were taken from a WMO list of observed hydrologic variables which is given in Table 4-1. It is noted that all of the listed variables can be sensed or monitored by remote sensing means. Moreover, certain hydrological modelling characteristics, such as radiation and land cover, are not given in the WMO list but are covered in this chapter.

The following section covers the various components of the hydrologic cycle along with the corresponding characteristics that can be remotely sensed, as well as, the expected accuracies of the observations and measurements. Those components that are considered operational are listed. The costs of obtaining and using remotely sensed data are covered for those variables for which information is available.

4.1 Geophysical Characteristics that can be Monitored by Remote Sensing Techniques

The selection of the geophysical characteristics (both hydro-meteorogical and physiographic) to be covered in this report has not been limited to those given in Table 4-1 entitled: "WMO Surface Type Observational Requirements for Hydrology". Other characteristics, such as radiation, which are used in hydrologic models are also addressed and were added to Table 4-1 under the supplemental group heading. The following observational requirements given in Table 4-1 are not addressed in this report.

1. **Lake and river ice parameters.** All ice parameters with the

TABLE 4-1 WMO SURFACE-TYPE OBSERVATIONAL REQUIREMENTS FOR HYDROLOGY

SNOW-LAND

Snowline
Snowcover
Water Equivalent
Free Water Content
Snow Surface Temperature
Snow Albedo

LAKE/RIVER ICE

Ice Line
Continuous Ice Cover
Ice Concentrations
Ice Movement
Type/Strength
Thickness
Surface Temperature

GLACIERS

Inventory/Dimensions
Snow Cover
Length Variations
Mass Balance
Surge Monitoring

SURFACE WATER

Areal Extent
Saturated Soil Area
Flood Extent
Flood Plain
Lake/River Stage
Waves, Seiches
Mud-flows

GROUND WATER

Aquifer Maps
Discharge Location (rivers)
Discharge Location (lakes)
Locations of Springs
Ground Water Level
Soil Type
Moisture Content
Temperature Profile
Infiltration
Percolation
Frost Depth
Permafrost Area

WATER QUALITY

Turbidity
Suspended Sediment
Colour
Algae Bloom
Surface Film
Surface Water Temperature
Temperature Profile

DRAINAGE BASIN CHARACTERISTICS

Drainage Area
Channel Dimension
Overland Flow Length
Surface Slope
Land Cover Type
Albedo

PRECIPITATION/ EVAPOTRANSPIRATION FOR OPERATIONAL HYDROLOGY

Precipitation
Evaporation
Evapotranspiration

LARGE SCALE WATER BALANCE (ATMOSPHERE)

Precipitation
Evaporation
Evapotranspiration
Atmospheric Moisture Storage
Atmospheric Moisture Divisions

SUPPLEMENTAL

Radiation (Atmosphere)
Snow Depth
Frozen Ground
Impervious Area

exception of ice movements and thickness, which can be monitored by Data Collection Systems (DCSs) and used for hydroelectric forecasting, will not be considered. Although the other parameters in this group can also be monitored by DCS, they are not useful for hydroelectric flow forecasting.

2. **Glacier Parameters.** Although most of the parameters listed under this grouping can be used for long-term flow forecasting, they are not presently used for hydroelectric flow forecasting. Therefore only glacial surges, which can be monitored via DCS, will be considered in the report.

3. **Surface Water.** The flood extent and flood plain characterization parameters are not applicable to hydroelectric flow forecasting and thus have been excluded from further study. Mud flow parameters are not used in hydrologic models and will not be considered; however, all other parameters in this category will be addressed.

4. **Groundwater.** Aquifer maps and aquifer discharge locations in rivers and lakes, as well as spring locations are not used in operational surface hydrologic models. They will therefore be excluded from further consideration.

   Soil type and temperature profile are not of significant importance to streamflow forecasting and shall not be addressed. Percolation, infiltration and frost depth are pertinent to hydrologic modelling, but they are not remotely sensed. Groundwater levels, moisture content and permafrost areas are the only parameters in this group that will be considered in the forthcoming paragraphs.

5. **Large Scale Water Balance (Atmospheric).** All the parameters under the large scale water balance are irrelevant to basin-wide hydrologic modelling, therefore these parameters will not be considered further.

6. **Water Quality.** Water quality parameters are not pertinent to hydroelectric generation; therefore, they will not be considered further.

Each of the parameters in Table 4-1 that were not excluded in the above list will be considered separately in the following section.

4.1.1 Remotely Sensed Characteristics

Information on remote sensing determination of parameters used in hydrologic models is scattered among many papers. A comparable degree of information is not available for each parameter. Data on costs, accuracies, time, and ease of application are nonexistent in many cases. The most comprehensive publication on the current status of using remotely sensed data with hydrologic models is by Dr. L.E. Link -a copy of this paper is given in Appendix B. His report constitutes a short status report on some of the remotely sensed parameters, and pertinent direct quotes will be made from his paper as the remote sensed inputs are covered in the following sections.

Most remotely sensed parameters are currently monitored via satellite-mounted sensors. The 1983 status on both operational, as well as, research and development systems pertaining to hydrologic modelling is given in Table 4-2 which is taken from Manual of Remote Sensing (MRS; p.1499). This table provides a good summary listing of available vehicles and sensors for usage in the water resource field. The following sections will refer to these sensors as each selected hydrological component is discussed.

4.1.1.1 Snow - Land Parameters

(a) Snowline and Snow Cover

Snowline and snow cover quantities are related. If one can sense

Table 4.2 **Selected Remote-Sensing Systems Available in the United States and Applicable for Water Resources Monitoring and Hydrological Studies**

Vehicle/Sensor	Spectral Bands	Nominal Spatial Resolution	Appropriate Image/Scene Areal Coverage	Frequency of Coverage	Period of Data Availability	Data Center
<u>Operational</u>						
Ground-Based Radar	cm Wavelengths	Variable or grids 5-10 km square	10^3-10^4 km^2	10^3-10^4 sec	Many years	Silver Spring, MD (NOAA/NWS)
Aircraft Gamma Radiation Flights	Emission from ^{238}U, ^{232}Th, ^{40}K	600 m 300 m altitude	5 km Flight lines	Variable	1972 to present	Silver Spring, MD (NOAA/NWS)
NOAA/VHRR	0.6-0.7 μm 10.5-12.5 μm	0.9 km	Subcontinent	1/day visible 2/day IR	1972 to 1978	Suitland, MD (NOAA/NESS)
ESSA-NOAA/ AVCS-SR	Visible (AVCS) 0.6-0.7 μm 10.5-12.5 μm (SR)	4 km	Subcontinent	1/day visible 2/day IR	1966 to 1978	Suitland, MD (NOAA/NESS)
SMS-GOES VISSR	0.55-0.7 μm 10.5-12.5 μm	1 km	1/3rd of globe (Western Hemisphere)	Several times per day	1974 to present	Suitland, MD (NOAA/NESS)
Tiros-N/AVHRR	4.5 bands visible, near infrared, thermal infrared	1.1-4.0 km	Subcontinent	12-24 hours	1978 to present	Suitland, MD (NOAA/NESS)
<u>Research and Development</u>						
Landsat 1, 2. and 3 MSS	0.5-0.6 μm 0.6-0.7 μm 0.7-0.8 μm 0.8-1.1 μm	80 m	34,000 km^2	Once every 18 days	1972 to present	EROS Data Center Sioux Falls, SD
NASA Medium Altitude Aircraft	Multispectral scanners and microwave instrumentation	Widely varying characteristics contact NASA/Ames Research Center				
High-Altitude NASA Aircraft	Visible and infrared photography	10 meters (approx.)	400-900 km^2	Variable	Occasional coverage in selected areas for 10 years or more	EROS Data Center Sioux Falls, SD
Skylab-EREP/ Multispectral Cameras, Spectometers	Visible and near-infrared, thermal infrared	10-70 m	10,000-30,000 km^2		1973, 1974 (three flights)	EROS Data Center
Skylab-EREP Microwave Scatterometer-Radiometer	2.2 cm	11 km	0-48° incidence angles	Variable	1973, 1974	EROS Data Center or NASA/Johnson Space Center
L-band Radiometer	1.4 GHz	124 km		Variable	1973, 1974	EROS Data Center or NASA/Johnson
Nimbus 1-7	Multispectral radiometers	4-55 km	Subcontinent	Daily in selected periods	Discontinuous coverage since 1964	Greenbelt, MD (NASA/Goddard)
Nimbus 5, 6 Microwave Radiometers	1.55 cm 0.86 cm	30 km	Subcontinent	Daily	Discontinuous coverage since 1972	Greenbelt, MD (NASA/Goddard)
Heat Capacity Mapping Mission (HCMM)	0.5-1.1 μm 10.5-12.5 μm	500 m	700-km swath	3 days	1978-1980	Greenbelt, MD (NASA/Goddard)
Nimbus 7/SMMR	6.6 GHz 10.69 GHz 18.0 GHz 22.2 GHz 37.0 GHz	92 x 144 km 57 x 88 km 34 x 53 km 28 x 43 km 17 x 26 km	1000-km swath	3 days	1978 to present	Greenbelt, MD NASA/Goddard
Seasat A/SMMR	(See Nimbus G)					Jet Propulsion Lab
Seasat A/SAR	1.35 GHz	25 m	100-km swath	(See remarks)	June to October 1978	Pasadena, CA and Suitland, MD (NOAA/NESS)

the snowline locations, then the extent of snow cover can be calculated. For some hydrologic forecasting the elevation of the snowpack is of the same importance as the snowpack extent. Hence, in mountainous or hilly regions values of both parameters are required.

There are three general categories of snow-cover delineation techniques. They are ground-based, airborne and spaceborne measurements. The ground-based measurements are usually taken by truck-mounted radiometers and scatterometers. There are many logistical problems to this technique; furthermore, the resolution is generally too high for operational snow hydrology applications (MRS, p.1529).

Airborne low altitude sensing involves light aircraft flying less than 600 m along a preselected flight line. This type of survey is not economical for large basins in which hydroelectricity is normally generated (larger than 1300 km^2).

Medium altitude observations are taken using aircraft flying between 600 and 7600 m carrying both passive and active microwave scanners and multisensor scanners. These sensor systems collect digital data from which snow extents can be delineated.

High altitude observations provide a larger field of vision; however, the possible payload in the aircraft is lower. As a result, this type is used for research purposes only.

Spaceborne measurements with the Nimbus 5 and 7 satellite microwave sensors have been used in experimental snow studies (MRS, p.1522). These satellites are not used for operational forecasting purposes because of the low sensing resolution (25 to 100 km).

Landsat Multispectral Scanner (MSS) data have been used to effectively map snowcover extent on basins as small as 10 km^2

(Rango, 1985). It is cost effective compared to other techniques on basins 25 km2 or larger, therefore this technique can be considered operational.

The Advanced Very High Resolution Radiometer (AVHRR) aboard the NOAA Satellites can be used to determine snow location and extent in a cost effective manner for basins larger than 10 km2. Furthermore, acceptable accuracy is attained for basins larger than 200 km2.

The Landsat data will provide snow location and extent every 16 days while NOAA and Nimbus satellites will provide the necessary data once a day. The current resolutions of Landsat data is 79 metres with the multiple spectral scanner (MSS) and 30 metres with the thematic mapper (TM). Since 1978 the polar orbiting, NOAA, TIROS-N Satellite AVHRR (Advanced Very High Resolution Radiometer) has been used for snow delineation. The NOAA resolution is nominally one kilometer and the resolution decreases with latitude due to the satellite's polar orbit.

Analysis Techniques

There are four main techniques of analysis for snowcover extent: 1) projection techniques such as the zoom transfer scope and the colour additive viewing, 2) density slicing techniques, 3) computer-assisted techniques such as supervised and unsupervised digital analyses, and 4) grid analysis techniques.

The projection techniques use remote sensing images in photographic positive format. They can be aerial photographs or satellite imagery, positives of approximately 25 cm by 25 cm. Colour or monochromatic images can be used. These positives are then inserted into a specialized projector where their images can be stretched, rotated and enlarged before being projected on standard topographic maps. The projected snow line and cover can then be planimetered directly from the topographic map.

The colour additive viewing technique uses composite images created from false colour monochromatic images. In all other aspects the zoom transfer scope and the colour additive viewing techniques are identical. These projection techniques have problems associated with discriminating among snow, clouds, bare rock and mountain shadows (MRS; p.1523); however, a trained operator can exercise judgement and achieve very good results.

The second analysis technique called "density slicing" makes use of monochromatic digital images. The image is displayed on a computer graphics terminal in various shades of grey where an operator selects the shades associated with snow. The system can then proceed with electronically planimetering snow covered areas. This technique is currently used by Trainer Surveys (1974) Ltd. for the New Brunswick Flood Forecast Center in Fredericton (Johnstone and Ishida, 1984) using a microcomputer. The biggest problem associated with this technique is cloud discrimination and the determination of the snow threshold level.

Digital computer-assisted techniques can be classified as supervised or unsupervised analyses. For this third technique, digital imagery is automatically classified and planimetered by the computer. During supervised analyses the operator has to select the classification table and interactively delineate snow cover. Unsupervised analyses are automatically completed by the system once the operator has "trained" the computer to recognize snow signatures from a wide spectrum of pixel reflectance values. With appropriate software these techniques offer high interpretive flexibility with the highest data resolution.

Digital analysis of Landsat spectral data has proven advantageous when snowcover in large basins or in many basins is to be delineated. When the snow cover extent of only a few basins is required, use of one of the above first two methods is more economical. When numerous basins are included in the analyses, digital methods become more economical and are easier to apply.

There is also another advantage to the digital method. By merging snow extent with conventional topographic data, the classification of snow not only by area but also by elevation is obtained.

The fourth technique is grid analysis, which uses photo interpretation on a grid basis. It is more time-consuming than the zoom transfer scope method, but may prove to be more effective in areas of discontinuous snow cover (MRS; p.1524). This technique is also a manual method and relies on technical judgement.

By determining the snowline by remote sensing techniques, one can also determine the areal extent of snow cover. Although snow line can be found by aerial photography, contemporary operational utilization is via satellite remote sensing. Thus one now determines these parameters jointly and uses the extents, elevations and locations of the snow cover on a basin-wide basis as parameters for the hydrologic forecasting models.

Link (1983) summarizes the current techniques in the following paragraphs.

> "Since 1973 NOAA polar orbiting satellites have been used to produce snow cover maps for selected watersheds in the western United States (McGinnis et al., 1980). Currently NOAA monitors snow cover in 30 basins primarily with the NOAA6/7 and GOES satellites. Photo interpretation methods using zoom-transfer scope equipment are routinely used to estimate the extent of snow cover. The presence of rough terrain and tree cover can significantly alter the snow cover signature making completely automated interpretation difficult.

> Bowley and Barnes (1979) and Rango (1980) have reported successful application of Landsat MSS imagery for snow cover mapping. Band 5 Landsat imagery showed striking differences in snow cover extent in the Sierra Nevada in both normal and drought years. Barnes et al. (1974) showed that in areas such as Arizona and the southern Sierra Nevada, the extent of the mountain snowpacks can be mapped from Landsat in more detail than is depicted in aerial survey snow charts. Weisnet (1974) compared Landsat and NOAA Very High Resolution Radiometer (VHRR) imagery (1.0 km resolution) and found that the snow cover mapped from the VHRR imagery was consistently less than that mapped from Landsat. Studies by Rango and Martinec (1979) and Rango (1980) have shown that snow cover information can be used to help estimate snowmelt runoff using hydrologic models. Landsat data for a basin in Wyoming was used to estimate snow cover extent for input to the Martinec snow melt model resulting in estimated snowmelt runoff within 5 percent of measured seasonal values."

The techniques of delineating snowline/snow cover are operational both by airborne and satellite monitored sensor methods. Landsat and NOAA are currently used.

<u>(b) Snow Water Equivalent</u>

The techniques for determining snowpack water equivalent have progressed significantly during the past five years so that some techniques are now operational. Snowpack water equivalent can be determined by active as well as passive microwave and by gamma ray surveys. (Chang et al., 1981) (Caroll and Larson, 1981). 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.

The most reported operational method of determining values of this parameter are by gamma ray surveys, although this technique gives the total of water equivalent of the snow and the free water in the snowpack.

Airborne gamma ray surveys have become operational during the past few years, and the data obtained have been used to some degree in an operational hydrologic forecasting model (Tang, personal communication, 1985). The technique is based on measuring the natural terrestrial gamma radiation attenuation, which originates mainly in the upper 20 cm of the soil mantle, as it travels through the snow and the atmosphere to the sensor aboard an aircraft. After measuring the soil moisture and the no snow attenuation rates, the snowpack water equivalent can be calculated. Hence surveys to determine soil moisture content and background gamma ray radiation must be taken in the autumn before the first permanent snowfall occurs during the first calibration year. Another survey must be made in the spring before the snowmelt runoff commences. For subsequent sampling years only the pre-melt flight is required using background radiation from the calibration year and soil moisture data.

The use of gamma ray survey obtained snow water equivalents in hydrologic models is still in its infancy. Theoretically, the soil moisture content could be surveyed in the spring only during the snow course; however, in order to be confident in the analyses, it would be prudent to carry out fall soil moisture determinations via gamma ray survey for several years before relying only on the point data obtained from snow courses.

A network of 300 gamma ray flight lines, each 15 to 20 km long, was established in the area encompassing parts of North Dakota, South Dakota, western Minnesota and southern Saskatchewan with surveys undertaken in the winter of 1979/80 (Carroll and Jones, 1982). The snowpack water equivalent was found to be about 80 mm which agreed with a series of ground-point measurements to a root mean squared error (RMSE) of 7.5 mm. Subsequently, it was found that the method gave accurate measures of snowpack water equivalent when the latter is less than 300 mm. Similar results were obtained in New Brunswick, Ontario and Saskatchewan. When the water equivalent becomes very high (over 300 mm) the technique underestimates the true value (Carroll, 1983). In New Brunswick when the snowpack depth over the Saint John Valley was 160 percent of normal in 1984 and its water equivalent was 450 mm in some areas, the gamma ray survey underestimated the quantity by 100 mm. Possible reasons for these underestimations are listed by Glynn et al. (1985).

In 1982 gamma ray snow surveys were conducted in Southern Saskatchewan by the Geological Survey of Canada (GSC) and the U.S. National Weather Service (NWS). Also, the latter carried out a survey with a passive microwave radiometer. All three survey results were compared with passive microwave data from a Nimbus 7 satellite where the snowpack water equivalent varied between 20 and 80 mm as determined from ground measurements. The two airborne survey results agree with each other with a RMSE of 4.5 mm. The GSC data agreed with ground data with an RMSE of 4.6 mm; the NWS survey agreed with ground truth data to a RMSE of 7.5 mm (Carroll, 1983).

Since 1982 gamma ray surveys have been carried out over both American and Canadian subbasins of the Lake Superior basin. The snowpack water equivalent can exceed 250 mm in this region. Both surveys agree with ground-measured data with a 19 mm RMSE and with each other to 4.5 mm. Statistical errors within the ground sampling procedure account for about one-half the RMSE between the two survey results and the ground measurements (Gauthier et al., 1983).

The Swedish Meteorological and Hydrological Institute (Thomas, 1980) has found that gamma ray snow surveys improve hydrologic forecasts in basins with high spatial variability in snowpack water equivalent compared with forecasts based on precipitation measurements.

It has been shown that gamma ray surveys can provide accurate snowpack water equivalent in the Canadian Prairie environment and in the forested environments of Eastern Canada. The currently available techniques are only able to give accurate results when the snowpack water equivalent is less than 300 mm; hence the technique cannot presently be used in the Canadian Rockies where the annual snowpack water equivalents are much higher than this value.

Glynn et al. (1985) reported that Canadian users of snow survey data, including hydroelectric utilities, have indicated that the desired average operational precision is 17 mm of snow pack water equivalent. The experience to date with gamma ray survey provides a precision of 10 mm for a wide variety of snow and terrain conditions (Carroll et al, 1983; Goodison et al., 1985).

In summary, microwave surveys of snowpack water equivalent are still experimental while gamma ray techniques are operational except for mountainous snowpacks.

(c) Free Water Content

This parameter can be found by ground-based surveys; however, it cannot be determined as an individual item by remotely sensed means. With gamma ray surveys the water equivalent of the snow and the free water content are determined as one quantity. Thus this parameter is intrinsically included under water equivalent of snowpack measurement.

(d) Snow Surface Temperature

NOAA TIROS thermal infrared data has been used to estimate snow surface temperatures in two southwestern United States basins by sensing the radiant flux and inverting the Stefan-Boltzman Equation (Frampton and Marks, 1980). Data from TIROS-N band 4 (10.5 to 11.5 µm) with a resolution of about 1 km at the subsatellite point was used. Temperature differences between satellite spatial results and surface point measurements from readings for three data sets (each in a different geographic location) were 3.60, 1.28 and 0.99°K.

With the better geometric rectification and registration provided by NOAA 6 and 7 satellites that superseded TIROS-N, better accuracies should be obtainable (Frampton and Marks, 1980).

Barnes et al., 1981, have shown that thermal infrared data sensed by the Heat Capacity Mapping Mission (HCMM) with its 600 metre resolution could provide snow temperature data; however, since HCMM is no longer operating, NOAA provides the best means of sensing snow temperature on an operational basis.

(e) Snow Albedo

The albedo of snow covered land varies considerably (Robinson and Kukla, 1985). In the visible range of the solar spectrum the albedo of deep snow pack ranges from between 50 and 95%. In the near infrared wavelengths the albedo is lower than in the visible range - decreasing to near zero at a wavelength range of 1.5 to 1.6 µm. At the latter wavelength range the albedo of snow is sufficiently different from that of clouds that the two can be easily differentiated using infrared sensors. (Barnes and Smallwood, 1975).

Snow cover albedo varies considerably with type and density of vegetative cover, age and depth of snowpack (Robinson and Kukla, 1985). Not only is the magnitude of snow albedo important, but also the spectral range of the measurements. Some satellites, such as GOES and NOAA 7 (AVHRR), are able to sense snow albedo in narrow bands only. Landsat 4 and 5 satellites equipped with thematic mappers are able to measure the albedo over a wide spectral band with increased resolution. The thematic mapper offers the following bands:

Band	Wavelength Range - μm
TM1	0.45 - 0.52
TM2	0.53 - 0.61
TM3	0.62 - 0.69
TM4	0.78 - 0.90
TM5	1.57 - 1.78
TM6	10.42 - 11.66
TM7	2.10 - 2.35

Saturation can occur in TM Bands 1 to 4; however, the TM 5 band can be used to discriminate clouds from snow covered areas. In the TM 5 and TM 7 bands, snow is much darker than clouds while water clouds are brighter than ice clouds in the TM 5 band. In the TM 5 band, water is less absorptive than ice, so water clouds are more reflective than ice clouds (Dozier, 1984). Thus from an analysis of the various reflectance band data, one can discriminate among water clouds, ice clouds and snow covered areas with a resolution of 30 m.

Once the reflectance is measured in various spectral bands, the thematic mapper data must be registered to terrain data so that corrections for varying illumination angles and sun shadowing by adjacent terrain can be made (Dozier, 1983).

Robinson and Kukla have used the Defense Meteorological Satellite Program (DMSP) imagery to sense snow albedo over the northern hemisphere in one degree latitude-longitude cells. The sensor was the Operational Lines Scan System (OLS) with a radar resolution of 2.8 km. The snow albedo variations with different land covers were noted. Neither of the above-noted studies discussed the obtainable accuracies.

Brest (1983) has developed a procedure of determining snow albedo from reflectance values sensed by four Landsat MSS bands. No statistical analyses were reported of comparisons with ground measurements; however, gross values of albedo agree well with published results of other studies. Since Brest's study, Landsats 4 and 5 have been launched providing greater spectral data from Thematic Mappers, hence Brest's techniques could be applied to TM data on an operational basis.

(f) Snow Depth

Digital data from Nimbus 5 and 7 satellites can be computer - processed to give brightness temperatures. Using photo interpretation techniques to overlay brightness temperature, with conventional ground based snow depth measurements and base maps can give areal snow depths. The resulting regression equation has a coefficient of determination of 0.86 and a standard error of estimate of 30 mm. Because of the low sensor resolution (25 to 30 km) this method can only give results useful for forecasting in large basins with flat, homogeneous terrain (RMS; p. 1522). Sensors with better resolutions are required before this technique can become operational for basins in which hydroelectricity is generated.

4.1.1.2 Lake and River Ice Parameters

(a) Ice Thickness and Movements

Due to their high sampling frequency (less than 24 hours), NOAA and GOES satellites can provide information on ice movements that would be useful for short-term hydrologic modelling. A study by McGinnes and Schneider (1978) demonstrated this for the Ottawa

River system. The low sensor resolution limits applications to only large river and lake systems.

Values for ice thickness and movement can be determined by analysis of Thematic Mapper data obtained from Landsat 4 or 5 when the two satellites are in operation; however, the 9-day plus frequency of measurement are not sufficient for operational forecasting purposes.

The only operational technique to monitor these parameters is by using DCSs.

4.1.1.3 Surface Water

a) Areal Extent

The areal extent of water bodies - both lakes and rivers - can be found. Shores can be delineated by both airborne and spaceborne sensors. The airborne techniques can be any scale corresponding to a topographic map, while the satellite obtained results are limited to water bodies, the smallest dimension of which is at least equal to the satellite sensor resolution. The best presently available resolution is 30 metres provided by the Thematic Mapper onboard Landsat 4 and 5.

In some cases where high resolution topographic mapping is not available a reservoir stage-storage relation can be found by means of satellite data. The area extent of the water body (at various water surface elevations) during the initial reservoir filling can be determined. This technique was researched at Diefenbaker Lake in Saskatchewan where the stage-volume relation determined from airborne techniques compared within five percent to results obtained from topographic maps. It has been used operationally with the Temergore Dam reservoir in Malaysia. Another application was sited by Gervin and Shih (1981) for Lake Okeeshobee in Florida. Although no statistical measures of goodness of fit are available for stage-storage curves determined by Landsat and topographic maps, the agreement between the two should be good.

Analyses using four techniques using landsat MSS data for six small reservoirs (all less than 130 km^2 in surface area) were carried out at 1:1,000,000, 1:500,000 and 1:250,000 scales (White, 1979). The percentage errors in surface area are large and not consistent among the four evaluated measurement techniques. There is a reservoir size below which an accurate stage-storage relation cannot be determined using these techniques; however, this is not an issue in Canada in locations where hydroelectricity is generated since basins are large and 1:50,000 topographic mapping is available.

b) Saturated Soil Area

This parameter is important in hydrologic modelling; however, very little could be found in the literature on its operational determination, although work by Solomon (1976) in delineating and classifying flooded areas show promise in this regard. This parameter will not be considered further.

(c) Lake/River Stages

These parameters are used in almost all hydrologic forecasting models where routing is included. Although they can be found by airborne and satellite data analysis techniques, the results are not very accurate. By the use of a DCS and stategically located hydrometric stations this parameter can be evaluated for use in hydrologic forecasting models.

(d) Waves and Seiches

Wave statistics are not used in hydrologic forecasting models. Seiches do have some applications to flow forecasting techniques.

For example, the seiches that build up the water levels on the eastern shore of Lake Erie have a direct influence on the flow rate a few hours later at the hydroelectric plants located on the Niagara River. A similar but lower magnitude effect occurs with the hydroelectric plants on the St. Lawrence River from seiches occurring on Lake Ontario. These water level changes can be operationally monitored by stage recorders and transmitted to an operation centre via a DCS. These levels can be used to adjust flow rate, for example, to satisfy prescribed electric demand in the most economical way.

4.1.1.4 Drainage Basin Characteristics

a) Drainage Area

This parameter can be determined from topographic maps; the larger the map scale, the more precise the value. Most basin areal determinations in Canada are done with 1:50,000 scale National Topographic Series maps with 50-foot contours for the old imperial editions and 10 metre contours on the recent metric editions.

There are three commonly used topographic map scales in Canada - 1:25,000, 1:50,000 and 1:250,000. The 1:25,000 scale only covers a small percentage of Canada's land area, and there will be no new mapping carried out by the Survey and Mapping Branch of Energy Mines and Resources at this scale. The 1:250,000 maps are usually compiled with data that were used to make the 1:50,000 topographic maps. Therefore the accuracies of the two map sets are the same, but the resolution of the 1:250,000 map is less. Thus, the topographic maps used to delineate drainage areas in Canada in most cases are of the 1:50,000 scale. This latter scale of maps covers all areas of Canada at latitudes below 60 degrees North except two "pockets" in Northern Ontario.

An outline of horizontal and vertical accuracy specifications for various map scales by the Survey and Mapping Branch is given in Appendix C. All published maps in Canada are specified as B2 or better. This minimum standard criteria means that 90 percent of all points represented on a 1:50,000 scale map are within 50 metres of a point on the map representing its true position. Furthermore, 90 percent of all contours are within one contour interval of the true elevation.

Since these maps are available in most parts of Canada, it would be very unlikely that Landsat data would be used to delineate drainage areas. Moreover, ground elevations cannot be determined from operational satellite sensors.

The drainage area could be found by areal photography means; but this is not a practical consideration since the 1:50,000 maps are available for most of Canada where hydroelectricity is generated and their accuracies are to an acceptable level.

(b) <u>Channel Dimension and Overland Flow Length</u>

The channel dimensions and to a lesser degree overland flow lengths can be estimated from data recorded by the Thematic Mapper aboard Landsat 4 and 5 with a resolution of 30 metres; however, these quantities are more precisely determined from 1:50,000 topographic maps.

Link (1983) states:

> "Channel and valley cross section data and the drainage network in a basin are critical to most modeling efforts. While general slope and valley section data have been provided by photogrammetry, it is an expensive method for large areas. Airborne laser mapping systems have significant potential for cross section mapping in both open and wooded areas (Link and Collins, 1981). A pulsed laser system, the NASA

Airborne Oceanographic Lidar, produced profiles over 2 km length flightlines that had a root-mean-square difference of from 12 to 27 cm in unforested areas and less than 50 cm in forested areas".

Both topographic mapping and the pulsed laser system technique are operational.

(c) Surface Slope

This parameter cannot be determined from current satellite sensed data, although some of the planned satellites equipped with radar sensors could determine slopes. The slopes could be determined by obtaining aerial photographs for analysis by photostereoscopic means; however, the accuracy obtainable from 1:50,000 topographic maps will suffice for hydrologic modelling purposes in large basins where hydroelectric generation is considered.

Surface slope data can be calculated by computer software if digital forms of NTS maps are available. The elevation contours would be processed to produce a digital terrain model (DTM) from which slope information could be extracted. Limitations on this technique are source materials since only a fraction of the country is available in digital map format.

(d) Land Cover/Land Use

The various land covers that exist on a basin have a strong bearing on the runoff coefficient and basin hydrologic responses. For calibration of many hydrologic forecasting models, statistics of the various land covers that exist on each modeled sub-basin must be known. Also the changes in land cover throughout a year may have to be considered for updating the state variables. For example, the seasonal canopy variations in a hardwood forest have a bearing on evapotranspiration rates and in turn on runoff amounts. These requirements are a function of model sophistication, which, in turn, depends on accuracy required. Land cover categories are conventionally derived from topographic maps, which are based upon aerial surveys, and are extensive in number; whereas there are fewer obtainable land cover categories from satellite imagery. The satellite that currently gives the best resolution and the highest accuracy is Landsat. In most land use/cover studies the following land types are mapped:

Agricultural
Residential
Industrial/Commercial
Hardwood Forests
Softwood Forests
Undeveloped Open Space
Water
Cropland/Pasture
Quarry

The U.S. Army Corps of Engineers (1979) studied Landsat MSS-derived data for four basins in California varying in size from 15 to 350 kilometres. The average accuracy of the land cover classification determined with Landsat data was 62 percent at the grid level studied. When the data was aggregated to the basin level, the accuracies increased to 92 percent and in some basins to 98 percent. With data from the Thematic Mapper aboard Landsat 4 or 5, the average classification error is further reduced due to the sensor's superior resolution.

Link (1983) states:

"Classification of Landsat MSS imagery for land use/land cover information has been the most widely investigated application of space remote sensing in hydrologic modeling. The bulk of these efforts have centered on using the land use information to estimate SCS runoff curve number values for streamflow forecasting and flood studies. Slack and Welch (1980) used Landsat I data to estimate SCS curve numbers for the 125 mi2 Little River Watershed, Georgia. Average SCS curve numbers were computed for each of six sub-basins and compared to conventionally derived values. Agreement was within 2 curve numbers. They reported land use classification accuracies of 88 percent for agricultural lands (vegetated and bare soil), 87 percent for woodlands, and 27 percent for open water.

Webb et al. (1980) used Landsat to acquire land use data by unsupervised classification techniques for six watersheds across the United States. In four of these basins the Landsat classifications and simulation results were compared to those from conventionally acquired data. In the Rowlett Creek (24.6 mi2) Landsat data provided nearly the same lag time as the conventional data and flow-frequency curves derived from simulations using Landsat and conventional data were very close. While the average basin parameters derived from Landsat and the resulting simulation results were determined to be within acceptable error limits for hydrologic modeling, individual cell classification accuracies were relatively poor. In general, at the grid cell level Landsat land use was in error about one third of the time. By aggregating land use over large areas, the average percentage of area covered by each major land use class reduced to less than 8 percent.

Taylor et al. (1980) compared the use of Landsat derived and conventional land cover data for six watersheds. The cost effectiveness of Landsat was proven for areas greater than 26 km^2 (10 mi^2). Their analyses showed Landsat and conventional methods to be nearly equally effective in producing land cover data for hydrologic studies.

Jackson et al. (1977) used the Hydrologic Engineering Centre model STORM and the WREM model to assess land use data from Landsat for hydrologic modeling. Landsat bands 5 and 7 were used to classify Forest, Residential, Grass, Highly Impervious, Moderately Impervious, and Bare Soil. Agreement between air-photo and Landsat estimated land cover classes decreased as the size of the area over which values were lumped decreased. The WREM model was used to model 179 subcatchments with Landsat providing input on the percent impervious area for each. The error in this estimate was very substantial for small subcatchments, confirming the relationship observed for land cover.

Bondelid et al. (1981) compared Landsat and conventionally derived SCS curve numbers for three watersheds in Pennsylvania. The results showed that in general the curve number estimation was not highly sensitive to the land cover data source, although Landsat was not able to identify land cover at the same level of detail as is normally used in the SCS procedure. The study also showed that while Landsat-derived and conventional curve numbers may agree well over an entire watershed, there may be large differences for individual subwatersheds."

Harvey and Solomon (1984) compared Landsat MSS, GOES visible band and GOES visible plus infrared bands and landcover mapping errors of the Serpent River Basin in Northern Ontario with those derived from 1:50,000 topographic maps. Three landcover types were classified - water, forest and urban/barren areas; these classification types represent the land cover on most Canadian basins where hydroelectricity is or can be generated economically.

Harvey and Solomon (1984) report the following studies pertaining to obtainable accuracies from different technologies.

Conventional Mapping

The overall accuracy of the conventional mapping (based on low altitude aerial photography), although the best, was not as high as expected. Based upon standard errors of estimate at a 1 km x 1 km grid size, water was most correctly classified (6.6% error), followed by urban/barren (14.7%), and then forest (16.8%). As expected, as the grid size increased, the standard errors for all three classes decreased. Water was least affected; the standard error of urban/barren decreased by 8.3% to 6.4%, and that of forest decreased by 7.3% to 9.5%.

Based upon the mean error bias, both the water and urban/barren classes tended to be underestimated, while the forest class tended to be overestimated. These trends were independent of grid size.

LANDSAT MSS Mapping

Overall, the LANDSAT MSS mapping was about as accurate as the conventional mapping. Accuracies of the forest and urban/barren classes were the same or better, while accuracies of the water class were only slightly poorer. Standard errors again decreased with increased grid size but only up to the 3 km x 3 km grid size. The trends of underestimating water and urban/barren, and overestimating forest, are apparent with the LANDSAT estimates also.

GOES VIS Plus IR Mapping

The accuracy of the GOES VIS + IR mapping was by far the poorest of all, as may have been anticipated by a visual comparison of the four maps. The least standard error was that of water estimated from a 4 km x 4 km grid: 18.4%. The urban/barren class was the most poorly estimated, having a standard error of 52.2% at the 1 km x 1 km grid size. The forest class fared little better, with a standard error of 50.7% at the same grid size. Most standard errors decreased with increased grid size but remained poor. Water was underestimated much more than in other methods and, contrary to the other methods, forest was generally underestimated, whereas the urban/barren class was usually greatly overestimated.

GOES VIS-only Mapping

The overall accuracy of the VIS-only mapping was surprisingly high. Generally, the standard errors of all classes were a little poorer than those of the conventional and LANDSAT mapping at grid sizes of 1 km x 1 km and 2 km x 2 km, but the standard errors were as good at the larger grid sizes. All standard errors decreased with an increase in grid size. As with both the conventional and LANDSAT mapping, water and urban/barren classes were usually underestimated, and the forest class was usually overestimated.

The 30-metre resolution provided by the Thematic Mappers of Landsat 4 and 5 satellites provides the highest resolution presently operationally available. Differences of opinions exist on the usefulness of using Landsat data to delineate and classify land cover types and other watershed characteristics. Many hydrologists using Landsat claim that it provides data with acceptable accuracy while the cartographers assert that the delineations are not as accurate as those available from 1:50,000 topographic maps (MacDonald, Fleming, personal communications, 1985). Nevertheless, it is fair to state that Landsat provides land cover delineations with sufficient accuracy that any resulting errors in hydrologic modelling are insignificant (Franz and Liew, 1981). Moreover, most land cover delineation obtained from topographic maps are dated; whereas, Landsat data provides the means of obtaining contemporary land-cover information.

(e) Land Albedo

There are two methods of determining estimates of albedo from sensors. One method is to measure the reflectance in one or more wavelength bands and apply equations or "conversion factors" to obtain the reflectance over the total solar spectrum and hemisphere (Pinty et al., 1985). The other method is to measure the albedo directly.

Surface albedos have been measured with sensors mounted in METEOSAT (Pinty et al., 1985) NOAA-6, and Landsat, (Otterman and Tucker, 1985).

Using data obtained from METEOSAT over Upper Volta, under clear sky conditions, albedo values for a 50 km by 50 km grid were obtained. Accuracies of approximately 10 to 20 percent of ground based point measurements were noted (Pinty and Szejwach, 1985). The difference between ground and satellite-based albedo measurements is 0.03 over the spectral range of the METEOSAT sensor (0.4 - 1.1 μm). Conversion of the METEOSAT spectral albedo into solar spectrum-weighted albedos still requires additional research.

Dugas and Heuer (1985) reported on comparisons between ground measured and GOES-sensed solar irradiances for twenty locations in Texas over a two to three year period. RMSE between irradiances averaged 2.5 MJ m-2d-1 which is 12% of the mean annual.

Brest (1983) used Landsat MSS bands 1 and 4 and a linear regression equation to predict surface reflectance from satellite sensed radiance for 14 land cover categories. No direct comparisons with ground based measurements were stated; however, some satellite-obtained values were compared favourably with other reported values for urban areas. The reported technique seems promising and could be applied to large watersheds, nevertheless it cannot be stated operational until ground truthing is completed.

Berg et al. (1981) did a similar analysis using NOAA 5 VHRR data for the Red River of the North with a zoom transfer scope to delineate the area at the 1:250,000 scale. The areas delineated from the rectified imagery are probably accurate to about 50 km^2. The main advantage of using the NOAA data is the twice daily coverage provided no cloud cover is present. This means of analysis could be considered operational.

To date the problems of determining albedo values for various land-cover types by satellite-mounted sensors and different atmospheric conditions have not been resolved. Most efforts to date have been investigated using satellite data for climatic forecasting models. The smallest spatial resolution considered in these types of models is 50 km by 50 km grids. This is too low a resolution for use in hydrologic streamflow modelling in Canada.

4.1.1.5 Groundwater

(a) Groundwater Levels

The groundwater levels could be monitored by DCP and transmitted to a flow forecasting centre via DCS. Subjective indicators of groundwater levels are used as model state variables and could be determined by monitoring occurrence and magnitude of aquifer extent, location and flow magnitude of springs in some basins. Techniques which incorporate these analyses are outlined in Bobba et al. (1981) and Kohout et al. 1981.

(b) Soil Moisture Content

Schmugge et al. (1979) outlined the properties observed in each spectral region of satellite and aircraft mounted sensors that could be used to estimate soil moisture. They are listed below.

Wavelength Region	Property Observed
Reflected Solar	Soil albedo/index of refraction
Thermal Infrared	Surface temperature
Active Microwave	Backscatter coefficient, dielectric properties
Passive Microwave	Microwave emission/dielectric properties & soil temperature

The use of reflected solar energy is not a very promising technique since the soil spectral relectance as a function of moisture content depends on several other variables, such as reflectance of dry soil, surface roughness, organic matter and others (MRS; p.1508).

Link (1983) noted that, "The use of reflected energy in the form of tone or colour on aerial photographs is useful for qualitative estimates of wet or dry conditions. Since spectral reflectance of dry soil, surface roughness, and other factors influence the spectral signature of wet soils, Landsat has not provided a reliable quantitative tool for soil moisture mapping". This technique will not be considered further; however, thermal and microwave techniques have promising potential.

Soil temperature is influenced by the entire soil matrix at greater depths than those measured by reflectance measurements.

> Link (1985): "Thermal methods rely on measurement of the diurnal range of surface temperature or measurement of crop canopy temperature (Schmugge, 1978). Thermal band provides relatively high resolution (1 km or less). Limitations include the inability to sense moisture content in areas of cloud cover and interference from partial vegetation cover and surface topography. By coupling topographic data with the thermal imagery, some influences of topography can be normalized. Heilman and Moore (1979) demonstrated the potential of the HCMM thermal imagery for detection of near surface soil moisture. Thermal inertia values were shown to relate reasonably well to soil volumetric water content for areas in South Dakota. The thermal band on the NOAA-6 AVHRR has similar potential for soil moisture sensing."

Thermal infrared measurements in the 8 to 12 μm wavelengths are a function of thermal conductivity and heat capacity of the ground - both of which are strong functions of soil moisture. The results of satellite surveys are representative of soil moisture over the top four centimeters of cover. Derived equations relating soil water content to amplitude of diurnal surface soil temperature can be obtained with a correlation coefficient of 0.8 (RMS, p. 2165). It can be used to obtain indications of soil moisture status, but as of yet cannot be used operationally to obtain quantitive values for hydrologic forecasting techniques which require indices of soil moisture over the depth of the root zone.

Microwave in the 1 to 50 mm wavelength band can be used to sense soil moisture. The sensing of soil moisture in the microwave frequency (both active and passive) can be achieved because of the soils dielectric properties (MRS, p. 2161). These techniques can be considered operational, although not with the resolution required for hydrologic forecasting purposes.

Active microwave sensors rely on changes in soil dielectric properties (Lundien, 1971) or backscatter coefficient (Batlivala and Ulaby, 1977) with changes in soil moisture content. Feasibility of using microwave sensors for soil moisture determination has been established by aircraft and ground measurements; however, sensor systems with reasonable resolution are not currently available for spacecraft. The synthetic aperture radar (SAR) system on the experimental SEASAT satellite was the first system with high resolution (25 m); however, the incidence angle employed was not optimal for soil moisture determination and there is difficulty in calibrating such a system with enough precision to extract soil moisture data. Moreover, SEASAT is not currently in operation.

Passive microwave systems provide some advantages over thermal systems but suffer from poor resolution (5 and 10 km). McFarland (1976) showed a close correlation between the 21 cm passive microwave (Skylab) brightness temperature and the Antecedent Precipitation Index for areas of Texas and Oklahoma. Since passive microwave systems sense emitted energy, they are sensitive to both temperature and emissivity.

Aircraft-mounted sensors flown over South Dakota provided data to relate soil moisture to sensed brightness temperature. Correlation of results with measurements in the top 2.5 cm of soil depth and brightness temperature are greater than 0.85. (MRS; p.1509)

The microwave techniques can be used with airborne sensors with good resolution but when on satellites the resolution deteriorates. Normally for hydrologic modelling purposes the soil moisture from ground level to root depth is an important variable. Hence, since both methods cannot sense soil moisture to an adequate depth they cannot be considered operational for hydrologic forecasting.

Recent work by the U.S. Army Corps of Engineers using gamma ray surveys from aircraft flight lines over individual basins of the Lake Superior watershed has shown much promise (Gauthier, 1985; private communication). The technique used is based on the difference between the natural terrestrial gamma radiation flux measured for comparatively wet and dry soils.

A comparison of remote sensing approaches for estimating soil moisture is given in Table 4-3 which was taken from the Manual of Remote Sensing (1983). In conclusion, soil moisture characteristics can be qualitatively inferred from NOAA Satellite Imagery. None of the techniques are operational as yet, but it appears that gamma ray surveys could be operational in the near future.

Closely allied with soil moisture is infiltration. There is nothing in the literature on research efforts to monitor this parameter by remote sensing techniques.

Table 4-3

Comparison of Remote Sensing Approaches for Soil Moisture Sensing (from Schmugge et al., 1981)

Sensor	Advantages	Disadvantages	Noise Source
Thermal infrared (10-12 μm)	High resolution possible (400 m) Large swath Basic physics well understood	Cloud cover, limits frequency of coverage	Local meteorological condition Partial vegetative cover Surface topography
Passive microwave	Independence of atmosphere	Poor spatial resolution (5-10 km at best)	Surface roughness
	Moderate vegetation penetration	Interference from man-made radiation sources, limits operating wavelengths	Vegetative cover Soil temperature
Active microwave	Independence of atmosphere	Limited swath width	Surface roughness
	High resolution possible	Calibration of SAR	Surface slope Vegetative cover

(c) Permafrost

The remote sensing of permafrost is directly related to that of frozen ground, which is covered in subsection 4.1.1.10 ; however, the permafrost has an active layer - an upper layer that melts each summer and below which there is perennially frozen ground. Since permafrost covers fifty percent of the land mass of Canada it has a significant effect on hydrological forecasting. Not only is the areal extent of permafrost important but also the depth of the active layer.

Efforts by Morrissey (1983) and Schreier and Selby (1981) have concentrated on sensing various vegetation types, dense spruce forest, Ledum-Sphagnum groups, Eriophorum tussock and Carex tussock - by colour and thermal infrared sensors to infer permafrost conditions underneath, such as depth of active layer, moisture content in the active layer and temperature at the 20 cm depth.

Schreier and Selby (1981) found the relationship between the thermal pattern and the distribution of some of the above listed five plant communities, but it is not consistent enough to obtain a direct inference of permafrost conditions from thermal data. The use of vegetation communities as an indicator of the active layer seems to hold promise.

Airborne mounted short pulse radar - 480 MHz - has been used experimentally to measure subsurface permafrost features such as ice wedges, ice lenses and pingo ice cores to depth greater than nine metres (Hall, 1981).

In summary, although considerable experimental work has been done on the remote sensing of permafrost conditions, further research is required before any of these techniques become operational.

4.1.1.6 Soil Temperature

Vieira and Hatfield (1984) used an airborne infrared thermometer with a 10.5 - 12.5 μm filter to measure soil surface temperature for both clear and cloudy sky conditions. The accuracy increased with shortening duration between measurements. They found that there was a relation between surface and air temperatures.

Sequin and Itieu (1983) and Hatfield et al. (1983) have recently carried out work on using remotely sensed data to aid in determining regional daily evaporation and evapotranspiration quantities. Hatfield et al (1983) have used remote sensing means to determine surface temperatures while Sequin and Itieu confirmed these findings and developed a theoretical foundation. Thermal IR data is presently available from GOES and NOAA satellites. This enables temperature statistics to be determined by remote sensing techniques. Work is presently underway to incorporate algorithms and data in a distributed model (Fortin, personal communication, 1985).

4.1.1.7 Radiation

The net radiation balance can be expressed by the relation:

$$N = (1-A)Io-E \qquad \text{(MRS; p.1325)}$$

where,

N = net radiation
A = albedo of the earth-atmosphere system
Io = Incoming solar radiation
E = Outgoing longwave radiation

The solar radiation constant, Io, can be measured by satellites. NIMBUS-7 achieves this with a precision of greater than 95 percent.

From TIROS and NOAA satellites full spectrum albedo is determined from the visible channels by assuming that the reflectance in a narrow spectral band is a good estimate of the full spectral reflectance. Using NIMBUS satellites, albedo is determined from a wide spectral channel with corrections for the anisotropic reflection properties of the surface. The techniques provide "reasonable values". (MRS; p.1325)

Longwave radiation has been calculated from TIROS and NOAA satellite data from the 10-12 μm window using regressional models which consider model atmospheres, temperature, moisture and overcast parameter as well as clear sky conditions as independant variables. A developed linear equation explains 98 percent of the variance. (MRS; p.1325)

The amounts of hourly solar radiation reaching the earth's surface can be estimated from GOES satellite visible brightness measurements using a semi-empirical equation. These estimations agree with pyronometer measurements to within 90 percent. Questions still remain on the appropriateness of the method when snow is present on the ground (Gauthier et al., 1980).

Raphail (1983) studied the application of the Gauthier model with one developed by Hay and Hanson (1979) and demonstrated the former's superiority for partly cloudy and overcast conditions; the latter model gives better results under clear sky conditions.

From the above it may be concluded that net radiation may be calculated from data recorded by satellite-mounted sensors with reasonable accuracies. Although there are no cases in the literature of the above techniques being used to determine radiation statistics on an operational basis, there is no reason to believe it cannot be used. No costs can presently be put on the operational use of the techniques and the accuracy of the derived net radiation statistics cannot be assessed; however, the technique is nevertheless operational.

4.1.1.8 Precipitation and Evapotranspiration

(a) Evapotranspiration

This quantity cannot be directly measured by remote sensing techniques. Pan evaporation can be measured at observation sites and the data can be transmitted to a central location by a DCS where it can be transformed into evaporation estimates. Both evaporation and evapotranspiration can be estimated from meteorological parameters such as wind speed, vapour pressure and solar as well as terrestrial radiation. Net radiation values can be monitored by satellite and was addressed in the previous section.

A study was carried out by Khorram and Smith (1979) in which the daily total potential evapotranspiration is related to mean daily temperature and daily incoming solar radiation. The temperatures were obtained from NOAA VHRR and the ground-level solar radiation was derived from temperature, duration of daylight, total incoming radiation, cloud cover, albedo, slope and aspects parameters. Some of these parameters can be determined by remote sensing methods, and they are covered in the appropriate subsections.

(b) Precipitation

Of the many components of the hydrologic cycle, precipitation is the most important parameter in terms of water input to a basin. Although snowmelt and spring runoff constitutes a large portion of the total yearly reservoir inflow in northern latitudes, it is the temporal distribution of precipitation storms throughout the year that cause most of the reservoir operational decisions to be made. Forecasting these precipitation events becomes a major concern, since through accurate forecasting timely and proper operational decisions can be made.

Due to the nature of precipitation (the most highly variable meteorological element through space and time) accurate precipitation forecasts for one or more months are unlikely. There may exist methods which use past records on a time series-type approach, but the timely nature of remotely sensed data would not be required. For this reason, it is assumed that long-term forecasting of precipitation using remotely sensed data will not be considered.

Short-term forecasting of precipitation for a period of 10-15 days ahead may also be questionable. In terms of recent work in the field, existing remote sensing techniques are actually used for "nowcasting" precipitation events. This means that the precipitation events are examined on a real-time basis, and leads to a forecasting period equal to the lag time between the occurrence of rain and the resulting inflow to the reservoir. This lag time is typically a few hours to a few days, depending on the size of the basin. It is from this point of view that use of remotely sensed precipitation data in forecasting models is approached.

Measurements of Precipitation By Weather Radar

Weather radar has long been an experimental tool used by hydrologists to determine rainfall on a real-time basis. Only recently have the methodologies been developed to the state where they can be used in an operational sense. These methodologies are used to determine rainfall amounts and areal extents. Unfortunately, operational radar installations in Canada are located in a narrow band along the border with the United States as shown in Figure 4.1 and listed in Table 4-4. Ideally with a 250-km operating range a circular area of 50,000 km2 can be sampled. From Figure 4.1 it can be seen that the following regions, which have intermediate-sized basins and hydroelectric

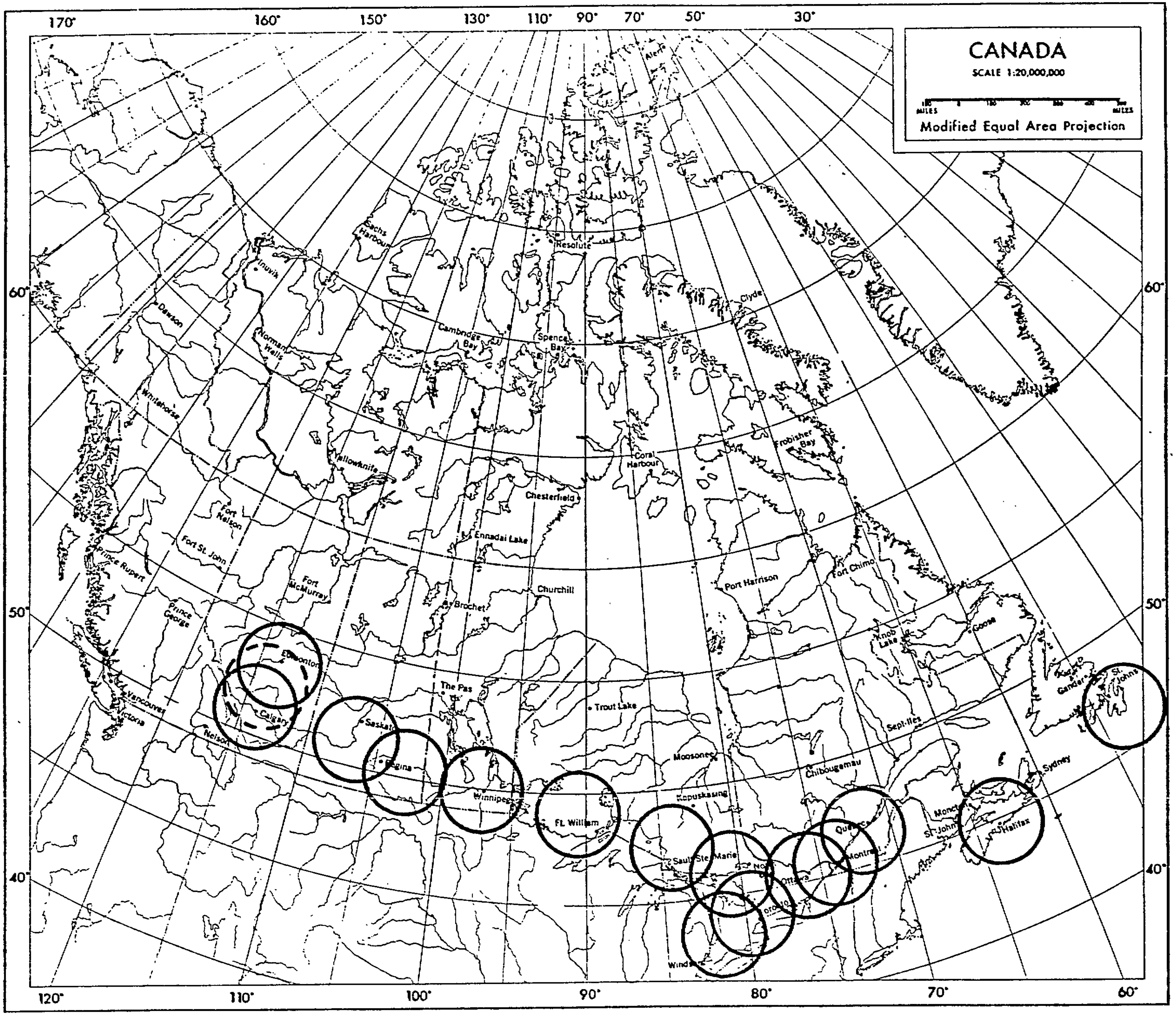

FIG. 4-1 AREAL COVERAGE OF CURRENT AES WEATHER RADAR STATIONS

Table 4-4 AES Weather Radars - National Network (C-BAND/5 cm)

	Centre/Area	Location	Lat. (N)	Long (W)	Type
*	St. John's	Trepassey	46° 46'	53° 11'	R
**	Halifax	Intnl. Arpt.	44° 53'	63° 31'	E
*	Quebec City	Villeroy	46° 27'	71° 55'	R
*	Montreal	McGill-Macdonald	45°25'27"	73°56'20"	C
*	Ottawa	Carp	45°19'05"	76°00'00"	R
*	Toronto	King	43°57'50"	79°34'27"	S
*	London	Exeter	43°22'12"	81°23'12"	R
	North Bay	Britt	45°47'30"	80°32'00"	E
	Sault St. Marie	Montreal River	47°14'52"	84°13'45"	E
	Thunder Bay	Upsala	49°02'15"	90°29'30"	E
	Winnipeg	Vivian	49° 53'	96° 28'	E (1984) (a)
	Regina	Broadview	50°22'40"	102°41'30"	E
	Saskatoon	Elbow	51°07'42"	106°35'00"	E
	Edmonton	Stony Plain	53° 19'	113° 35'	E (1984)
	Calgary	Vulcan	51° 07'	114° 01'	E
*	(Penhold)	(Red Deer)	52° 08'	113° 57'	A

<u>LEGEND - TYPE</u>

CW - Curtiss-Wright FPS-1001; modified and with record/TX system
R - Raytheon WSR807; SCEPTRE record/TX system
E - Enterprise CWSR-81
C - Contract - McGill 10 cm radar
S - Toronto Replacement/Relocation - dual 5 & 3 cm; Doppler facility
A - Alta. Res. Council, 5 cm; polarization diversity
(a) - Exact location undetermined, neighbourhood location only, 12.01.83

29 August 1985

* Archive Data Available
** Not being Archived currently

plants situated within them, are currently covered by weather radar.

1. Eastern slopes of Rocky Mountains between Edmonton and Calgary.
2. North and East of Winnipeg in Manitoba.
3. North side of Great Lakes and St. Lawrence River from Thunder Bay to Saguenay River.
4. Mainland portion of Nova Scotia.

Basically, a weather radar operates by an antenna transmitting a pulse of microwave radiation for a duration of a few microseconds. When this pulse intercepts precipitation some of the emitted energy is scattered back to the antenna. The time between transmission of the pulse and the reception of the back scattered energy determines how far away the precipitation is. The antenna position determines the azimuth as well as the elevation of the precipitation, while the magnitude of the received signals is a measure of the precipitation intensity.

Doviak and Zrnic (1984) have described various weather radar methods. Two methods are based on the remote measurement of one parameter, and three methods are based on measurements of two parameters. The former group consists of the attenuation rate and reflectivity factor techniques. The one based on attenuation determines the relation between microwave attenuation and rainfall rate. There are difficulties in acquiring data at high rainfall rates over large areas with this method. It is still experimental.

The second group of three methods, involving the measurement of two parameters, consist of the dual wavelength method, the dual polarization method and the rain gauge and radar technique. The first involves the joint measurements of the reflectivity factor and the attenuation rate. This method is not operational, and no measures of accuracy were found in the literature.

The second method - dual polarization - relies on the echo intensity of two orthogonally polarized waves, which can differentiate at times between the ice phase and the liquid phase of water. No measures of rainfall rate accuracies are known. There are indications that the two parameter methods do not give as good results as the one parameter methods (Austin, personal communication, 1985).

The combined rain gauge and radar method takes advantage of raingauges that give relatively accurate point readings and radar which, although it gives less accurate rainfall rates, gives areal values and millions of measurements per minute.

Brandes (1975) showed that radar derived rainfall corrected by gauge precipitation data decreased the error from 24 percent for gauges alone to 14 percent for combined radar - precipitation gauge measurements with a gauge density of one gauge per 1600 km2.

The reflectivity factor method by Doviak and Zrnic (1984) briefly described above seems to be the most commonly used approach. With this technique the magnitude of the signal returned to an antenna is called the reflectivity factor. The general relation between the two is:

$$Z = a R^b$$

where R is precipitation rate and b values vary with storm type as well as geographic region (range between 1.2 and 2.0).

The coefficient of the applicable equation can be found from calibration with surface measuring precipitation gauges or usually less accurately by using some empirical climatological Z - R relation.

There are many empirical relations developed between radar reflectivity factor and precipitation. Battan (1973) has shown that for precipitation rates between 20 and 200 mm/hr, the equations agree reasonably well. Battan gives typical relations for various types of rainfall. These are:

Stratiform Rain	$Z = 200\ R^{1.6}$
Orographic Rain	$Z = 31\ R^{1.71}$
Convective Rain	$Z = 486\ R^{1.37}$
Snow	$Z = 2000\ R^{2}$

where Z is in millimetres to the sixth power per cubic meter and R is in millimeters per hour.

It has been found by Richards and Crozier (1983) that the relation $Z=295R^{1.43}$ was applicable to instantaneous rainfall for Southern Ontario, using the C-band radar. A standard error of estimate of 0.288 m was determined when considering the logarithm of R. Also, the correlation coefficient was 0.79. They also give Z-R relations for various synoptic and rainfall types with standard errors of estimates ranging between 0.217 and 0.348 when compared with rainfalls measured by a disdrometer rain gauge.

The data provided by this weather radar to a forecasting center is for two kilometer squared grids (normally every ten minutes). Although it does not have to be, precipitation amounts are given in terms of a grey scale. For example, those given to the Ontario Conservation Authorities Flood Forecasting Centre are discretized into the following bands:

Grey Scale Level	Precipitation Rate
1	0 - 1 mm/hr
2	1 - 2 mm/hr
3	2 - 4 mm/hr
4	4 - 8 mm/hr
5	8 - 16 mm/hr
6	16 - 32 mm/hr
7	32 - 64 mm/hr

Thus, greater resolution is given to low intensity storms.

The accuracy of radar determined precipitation data for various basin sizes and time intervals are given in Table 4-5. The values given in this table are derived from a ground-based measurement study of various gauge densities completed under the Alberta Oil Sand Environmental Research Program (AOSERP; p.19).

Wilson (1976) indicated that radar precipitation estimates to within 10 to 20 percent error can be obtained with the following conditions:

Area larger than 100 km^2
Integration time interval larger than 3 hrs
Radar range 50 - 100 km
Calibration gauge density: 1 per 3000 km^2
Collection frequency $\geq$ 6 per hour
Precipitation rates $\geq$ 1 mm/hour

Joss et al. (1970) found good agreement between ground measured and radar determined daily rainfall amounts. When the daily total is more than 10 mm, the standard deviation is 28 percent. When different Z - R relations were used for drizzle, showers and thunderstorm rainfalls the standard deviation was 13 percent.

Table 4-5 Comparison among experiments of the average error in gauge adjusted radar estimates.

Data Source	Experiment [Reference]						
	Wilson['70]	Brandes['75]	Woodley['75]	Wilson['75]	Harrold['74]	Collier['75]	Wilson['75]
	Oklahoma Thdrstms	Oklahoma Thdrstms	Florida Showers	Great Lakes Summer	Wales Rain	Wales Rain	Great Lakes Winter
Area Size (km^2)	3500	4000	570	170	500	700	855
Time Interval	storm	storm	24 hr	24 hr	1 hr	3 hr	24 hr
Radar Range (km)	37-95	37-95	65-140	95-112	12-48	12-48	18-64
Collection Frequency (per hr)	6-12	12	12	6	60	60	6
Calibration Gauge Density ($1/km^2$)	1/1100	1/900	1/3250	1/275	1/700	1/700	1/800
Adjustment Procedure*	A	F	A	F	A	W	F
Average Error (%)	28	13	~20	24	14	9	15

* A - average adjustment, F - field adjustment and W - weighted adjustment.

From: The Feasibility of a Weather Radar Near Fort McMurray, Alberta, Alberta Oil Sands Environmental Research Program, 1977.

The above errors are of comparisons between the rainfall amount derived from radar data and ground measurements at precipitation gauges.

Most accuracy studies of precipitation amounts in which radar derived rainfalls are compared with precipitation gauge-measured rainfalls are carried out with the values being measured in an atmospheric column. In other words, the rainfall sensed by radar during a storm over a particular location is compared with the amount that is measured in a precipitation gauge at the same location during a common interval.

Browning et al. (1981), in an analysis of hourly rainfall amounts for forecast periods of 0 to 6 hours of 29 frontal rainfall events in England, found that the percentage errors were about 75 percent of objective forecasts and about 50 percent for subjective forecasts (both independent of forecast interval).

Austin found for a study in the vicinity of Montreal that radar-derived and ground-based precipitation for a one hour forecast interval had about a 35 percent error, and this error increased with forecasting interval and decreased with area (Austin, personal communication, 1985).

Both the Ontario Conservation Authorities and Ontario Hydro have been using radar for flood and flow forecasting, but accuracy studies of radar derived precipitation data have not been carried out as yet by these organizations. (B. Fox, H. Lamb, personal communications, 1985).

The most promising use of weather radar has been over relatively flat regions. In mountainous regions the effective ranges are decreased and there is difficulty in discriminating precipitation echoes from ground echoes. Doppler radars could be effective in these regions.

Doviak and Zrnic (1984) concluded that there is currently no satisfactorily proven method for accurately estimating rainfall when high spatial and temporal resolution are required.

Measurements of Precipitation by Satellites

Rainfall statistics can be determined from GOES, NOAA and Nimbus satellite sensed data; however, the systems can only operationally determine rainfall amounts and areal extent for convective storms (Barrett, 1981; Scofield and Oliver, 1981; Woodley et al., 1981). These systems mainly are used for flash flood forecasting and their utilization for hydro-electric generation forecasting in intermediate and large basins is minimal.

Using GOES satellite data and measuring several cloud temperature thresholds from a thermal infrared image, the amount of rain can be estimated (Scofield and Oliver, 1981; Jolly, 1981). These temperature thresholds have been related to convective storm precipitation amounts with correlation coefficients higher than 0.8 (Whitney and Herman, 1981). The calculated two-day rainfall amounts of 88 mm compares fairly well with ground measurements averaging 87 mm. Spatial rainfall estimates determined by this method agree with ground based measurements to within ten percent. This method tends to underestimate rainfall amounts (Johnstone et al., 1984). This method is limited in application to convective and to tropical storms, sensing cloud top temperatures and the rate of cloud top area expansion.

The Scofield-Oliver method, when used for analysis of the Big Thompson flood rainfall, gave total storm rainfall amounts to within 96 percent of ground-based measurements.

Neil (1984) has reported on experiments carried out in British Columbia using GOES infrared images to delineate precipitation areas and Tiros Operational Vertical Sounder to give reliable values of precipitable water content. This method is based on measuring the vertical upward movement of the cloud which is related to storm precipitation. This study has been conducted with data at one hour intervals for all cloud types. A polynomial equation has been developed between precipitation, precipitable water content, a resolution factor, as well as number of pixels (picture elements) that are colder than a predetermined threshold value. The coefficient of determination is 0.73, and the standard error of estimate is 0.36 mm. The analysis indicates that hourly precipitation could be predicted to within 15 percent of ground-based measurements 68 percent of the time. This technique is promising, but experimental and developmental work is still being carried out; hence it is not an operational system.

Link (1983) summarized the current status by:

> "Cloud cover information has been used to estimate precipitation using both GOES and TIROS-N AVHRR imagery. One of the most popular methods of estimating rainfall from GOES visual and infrared imagery is the Scofield and Oliver (1979) technique. It was primarily developed for convective storms and involves a decision tree structure used by analysts to estimate point precipitation intensity. None of the visible/IR satellite techniques are applicable for all precipitation types and climatic regimes (Atlas and Thiele, 1982); there is particular concern for stratiform precipitation.
>
> In general, cloud indexing techniques used with GOES imagery can provide reliable estimates of areas having no rainfall and intense rainfall. Areas of light rainfall are not reliably determined. Procedures such as the Scofield and Oliver technique used with GOES

imagery can provide point rainfall intensity estimates for some storm types. Cloud indexing methods developed by Barrett (1970), Follansbee (1973), and Follansbee and Oliver (1975) provide weekly or monthly average rainfall estimates over large areas".

The methods based on GOES satellite data cannot be used for rainfall prediction in basins large enough for viable hydroelectric generation. Neal's (1984) method applied to British Columbia shows promise, but it is still experimental. Cloud indexing methods provide weekly and monthly averages for large basins; however, they cannot be used in accurate hydrologic forecasting.

4.1.1.9 Impervious Area

This parameter is a special case of land use and cover which was previously discussed. Impervious areas can be determined by aerial photography with a resolution of 1 to 10 metres and by sensors on Landsat satellites with a resolution of 30 or 79 m.

Thematic Mapper	- 30 m	can be determined
MSS	- 79 m	by using both.

There is usually a nine day or longer access time for satellite data, and the image quality is subject to cloud cover. The correct areal discrimination of impervious areas has an accuracy of between 85 and 90 percent; furthermore, ground truthing is highly recommended (Peck et al., 1981).

4.1.1.10 Frozen Ground

Although permafrost (see previous section 4.1.1.5(c)) and frozen ground are different in a hydrologic sense, they are detected by the same remote sensing techniques. The frozen ground variable has a great influence on basin runoff processes. For example, a heavy rainfall on frozen ground can result in virtually 100 percent of the rainfall reaching the stream system. Frozen ground can be detected by both airborne- and satellite-mounted sensor systems. In the former, it can be measured with active as well as passive microwave systems and by thermal infrared sensors with a resolution of 100 metres. Using satellites, frozen ground can be measured by microwave sensors aboard the Nimbus Satellite with a resolution of between 2 to 10 km.

As of 1981 (Peck et al., 1981) the technique was still considered experimental, and some of the problems being addressed were: 1) the technique is only good for homogeneous areas, 2) the technique is only effective with a shallow snow depth, 3) the technique is not applicable in areas with vegetation cover, and 4) it is difficult to distinguish frozen ground, rough ground and vegetation. Therefore the technique is not currently operational (Peck et al, 1981).

4.1.2 Data Transmission System

Hydrologic forecasting methods can utilize data that is transmitted from a number of observational points to a central forecasting center.

Examples of where geophysical data are used in hydrologic forecasting methods are:

1) The Lake Erie water levels at the head of the Niagara River are transmitted to the hydroelectric plants near Niagara Falls, where they are used to forecast the flows in the Niagara River.

2) Precipitation data measured at one or more remote precipitation stations are transmitted, either directly or via a central data receiving and processing location, to a forecast center. There it is used usually with other remote

sensing data as hydrological model input parameters or directly in forecasting streamflows.

There are four means by which geophysical data can be transmitted. Common to them all are sensors, data collection platforms (usually including data storage) and data receiving facilities. The four means by which the data are transmitted are:

1) telephone or telegraph links
2) direct radio link
3) transmission via satellites
4) meteor bursts (Sytsma and Leader, 1982)

The main advantage of transmitting and relaying hydrometric and meteorologic data for use in hydroelectric flow forecasting is that data from many sensor types and at various locations can be concurrently received at a forecasting centre soon after being recorded, thus enabling more accurate forecasts to be made in an efficient manner.

Currently the most commonly used system in Canada to transmit and relay meteorologic and hydrometric data is a satellite data collection system (DCS). The basic components are: 1) a data collection platform (DCP, field radio) that is connected to a sensor or a group of sensors, 2) a radio transponder (receiver/transmitter) on an earth-orbiting satellite that is capable of receiving data from a large number of DCPs, and 3) a data receiving station where data are retrieved from satellites, processed and disseminated to users. The satellites used today as part of DCS in North America are GOES and TIROS.

More detailed information on DCS can be obtained from publications by Nelson (1981), Carter and Paulson (1978), Paulson (1976), and Reid et al. (1981).

4.2 Operational Remote Sensing Techniques Pertinent to Streamflow Forecasting

From the parameters considered in subsection 4.1.1, the following parameters may be estimated by means of operational remote sensing techniques:

- Snowline
- Snow areal extent
- Snow water equivalent
- Snow surface temperature
- Snow and land albedo
- Land cover/use (including impervious areas)
- Precipitation
- Surface Slope
- Channel Dimension & Overland Flow Length
- Drainage Area
- Wave & Seiches
- Lake & River Stages
- Ice Concentration & Movement
- Radiation

Recently, there has been considerable developmental work conducted on remote sensing of radiation and soil moisture. From radiation measurements, estimates of evapotranspiration can be made. The evapotranspiration and soil moisture values are of paramount importance to most hydrologic modelling. This ongoing research will no doubt be aided by the more sophisticated, higher resolution sensors being planned for future satellites. Thus, it is anticipated that remote sensing means of operationally quantifying these parameters will become available in the next few years.

Precipitation warrants a special mention since it is the primary input to models and the most variable - spatially and temporally - over a basin. Determination of this parameter by satellite remote sensing means is confined to convective storm precipitation. Studies have indicated that accuracies may be achieved to within twenty-five percent of ground-based measurements. For Canadian basins, of the size that hydroelectricity is generated, these storms are not significant with regard to runoff volume, since most of the runoff in nonmelt periods occurs as a result of frontal storms.

The precipitation statistics from these frontal storms cannot be operationally sensed by satellites; however, research in this field is active and promising. The only means by which they can currently be obtained operationally in Canada is weather radar. As Figure 4.1 shows, only a small portion of Canada below 60 degrees North latitude is presently covered by weather radars. In order for this technique to come into general use in Canada for hydroelectric forecasting, a larger portion of Canada has to be covered by radar. The accuracy of the technique has not been determined for most Canadian basins.

4.3 Cost, Time and Ease of Application

The parameters covered in section 4.1.1 cannot be addressed with equal weight, or emphasis, and precision. In many cases little information is available; it is fragmented to such an extent that it cannot be quantified into useful statistics. Nevertheless, each operational parameter will be addressed and qualifying statements on cost, time and ease of application will be put forth.

Cost, time and ease of application are interconnected since the amount of time involved in carrying out tasks can be expressed in monetary terms, and ease of application directly influences the amount of time required to carry out functions and, in turn, costs. In some cases cost information has been obtained from the literature; in others it has been estimated based on conversations with individuals directly involved in measurements and work tasks. In still other cases it is based on A. J. Robinson & Associates Inc. collective experiences in hydrologic as well as remote sensing analyses and, finally, some are rough estimates based on 35 years of accumulated, joint study team employment in civil engineering.

(a) Snowline and Snow Cover

Castruccio (1980) estimated the cost of delineating snow area using the zoom transfer scope method to be $2,050 in 1979 U.S. dollars for a 6,800 km2 basin.

Commercial analyses of snow cover areas on the Saint-John River for the New Brunswick Flood Forecast System cost approximately $300 per NOAA image. This cost would not be representative for a new basin since system set-up is not included here.

Technicians would require training for either of the four methods discussed in section 4.1.1; however, the projection techniques are easier to learn but more time consuming for larger tasks when compared to the digital techniques.

(b) Snow Water Equivalent

The only operational technique to quantify this parameter is gamma ray surveys. Glynn, et al. (1985) considered various alternatives to providing a gamma ray snow survey with a precision of 10 mm. One option that gave a cost-effectiveness ratio between 1.32 and 2.64 involved 500 hours of flying time per year. This would be sufficient to monitor 1,165 survey lines each 20 km long. Their original cost estimate of $349,500. per year has been increased to $394,500. to reflect the economic cost of providing a technical officer. Thus the cost per survey line is $338.

A question that has not been addressed in the reviewed literature is how many flight lines there should be in a basin to give accurate snowpack water equivalent estimates. Normally a snow course survey consists of five point measurements taken 200 m apart. A twenty kilometre long gamma ray flight line represents an area of six km2. The 1984 New Brunswick experimental survey has a density of approximately 1100 km2 per flight line. It is assumed that in an operational program there would be one flight line per approximately 3000 km2.

(c) Snow Surface Temperature and Snow Albedo

Information on these parameters can be transmitted by DCS. They could be transmitted from a climatic or hydrometric station equipped with a DCP. The only cost would be their share of the costs of transmission with the other variables (most DCPs can store and transmit data from sixteen sensors). The total cost would be $2,250 for a hydrometric station and $6,200 for a climatic station.

The techniques for setup and obtaining data is well founded and easily initiated (Mr. Hare, AES, personal communication, 1985).

(d) Drainage Area

This quantity can be delineated and measured from topographic maps. The costs and ease of application vary with the basin size, ruggedness and scale as well as contour interval of the best available maps. Experiences show that duration of compilation and analysis have ranged from one hour to four days per basin. The associated range cost is $25 to $750. There is no difficulty in carrying out the tasks provided topographic mapping is available.

(e) Channel Dimension, Overland Flow Lengths and Slopes

These quantities may be obtained operationally from topographic maps. The cost of this varies with the basin size, topography, scale and contour interval of available topographic mapping and the spatial resolution and precision of the modeling. The cost of time to carry out the function is approximately $25. per hour.

Digital geographic analyses using DTMs are generally expensive and usually only economical on large watersheds. The cost to carry out the analyses runs at $75. per hour.

(f) Land Cover

Land-cover delineations and compilation can be undertaken with topographic maps. The costs vary with size of the area to be delineated and scale of mapping available. It is estimated that one 1:50,000 topographic map sheet would involve six hours of a technologist's time, to compile land use data, the economic cost of which is $150.

The time and costs involved in determining landcover statistics using Landsat data depend on many factors. Primary among them are required accuracy, study area, watershed size, type of analyses accessibility for ground truthing and the ruggedness of the topography. Two examples are: one, the land cover of the State of Connecticut was delineated at a cost of about $0.10 per sq. kilometer; and two, it was estimated that Riding Mountain Park, Manitoba, land cover and vegetation could be mapped at a cost of $3.50 per square kilometer.

The following is a case where the Landsat analysis was carried out on specific watersheds. The U.S. Army Corps of Engineers (1979) were able to determine and estimate the costs of the analysis by analyzing the land cover statistics of two basins in different geographic areas. The results are tabulated below in U.S. dollars.

Basin	Classified Area Sq. Mile	Cost	Cost per Sq. Mile	1985 Cost/ Sq. Mile
Crow Creek	18	$4,527.	$251	$406
Walnut Creek	55	4,209.	76	123
Bendix (1977)	54	8,607.	159	257
Battelle (1979) (Walnut Creek)	56	6,619.	118	190

These statistics included direct labour, computer (as well as supplies) and indirect costs. They were based on a base salary of $9.26/hr ($15.00/hr in current prices). In addition five weeks of engineer/technician labour was required for each study. The 1985 economic costs of this labour is $6,000.

Taylor et al. (1980) found that land cover for hydrologic modelling could be more economically determined by Landsat MSS data analysis for basins larger than 25 km^2.

(g) Precipitation

It is difficult to estimate the costs of precipitation analyses using satellite-obtained data. The only currently operational technique gives convective rainfall statistics from GOES data. An analysis of 50,000 km^2 mountainous area required six days of engineering time for three days of convective storm activity. The associated engineering cost of the analysis was $1,500. This analysis is not difficult, but it is difficult to maintain good quality control (Jolly, personal communication, 1985).

Estimating the cost of using weather radar data for hydroelectric forecasting is difficult with the present state of knowledge. Although Canada is presently far from completely covered by weather radar, it is assumed for costing purposes that a basin would be completely covered by two weather radar stations. It is further assumed that one technologist is employed by a forecasting centre to reduce and analyze the radar data. The cost (capital and operational) can be estimated; however, the fraction of the total to be borne by precipitation forecasting on a particular basin cannot be precisely estimated at this state in weather radar network development. Thus the currently levied charge by AES of $500/month per weather radar station for data will be used. It also is assumed that each weather radar station is 100 miles from the forecasting centre and the data is received on a 1200 Baud line.

The annual costs are estimated below.

Hardware $15,000 - annual recovery cost	=	$ 2,500
Line charges $15/mile/month x 100 miles x 12 months	=	18,000
AES data charges $500/month x 12 months	=	6,000
Subtotal	=	$26,500
For Two Stations	=	53,000
Technologist time $25,000/ year salary x 2 (for overhead, etc.)	=	50,000
Total	=	$103,000

The above costs represent only costs to a user who utilized AES weather radar. If an organization obtained its own weather radar then an estimated cost, based on values obtained from the U.S.

Department of Commerce (Kachic, 1984), is given below in 1985 Canadian Dollars:

Purchase of 10-cm radar and associated hardware	=	$565,000.
Assuming a 10-year life; with 10% interest rate annual charge	=	$ 92,000.
Annual operation and maintenance cost	=	$192,000.
		$284,000./year

(h) Cost of Collection and Transmission of Hydrometric and Meteorologic Data in Canada

Specific costs cannot be given, since individual parameters and costs are lumped together within a data set. However, an attempt is made in the following paragraphs to estimate the various available costs.

Hydrometric Data

In 1983-84 (P. Campbell, personal communication, 1985), the total cost to the Water Survey of Canada to operate 2,596 hydrometric stations (excluding those operated by the Province of Quebec) was $22,698,000 or about $8,700 per station. This figure represents both capital and operational costs. Since there are very few new stations being installed, it is assumed that these approximately represent operating costs. Also, these costs are financial costs to the Water Survey of Canada and allied provincial agencies. As such, they do not take into account administration support costs. Thus, the $8,700 has been increased to $10,000 arbitrarily to represent the economic cost of operating a hydrometric station for a year. Since the majority of stations are not currently equipped with DCPs, these estimates do not include DCS related expenditures.

A hydrometric station costs about $40,000 to build. The economic costs of maintaining operations, conversion to flow statistics, and associated technical functions is approximately $10,000 per year. Assuming a forty year economic life of the structure and equipment, the annual capital cost of a conventional hydrometric station is $4,100 (with a 10 percent capital recovery rate). The total annual cost of a conventional hydrometric station is $14,100. A hydrometric station equipped with a DCP has an additional cost of $9,000 which represents both capital and installation costs. Operation and maintenance for the DCP amounts to $700/year. The technical life of a DCP has been assumed to be ten years. Thus the additional annual capital cost is $1,500. Thus the total cost of a hydrometric station with a DCP is $16,300.

Meteorologic Data

The following costs are estimates only and are based on information provided by Mr. Miller of AES.

Climatic Station

DCP Capital and Installation	$15,000.
annual charge (10 years payback)	$ 2,500.
Operation and Maintenance	$ 5,000.
Total annual cost	$ 7,500.

Climatic stations record precipitation and air temperatures.

Automatic Synoptic Station

With DCP full capacity	= $70,000.
Annual Capital Cost (Design Life 10 Years)	= $11,400.
Annual Operational and Maintenance Cost	= $ 5,000.
Total	= $16,400.

With DCP

Limited capacity (without relative humidity)

Capital and Installation	=	$35,000.
Annual Capital Cost (Technical Life 10 Years)	=	$ 5,700.
Annual Operational and Maintenance Cost	=	$ 5,000.
Total	=	$10,700/year

Synoptic Station: Parameters measured include cloud cover, vapour pressure, air temperature, dew point, precipitation, snow cover, and wind speed and direction. Measurements are taken four times a day.

4.3.1 Summary

The preceding review outlined the pertinent geophysical and meteorological characteristics of the hydrologic cycle that can be remotely sensed. The discussion concentrated on the applicable characteristics to the scope of the study which focused on utilization with hydrological forecasting techniques specifically pertaining to watersheds in which hydroelectricity is generated.

Parameters which can be remotely sensed on an operational basis were identified and evaluated in terms of cost, time and ease of application. This review process effectively qualifies the application of operational remote sensing techniques with hydrologic forecasting both for resolution of data and introduction of specific processes which are not easily monitored by more conventional means.

The applicability of remotely sensed data to hydrological forecast models has to be evaluated. The subsequent chapters review available hydrological forecast models concentrating the review process on model flexibility and adaptability to remotely sensed input.

5.0 HYDROLOGICAL FORECASTING METHODS

This section of the report elaborates on hydrological forecasting methods which are applicable to Canadian conditions and have been designed for or are adaptable to modern remotely-sensed inputs. The logical progression in the chapter begins with a definition and classification of the various hydrological forecasting methods and ends with a recommended set of models. Intermediate sections on selection criteria, selection process, selected model descriptions and ranking are also included.

5.1 Classification of Hydrological Forecasting Methods

The term "Hydrological forecasting methods" is synonymous to the term "hydrological forecasting models" where the latter takes on a general definition to include any process by which hydrological simulation can be completed. The word "forecasting" merely qualifies the hydrological model in that it should be capable of simulating future events given certain assumptions such as precipitation predictions.

The classification of hydrological models is well described in a monograph published by the American Society of Agricultural Engineers in 1982 and is schematically depicted by Figure 5.1. Although the classification could be applicable to many fields, it is also representative of hydrological models. This section forms an edited synthesis of this classification.

There are two distinct groups of models: **material** and **mathematical.** The advent of computerization has favoured mathematical model development. Costs and complexity associated with the solution requirements of drainage system problems effectively renders material models impractical.

Material models are physical representations of the prototype and include both **iconic** models which are simplified versions of the

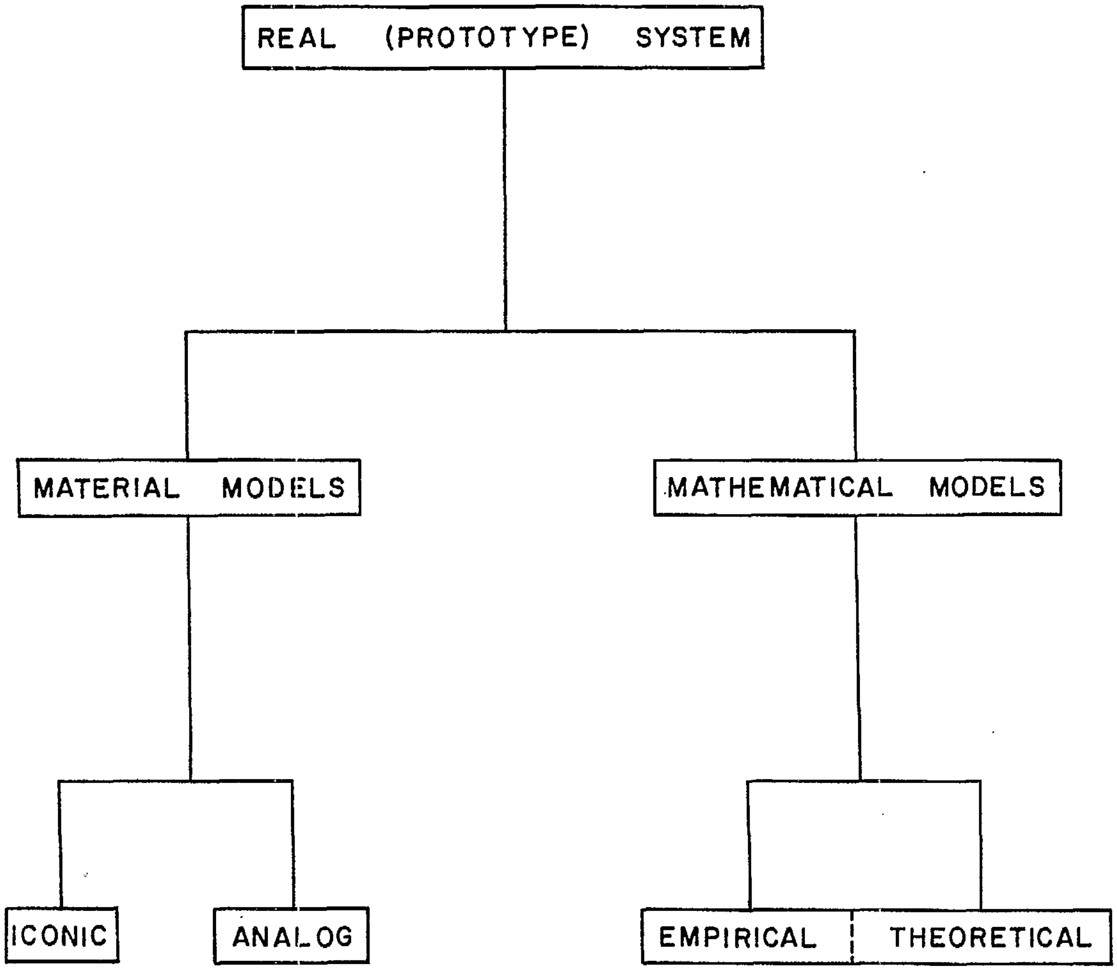

Figure 5.1: Model Classification [ASAE, 1982]

real world using actual materials, and **analog** models that substitute the actual physical materials with other media. Examples of iconic physical models include lysimeters and the earlier versions of the Tank model (Sugawara et al., 1984). An example of analog physical models is the substitution of electrical current for flow of water.

This chapter focuses on mathematical models which can also be sub-classified into two groups: **empirical** and **theoretical.** Theoretical models are based upon a series of generalized laws or theoretical principles and sometimes contain a set of empirical statements. Empirical models are not based on general laws and theoretical principles but are rather a representation of the database.

In reality, most currently available hydrologic models combine simplified theory and empiricism, and therefore form hybrid models which include both characteristics. Examples of hybrid models are abundant in all components of the hydrological cycle: surface flow is depicted by equations describing conservation of mass and momentum which usually contain empirical hydraulic resistance terms; and infiltration modelling is greatly simplified in the Horton, Holtan and Green-Ampt relations.

The following sections cover the hydrological model selection process that was adopted in this study. As previously mentioned only mathematical models are considered.

5.2 Selection of Models for Review

A literature search of available hydrological forecasting models revealed over one hundred models; however, our reviewing task was limited to only those meeting certain selection criteria. This section outlines the model selection criteria adopted. It also justifies the selection process by which candidate models were eliminated from further consideration.

5.2.1 Selection Criteria

The scope of work in reviewing the hydrologic models is governed by the Study Terms of Reference which stipulate the hydrological forecasting models are to have the following characteristics:

1) applicable to Canadian conditions;
2) have been designed for, or are adaptable to remotely-sensed input;
3) must have application to long-or short-term streamflow forecasting;
4) in addition, only deterministic and stochastic mathematical models are considered.

These general selection criteria need to be further qualified since they establish the basis upon which models were selected for review. Clarifying their definition within the context of this study is paramount to understanding the perspective that was adhered to during the selection process.

The first selection criterion states that models must be applicable to Canadian conditions. Political and economic conditions can safely be eliminated, therefore the study will focus on physiographic and climatic conditions of Canada. Climatic and physiographic conditions in Canada are diverse; however, several particularities with direct implications in this study are noteworthy. These are covered in the following paragraphs.

Watersheds can be large, such as the Lake Superior Basin which is approximately 130,000 km^2. This physiographic characteristic is common to most basins where hydroelectricity is, or can be generated. Timing of various hydrologic phenomena is important for large basins, therefore overland, channel and reservoir routing must be taken into account. **Models that did not account**

for routing of flows, either implied or directly, were rejected as review candidates.

Canadian watersheds occur in a wide range of physiographic types ranging from alpine to plains. Land uses are predominantly forest and agricultural, while urban land cover areas account for a very small fraction of the total when considering the country as a whole. This is also true for most basins utilized for hydro-electricity. **Mathematical hydrologic models with only urban type runoff components were not selected.**

The climate is also diverse across Canada. Climatic conditions including mountainous, desertic, oceanic and continental weather patterns are all experienced in one part or another of this country. The selected models should include the common northern hydrologic processes of snow accumulation and melt. Evapotranspiration should also be required as part of a long-term forecasting model; however, short-term simulation may not require this hydrologic component. **Models without snowmelt accounting algorithms were not selected for further review.**

The second selection criterion states that the selected models must have been designed for or are adaptable to modern remotely-sensed data. One of the main advantages that most remotely-sensed data offers is that it is areally distributed. Radar rainfall data, for example, can be given at a resolution of better than 1.0 km^2 within its operating range. Most of todays hydrological forecasting models were developed when only point source data (i.e. rain gauges) were available and are not specifically designed to accept spatially distributed data. With few exceptions, they cannot use the full resolution offered by the current operational systems such as satellite data. However, all models could be adapted to use modern remotely sensed data by merely averaging and lumping the spatial data into point data (Johnson et al., 1982).

An averaging procedure defeats most benefits that the remote sensing techniques offer, except that it can provide a better point data average for large areas. In order to retain the highest input resolution, the selection of hydrological models should favour distributed models over lumped models. **However, since all models could be interfaced with remotely sensed data the model selection process did not discriminate between distributed and lumped characteristics.**

The third selection criterion states that selected models should have application to short- or long-term streamflow forecasting. This criterion implies a minimum time domain for predictions and varies from one day to several seasons as discussed in Chapter 3. **This criterion did not significantly influence the selection process since it is "all inclusive". Several peak flow design methods such as the Rational Method and Caquot's (1941) Formula were nevertheless screened from further review under this criterion.**

The fourth selection criterion stipulates that only mathematical models, both deterministic and stochastic, were to be selected for review. **As previously stated, material or physical models were not to be evaluated.**

An additional, a fifth, selection criterion was added to the previous four. This criterion requires that the selected model:

5) must have been documented in the literature and reside in the public domain.

This supplemental criterion is self-explanatory in that there is no benefit in selecting poorly documented or proprietary models. **Models which have very poor or nonexisting documentation or are proprietary were not selected.**

5.2.2 Selection

A general list of candidate models was compiled from various sources, as discussed in Chapter 3, and included the A.J. Robinson & Associates Inc. library, textbooks, papers and the study team's knowledge of the subject. Water quality models, such as QUAL-II from the U.S. Environmental Protection Agency, and strictly urban hydrology models, such as OTTSWMM from the University of Ottawa, were not included when establishing the general list. These irrelevant types of models were eliminated from further assessment.

Table 5-1 lists the hydrologic models that were considered within this study and includes 60 models (both deterministic and stochastic). The list includes Canadian, U.S. and European models.

The five model selection criteria previously covered were applied to each candidate model listed in Table 5-1 based on the available knowledge. The table also shows, for each candidate model, reference(s) to any specific criterion or criteria that were **not** met. The models which have no reference meet all five selection criteria and were, therefore, evaluated in greater detail. Twenty-eight models were selected on this basis.

5.3 Ranking and Review of Selected Models

A systematic ranking and review approach was adhered to in this section in an effort to arrive at recommended models for further study. It was not the intention of this study to review single process models such as describing the Horton infiltration technique; however, Hortonian type infiltration techniques will be compared with physically-based Richards equations in selecting preferred computational methods. The ranking technique consisted of a two-step technique in which model characteristics were scored and weighted according to tabulated characteristics.

TABLE 5-1: GENERAL LIST OF HYDROLOGIC MODELS CONSIDERED FOR THIS STUDY

MODEL NAME	DEVELOPED BY	ELIMINATION CRITERIA
HEC-1	Hydrologic Engineering Centre	
HYMO	U.S. Department of Agriculture	1
HSP-F	U.S. EPA, Hydrocomp	
ILLUDAS	Illinois State Water Survey	1,2
MITCAT	Resource Analysis, Massachusetts	5
MMDW	Agricultural Eng., U. of Minnesota	5
RROUT	CH2M HILL Inc.	5
SSARR-4	U.S. Army Corps of Engineers	
STORM	U.S. Army Corps of Engineers	1,2,3
USDAHL-74	USDA Hydrographic Laboratory	
NWSRFS	U.S. National Weather Service	
SASK-6	UBC, Canada Government Agencies	
SLURP	Environment Canada, Water Resources Branch	
MANTHORN	Manitoba Water Resources Branch	
QUFM	Queens University, Ontario	
UBC	University of British Columbia	
PARAMETRIC	Shawnigan Engineering	5
SNORO3	University of New Hampshire	2,3
SCS-BSM	U.S. Soils Conservation Service	
USGS	U.S. Geological Survey	
SIMFLO	Queen's University	
GAWSER	University of Guelph	1,2
MOE-HYDR2	Ministry of the Environment, Ontario	
HBV	Swedish Meteorological and Hydrological Institute	
SHE	Institue d'hydrologie, France	
QFORECAST	MacLaren Plansearch Inc.	
SWMM-III	U.S. E.P.A., University of Florida	
HYMO-VUH	Ministry of Natural Resources, Ontario	
LANDRUN	Marquette University, Wisconsin	2
SWPM	Montana State University	5
NPS	Hydrocomp, Inc.	3,2
ARM	Hydrocomp, Inc.	3,2
HYDSM	Utah State University	2
TEHM	Oak Ridge National Laboratory	1,2
WHTM	Oak Ridge National Laboratory	2

TABLE 5-1: GENERAL LIST OF HYDROLOGIC MODELS CONSIDERED FOR THIS STUDY

MODEL NAME	DEVELOPED BY	ELIMINATION CRITERIA
STANFORD-Fortran	**Utah State University**	
MELTMOD	U.S. Department of Agriculture	1,2,3
LUMOD	U.S. Department of Agriculture	1,2,3
WBMODEL	U.S. Department of Agriculture	2,3
TR-20	U.S. Soils Conservation Service	1
CONIFER	University of Washington	2
HYDPAR	U.S. Army Corps of Engineers	1,2,3
QUALHYMO	IMPSWM, University of Ottawa Ministry of the Environment, Ontario	1
OTTHYMO	IMPSWMM, University of Ottawa,	1
CEQUEAU	**University of Quebec**	
CWB	Climatic Water Balance	5
FLOCAST	**B.C. Hydro**	
Hydro-Quebec	Hydro-Quebec	5
HMV-DORSH	Dorsh Consortium, Germany	5
CREAMS	U.S. Department of Agriculture	1,2,3
LSBR	**U.S. Army Corps of Engineers**	
Martinec	**Federal Institute for Snow & Avalanche Research, Switzerland**	
RFM	Environment Canada, Quebec Hydro, Ontario Hydro	5
GHM	U.S. National Weather Service and State of California	5
TANK	**National Research Center for Disaster Prevention, Japan**	
MANAPI	**Manitoba Water Resources Branch**	
VOLCAST	**B.C. Hydro**	
PREVIN	**Alcan**	
Ontario-Hydro	Ontario Hydro	5
ANSWERS	Purdue University	1,2

Note: **Bolded** models meet all five selection criteria.

Each major hydrological component was discussed and ranked. Selection of preferred techniques for any given modelled component is unavoidably subjective at times; however, efforts to consider computational requirements, data availability and data requirements, ease of use and adaptability to remotely sensed inputs were made.

The goal of this ranking process is to achieve an objective, sorted grouping and ranking of models according to the advantages offered by their individual operators. The five criteria described in Section 5.2.1 are applied when discussing merits of various techniques. Ease of application and cost estimates will also be described; however, detailed discussions on model accuracy, known Canadian applications, remote sensing interfacing and general recommendations will be given in Chapter 6. Model characteristics were considered separately in an effort to extract the advantages and disadvantages of various technical structures. The ranking criteria will therefore be discussed according to a more detailed mathematical model classification.

5.3.1 Ranking Criteria

Mathematical hydrologic models can be classified according to five criteria (Ozga-Zielinska, 1976):

a. model structure or modelling subject;
b. role of the time factor;
c. cognitive value of the model;
d. character of model; and
e. properties of operator functions.

The current hydrological modelling techniques encompass a wide range of complexity levels, from single empirical equations to computationally demanding solutions to the St-Venant equations. Using the above model classification, the currently-used modelling techniques were assessed and reviewed in terms of advantages, disadvantages and adaptability to remotely sensed data.

a) Model Structure or Modelling Subject

The first criterion relates to the hydrological completeness of the model. There are **single process models**, such as the capillary rise model; **component models**, such as the Green-Ampt infiltration model; **watershed models**, such as HSP-F which have linked component models; and **global models**, such as regressional models which simulate several hydrological processes intrinsically.

Single process models have an advantage over the three other types. Since only a specific hydrological process is simulated the complexity should be low. Individual model parameters and component variables are kept to a minimum; therefore, comprehension of underlying transformations should be easy. Single process models have drawbacks in that the problems associated with interfacing to other single hydrological processes can be difficult. Furthermore, single process simulations are more often exceptions rather than the rule in hydrologic applications; therefore, this type of model is usually limited to research uses and not operational uses.

Component models offer the advantages of the single process models, in that the individual processes can be monitored and adjusted while also providing an easier link between the different hydrological components.

Comprehensive watershed models do not usually provide the modeller with the capability of monitoring individual components due to the complex internal linkage of the different hydrological components. They, nevertheless, offer a convenient, complete hydrological package.

Global models reduce all hydrological components into common operators whereby it is assumed that there is a functional relation between a set of input and output variables. Remotely sensed soil moisture data, for example, would be useless in a regressional model relating climatic factors to mean monthly flow.

Based upon the information covered above, watershed models followed by component models are favoured over single process or global models, and will be scored higher. The scoring is based largely on practicality and overall completeness of the hydrology cycle components within each model. This study focuses on watershed applications not laboratory experiments.

b) Role of Time Factor

The role-of-the-time-factor criterion classifies models as **static** or **dynamic.** In the former, time is not an independent variable. An example of a static model is a regressional model relating mean monthly flows to climatic factors.

The capability of dynamically simulating hydrological processes is crucial if interactions among components must be observed. An argument could be made that the hydrological cycle itself is a dynamic phenomena; therefore, only dynamic models could ever approach similitude with the prototype. Static models are remnants of the past when only point source data was available (Link, 1983).

Models were ranked in such a manner as to favour dynamic rather than static models. Dynamic models are computationally more demanding than their static counterparts; however, with the advent of more powerful and cheaper modern-day computers, this negative point has become a non-issue.

c) Cognitive Value

The third classification criterion includes three categories: a) **physically-based models** are models which can be expressed by rigorous equations of mathematical physics, b) **conceptual models**, which are used to simplify the mathematical description of the hydrology, and c) **trend models**, which have no rigorous foundations and are usually empirically-derived relations of hydrological phenomena.

The history of mathematical hydrologic modelling strongly parallels that of the computer (Link, 1983; O'Loughlin, 1980). With the successively decreasing costs of today's computer and increasing computational power and memory, the hydrologist is provided with incentives to develop more comprehensive models and larger automated data acquisition networks. Current watershed models include computationally demanding finite element algorithms and numerical methods to solve the complex underlying relations governing each component of the hydrologic cycle.

The following paragraphs will discuss, by major hydrological component, the current techniques used in the three model types: physically-based, conceptual and trend.

Snowmelt

Physically-based models attempt to characterize in great detail the energy balance at the snow-air and snow-ground interfaces as well as the change in heat storage within the snowpack.

The generalized energy budget can be expressed as:

$$H = H_c + H_e + H_g + H_p + H_{rl} + H_{rs} + H_{gs}$$

where H = net heat transfer to snowpack,

H_c = convective heat transfer from the air,

H_e = latent heat transfer from condensation, evaporation and sublimation,

H_g = conduction heat across soil-snow interface,

H_p = heat transfer from rain drops,

H_{rl} = net longwave radiation exchange,

H_{rs} = net shortwave radiation exchange, and

H_{gs} = heat transfer to soil by solar radiation.

The rigorous quantification of all terms in the above physical model requires site specific and numerous data which translates to high computing costs and extensive field measurement programs. The implications are that the complex data requirements presently make the physically-based model impractical for operational uses (Anderson, 1976). This statement explains why few snowmelt models solve the complete energy balance equations but rather adopt simplifications to the generalized equation.

Conceptual and trend snowmelt models are more abundant and utilize approximate formulae to model the various components of the general energy balance equation. The data requirements are still extensive; however, difficult-to-measure coefficients have been replaced by empirically-derived relations. The U.S. Corps of Engineers Snow Hydrology (USACE, 1956) study is often used as an algorithmic source. The HSP-F model, for example, uses these techniques.

Data required for some of the simplified energy balance equation are:

- Incoming Solar Radiation
- Reflected Solar Radiation
- Evaporation
- Wind Speed
- Dew Point Temperature
- Air Temperature
- Precipitation

The simplest snowmelt models relate meteorological variables such as temperature to snowmelt. In some cases, enhancement of the basic temperature index methods account for wet or dry-day melts and snow cover variations. Land use can also be incorporated. Examples of current models using these techniques are USDAHL-74, QFORECAST, UBC, SIMFLO and the NWSRFS model.

Simplified energy balance snowmelt models have been shown to perform well (MacLaren Plansearch, 1984) and are the only realistic candidates unless one is prepared to invest in extensive data acquisition programs. The efforts of adopting a detailed physically-based snowmelt model on a watershed typically used for hydroelectricity would be enormous. Therefore, conceptual models are the preferred models, followed by trend models and will be scored in that order.

Infiltration

The governing laws of the infiltration process can be expressed by the Richards' equations (1931). Physically-based models using these equations require computationally demanding numerical methods to solve the non-linear equations. The problems associated with resolving the Richards' equations has undoubtedly contributed to its limited use in current hydrological modelling. None of the models listed in Table 5-1 use this rigorous approach.

Trend models are widely used and include Kostiakov's equation (1932), Horton's equation (1940), Philip's equation (1957), and Holtan's equation (1961). The conceptual Green-Ampt model (1911) has recently gained popularity and, unlike the previous trend models, it was derived by the simplified application of the theory of soil water movement.

Remotely-sensed data, such as soil moisture, could be adopted and used in most of the current infiltration techniques if soil moisture storage and ponding storage are accounted for within their algorithms. Although the move toward physically-based models is desirable, most conceptual and trend infiltration models are preferred since they have quantifiable parameters and are still compatible with remotely sensed data. Thus the scoring process will be weighted towards conceptual and trend models as opposed to rigorous techniques.

Evapotranspiration

The evapotranspiration processes are dependent on vegetation and land cover as well as the area's physiographic characteristics. Spatial variation of the evapotranspiration process is dependent on the nonhomogeneity of the vegetal cover and soil characteristics as well as other physiographic factors. Due to the variability of soil and vegetation types as well as cover, the evapotranspiration phenomena escape rigorous mathematics. Most methods used in estimating evapotranspiration follow a vertical water budget concept. The procedure considers the potential evapotranspiration, based on meteorological factors, then computes the amount of that potential that is utilized by the actual evapotranspiration processes.

Conceptual evapotranspiration models utilize a simplified vertical energy budget. Typical equations have been put forward by Penman (1956), Jensen-Haise (1963), Christiansen (1968) and Turc (1961). In these cases, only selected climatic parameters such as temperature and incoming radiation are used. Trend models are still popular in certain applications. The pan-evaporation equation and temperature index method fall into the trend model category. Recent comparative studies among various methods (Jensen, 1973; Parmele and McGuiness, 1974) indicate that simplified physically-based methods such as Jensen-Haise and Penman consistently perform better than trend models. The radiation data was found to be the governing parameter.

The impact of plants on evapotranspiration can be divided into the following categories: canopy, phenology, root distribution and water stress. The quantification of each of these causitive factors is empirically derived from actual field observations. There is abundant information for agricultural applications (Blaney-Criddle, 1966); however, deciduous and coniferous forest information is scarce.

The majority of applied models, such as the Stanford Watershed Model, use a simplified index method and do not separately account for evaporation and transpiration. Site calibration is highly recommended in order to obtain representative values.

Remote sensing determination of radiation, soil moisture, plant type and canopy in a distributed manner throughout the year could undoubtedly be used with most evapotranspiration models. Computational requirements for most commonly used models such as Penman's equation are not considered taxing for current computers. Most problems arising from using these component models are calibration related. The conceptual models that incorporate a radiation term should be preferred over trend models.

Routing

The routing of flows can be separated into three conveyance areas in hydrology - overland, channel and reservoir routing. All three areas of flow routing can be described by the Bare de St-Venant equations of conservation of mass and momentum. Solutions to the full St-Venant equations can be obtained by the method of characteristics using numerical techniques.

Simplification of the full equations is often used for overland routing by eliminating the dynamic term in the momentum equation. This is justified by the assumption that backwater effects are negligible. The result is a set of equations generally referred to as the kinematic equations. This simplification to the St-Venant equations does not significantly decrease the computational effort. The kinematic routing technique is used in SWMM-III and CEQUEAU and is gaining preference over conceptual models such as unit hydrograph and lag coefficient methods.

Channel and reservoir routing can also be calculated by solving the complete St-Venant equations. This is generally termed "hydraulic routing" and is used within the SWMM-III (EXTRAN) model. The majority of models use simplified conceptual methods for routing through channels and reservoirs. These methods are termed "hydrologic routing". Techniques such as the Variable Storage Coefficients (VSC) in the HYMO-VUH model, Muskingum in HEC-1 model and the Modified-Puls method for reservoir routing, simplify routing by generally assuming a series of linear processes.

Remotely sensed data could be helpful in characterizing the surface roughness by correlation to land cover inventories; however, streampath length, slopes and detailed stream geometry are more accurately obtained from maps and field surveys (Fleming, personal communication, 1985). Errors in routing are usually small for both hydraulic and hydrologic techniques when compared with those associated with the entire watershed simulation processes; however, simplified physically-based methods such as the kinematic wave equations are preferred over conceptual models and will accordingly be ranked higher.

d) Character of Model

Under the fourth classification criterion, character of model, models can be described as **stochastic** or **deterministic.** These terms were used to define the scope of models which are to be assessed within the study. Under this criterion, mathematical models that contain random variables which have probability distributions in time are known to be stochastic. If the model parameters are free from random variation the model is said to be deterministic.

Stochastic models are often equated to regressional models which have been used in hydroelectric operations for a number of years. They either estimate water levels or flow in a river or reservoir by taking into account hydrometric or meteorological data, or both, sensed in a watershed, and in some cases, in neighbouring watersheds.

Meteorological data sets are correlated to hydrographical data sets in order to develop regressional equations that can be used to forecast either water flow or depth. The method can be used to estimate short-term flow rates and flow volumes over both short and long intervals, i.e. one day up to several seasons. Many major disadvantages arise with this type of model:

1) They are strongly dependent on many years of complete, continuous and stationary data being available;
2) they cannot estimate any other hydrological component other than the ones for which the predictive equations were established;
3) they produce information that is valid for only the specific geographic site at which the regressed data was obtained, and
4) re-calibration is required should physiographic and operational characteristics change (i.e. change in reservoir operation).

One type of regressional model used for hydroelectric flow forecasting in Canada is PREVIN. This model is applied to flows on the tributaries of the Saguenay - Lac St. Jean Basin in Quebec by Alcan Smelters and Chemicals Ltd. This technique is used to estimate the runoff volume over various durations during the spring freshet period (Alcan, 1982).

The general form of a regressional equation is:

$$y = a_0 + a_1 X_1 + a_2 X_2 + a_3 X_3$$

where y = the dependent variable representing uncontrolled flow rate or volume, on a particular day or over a specified duration, and X_1, X_2, X_3 are specific independent variables such as antecedent snow cover, precipitation and flow magnitude at a particular upstream cross-section. The coefficients a_0, a_1 and a_2 and a_3 are regression coefficients determined from historical data.

Specific meteorological factors such as glacier melt and evaporation indices are included in the general equation for long-term forecasting purposes and where geographically appropriate.

Ontario Hydro also uses regressional equations on many of its watersheds where hydroelectricity is generated. Usually the independent variables are accumulated winter precipitation, snowpack water equivalent, and snow evaporation as a function of snowmelt runoff flow volumes. These are the independent variables used in forecasting on the Madawaska River. Other river flood forecast centres use identical or similar independent variables. In Table 5-2, Dyhr-Nielsen (1982) has listed the independent variables generally used in regressional forecasting equations and has given their relative significance to explain the variance of spring runoff volume. The term "significance" refers to the percentage of the variability accounted for by a multiple regressional equation (either linear or non-linear) that is attributable to a particular independent variable. Snowpack water equivalent and winter precipitation are the most significant variables.

Although written information on specific regressional techniques is difficult to obtain, many regressional techniques are used in Canada for hydroelectric flow forecastings.

TABLE 5-2: EXPLAINED VARIANCES BY INDEPENDENT VARIABLES IN REGRESSION MODELS

Variable	Relation to Runoff Volume	Relation to Peak Flow	Significance %
Snowpack water equivalent	Positive	Positive	60 - 90
Antecedent streamflow	Positive	Positive	5 - 15
Base Flow	Positive	Positive	5 - 15
Soil Moisture	Positive	Positive	5 - 10
Precipitation			
Autumn	Positive	Positive	5 - 20
Winter	Positive	Positive	30 - 60
Spring	Positive	Positive	10 - 25
Temperature	Negative	Positive	10 - 25
Wind	Negative	Negative	5 - 20
Radiation	Negative	Negative	5 - 15
Relative Humidity	Positive	Positive	5 - 10

Deterministic models which include both physically-based and conceptual models offer the possibility of closely monitoring the hydrological processes as they evolve in time. Since timing of most operational processes (such as opening and closing reservoir gates) is important, deterministic models offer a distinct advantage over regressional models.

Operational and physiographic changes within the basin can usually be incorporated, at low costs, into deterministic models.

Deterministic models generally offer more flexibility to change than their stochastic counterparts. Furthermore, remotely-sensed areally distributed data must be averaged into single values to be incorporated within a regressional model, while some deterministic models offer full resolution potential.

Deterministic models currently offer more advantages over regressional models and will, therefore, be scored higher.

e) Mathematical Property of Operator

The final classification criterion describes the mathematical properties of the operator. The models are classified as **linear** or **nonlinear**, **lumped** or **distributed**, and **stationary** or **nonstationary**.

A model can be qualified as linear if the principle of superposition is valid. Lumped models do not account for spatial variations of input, outputs and parameters while distributed models include spatial variability. Deterministic models are considered stationary if their form and parameters are invariant in time. Stochastic models are said to be stationary if their properties do not change in absolute time.

The properties of the operator have a significant importance to this study. If full spatial resolution of the remotely-sensed data is to be preserved then distributed models should be used. Otherwise, averaging to point source input would be required for lumped models. Distributed models were, therefore, ranked higher and are preferred over lumped models.

Linearity is a property of all reviewed models; therefore, this criterion was not used.

Deterministic models have the possibility of having their parameters updated with time (ie. state variables) and are generally known to be nonstationary. This characteristic is also possible for regressional models; however, it can only be accomplished by re-calibrating the predictive relation. Regressional models are usually developed to predict short time periods where the parameters can be assumed stationary. This requires several models to account for a long period. The numerous Canadian climates have strong seasonal variations which support nonstationary processes.

Nonstationary, distributed models, will therefore score higher than stationary or lumped models.

The description of each classification criterion presented in this section preceeds any discussions on model recommendations and was intended to establish a base for understanding, qualifying and ranking each model in following sections.

5.3.2 Description of Selected Models

The general overall list of models was reduced to twenty-eight with the criteria established in section 5.2.1. Table 5-3 outlines a description of the models selected for the review process. This table is divided into general descriptors of model type as well as addressing the hydrologic components which comprise the models. The table also provides a subjective evaluation of cost and ease of model application.

The general descriptors of model type have been detailed in the previous section (5.3.1). The hydrologic processes are sub-divided into pertinent functions which help to distinguish the character of the model as well as the level of sophistication used in the model development.

A subjective approach was used to qualify the ease of application of each of the selected models. The ease of application is dependent on the technical capability of the personnel assigned

TABLE 5-3 **MODEL CHARACTERISTICS**

MODEL NAME	REF.	MODEL TYPE: MODEL STRUCT.	TIME INDEPENDANCE	COGNITIVE VALUE	CHARACTER OF MODEL	OPERATOR PROPERTIES: DISTRIBUTED	STATIONARY
Canadian:							
SIMFLO	13	Watershed	Dynamic	Conceptual	Deterministic	Lumped	Non-stationary
MOEHYDR2	72	Watershed	Dynamic	Physical	Deterministic	Lumped	Non-stationary
CEQUEAU	27	Watershed	Dynamic	Conceptual	Deterministic	Distributed	Non-stationary
QFORECAST	74	Component	Dynamic	Conceptual	Deterministic	Lumped	Non-stationary
QUFM	21	Global	Dynamic	Trend	Deterministic	Lumped	Stationary
MANTHORN	21	Global	Dynamic	Trend	Deterministic	Lumped	Stationary
SASK6	21	Watershed	Dynamic	Conceptual	Deterministic	Lumped	Non-stationary
SLURP	92	Watershed	Dynamic	Conceptual	Deterministic	Lumped	Non-stationary
UBC	96	Watershed	Dynamic	Physical Conceptual	Deterministic	Lumped	Non-stationary
FLOCAST		Watershed	Dynamic	Conceptual	Deterministic	Lumped	Non-stationary
United States:							
SWMM III	56	Watershed	Dynamic	Conceptual	Deterministic	Lumped	Non-stationary
HEC-1	122	Watershed	Dynamic	Conceptual	Deterministic	Lumped	Non-stationary
HSPF	60	Watershed	Dynamic	Physical	Deterministic	Lumped	Non-stationary
Stanford IV	30	Watershed	Dynamic	Physical	Deterministic	Lumped	Non-stationary
SSARR-4	20	Watershed	Dynamic	Conceptual Trend	Deterministic	Lumped	Non-stationary
LSBR	48	Watershed	Dynamic	Conceptual Trend	Deterministic	Lumped	Non-stationary
SCS-BSM	130	Watershed	Dynamic	Conceptual Trend	Deterministic	Lumped	Non-stationary
NWSRFS	5	Watershed	Dynamic	Conceptual Trend	Deterministic	Lumped	Non-stationary
USDAHL-74	54	Watershed	Dynamic	Conceptual Trend	Deterministic	Lumped	Non-stationary
HYMO-VUH	73	Watershed	Dynamic	Physical Conceptual	Deterministic	Lumped	Non-stationary
USGS	100	Watershed	Dynamic	Conceptual	Deterministic	Lumped	Non-stationary
Other:							
MARTINEC	75	Component	Dynamic	Conceptual	Deterministic	Distributed	Non-stationary
HBV	12	Watershed	Dynamic	Conceptual	Deterministic	Distributed	Non-stationary
SHE	77	Watershed	Dynamic	Physical Conceptual	Deterministic	Distributed	Non-stationary
TANK	116	Watershed	Dynamic	Conceptual	Deterministic	Lumped	Non-stationary
Regression:							
PREVIN	1	Global	Static	Trend	Stochastic	Lumped	Stationary
VOLCAST		Global	Static	Trend	Stochastic	Lumped	Stationary
MANAPI	21	Global	Static	Trend	Stochastic	Lumped	Stationary

TABLE 5-3 MODEL CHARACTERISTICS (Cont'd)

MODEL NAME	REF.	COMPUTATIONAL TIME STEP	HYDROLOGIC PROCESSES: SNOWMELT	INFILTRATION /RUNOFF	EVAPORATION EVAPOTRANSPIRATION	ROUTING PROCEDURES: OVERLAND	CHANNEL	RESERVOIR	CALIBRATION/ OPTIMIZATION	COMPILER TYPE	EASE OF APPLICATION	MODEL COSTS	MINIMUM MODEL INPUTS	CANADIAN APPLICATION
Canadian:														
SIMFLO	13	Hourly or Daily	Temp. Index Modified	philip's eqn.	equilibrium evap. model	lag	parallel reservoirs				moderate	moderate	P,T	yes
MOEHYDR2	72	Hourly or Daily	Energy Balance 4 Options	regression type	met. data thornthwaite type				manual		moderate	moderate	P,T,S	yes
CEQUEAU	27	Variable	Energy Balance	transfer functions	penman or thornthwaite	modified kinematic	transfer functions	transfer function	automatic		complex	high	P,T,S	yes
QFORECAST	74	Hourly or Daily	Temp. Index	SCS method CN						FORTRAN	moderate	moderate	P,T	yes
QUFM	21	Daily	Temp. Index	graphical or regression	pan data	transfer function	transfer function	transfer function		hand calc.	easy	low	P,T	yes
MANTHORN	21	Daily	Temp. Index	regression equation		lumped unit hydrograph	none	none		FORTRAN	easy	low	P,T	yes
SASK6	21	Daily	Temp. Index	empirical	pan data	nash unit hydrograph	linear reservoirs		manual	FORTRAN	moderate	moderate	P,T	yes
SLURP	92	Daily	Temp. Index	linear reservoirs	parametric	lag	none	none	automatic	FORTRAN basic	easy	low	P,T,S	yes
UBC	96	Daily	Temp. Index	3 zn. soil moisture deficit	pan data	nash unit hydrograph	linear reservoir type				moderate	moderate	P,T	yes
FLOCAST		Daily	Energy Balance or Temp. Index	3 zone stanford type	pan data						moderate	moderate	P,T	yes
United States:														
SWMM III	56	Variable or Daily	Temp. Index or Energy Balance	horton or green ampt	pan data or met. data	PULS method				FORTRAN	moderate	moderate	P,T,S	yes
HEC-1	122	Variable	Temp. Index or Energy Balance	parametric loss function	none	unit (clark) hydrograph	muskingum	mod. PULS or R & D	automatic	FORTRAN	moderate	moderate	P,T	yes
HSPF	60	Variable	Energy Balance	parametric philip's eqn.	pan data	manning's	series of reservoirs	storage routing		FORTRAN	complex	high	P,T,R,W,D	yes
Stanford IV	30	Daily	Energy Balance or Temp. Index	3 zone lin. reservoir	pan data	time-area historogram			automatic	FORTRAN	moderate	moderate	P,T	unknown
SSARR-4	20	3,6,12,24 Hr.	Temp. Index or Melt Equation	index type 2 zone	index type or pan data	linear storage routing	SSARR routing		semi-automatic	FORTRAN	moderate	moderate	P,T	yes
LSBR	48	Daily	Temp. Index	tank cascade concept	thornthwaite	tank cascade concept			automatic	FORTRAN	moderate	very high	P,T,S	yes
SCS-BSM	130	Daily	Temp. Index	3 zone stanford type	pan data or evap. map data				manual	FORTRAN	moderate	moderate	P,T	unknown
NWSRFS	5	Variable	Energy Balance Temp. Index	parametric sacramento type	pan data graphs		lag and K or SSARR		automatic	FORTRAN	moderate	high	P,T,S	yes
USDAHL-74	54	Variable to 24 Hour	Temp. Index	holtan	pan data	empirical	average recession coefficient type			FORTRAN	moderate	moderate	P,T	unknown
HYMO-VUH	73	1,6,24 Hour	Temp. Index or Energy Balance	SCS method CN	pan data	unit hydrograph	VSC method			FORTRAN	moderate	moderate	P,T,S	yes
USGS	100	Daily	Temp. Index	holtan or SCS method	pan data	kinematic	mod. PULS		automatic	FORTRAN	moderate	moderate	P,T	unknown
Other:														
MARTINEC	75	Daily	Temp. Index								complex	high	P,T,S	yes
HBV	12	Daily	Temp. Index	non linear soil account. mois.	penman's	transfer function			semi-automatic		complex	high	P,T	unknown
SHE	77	Variable	Energy Balance or Temp. Index	porous media type equations	met. data						complex	high	P,T,R,W,V,S	unknown
TANK	116	Variable	Temp. Index	series of reservoirs							moderate	moderate	P,T	yes
Regression:														
PREVIN	1	N/A	Temp. Index	regression					automatic		easy	moderate	P,T,S	yes
VOLCAST		N/A	Temp. Index	regression							easy	moderate	P,T,S	yes
MANAPI	21	N/A	Temp. Index	regression	none	none	muskingum			FORTRAN	easy	low		yes

P - Precipitation T - Temperature S - Snow Pack R - Radiation W - Wind Speed D - Dewpoint Temp. V - Vapour Pressure to use the model, their knowledge of the model, and the complexity of the specific databases for the study basin. Qualifying the ease of application of each model was determined by the level of complexity of specific models.

A subjective approach was also used to qualify the model costs. Model costs are primarily associated with database management and consequently their qualification has to remain subjective due to the variability of data in study basins and the competence of technical personnel performing the calibrations. The computational capabilities of the modern-day computer have allowed most model operation to migrate down towards the micro-computer level. This has brought down the cost of operating most models and, as a result, data acquisition and preparation now comprises a major portion of any model's costs.

The information supplied on each model was subject to the availability of complete documentation. Most articles reviewed were either user manuals or discussion papers on the specific model. Most discussion papers limited their description to specific hydrological components of particular interest to the conference or the general theme of the journal in which it was published.

Many user manuals do not supply sufficient detail on distinct hydrologic functions used to develop specific components of the model. However, most manuals do provide general algorithms describing overall hydrological components modelled within a basin. This enabled the more generalized functionality of each model to be ascertained.

Most articles tended to concentrate on the attempts made to optimize model parameters with information obtained from a study basin or a series of study basins. Table 5-3 also reflects the information contained in the available literature. Any process or other information not adequately described in the available literature was left as a blank space in Table 5-3. This was intended to demonstrate how complete the available documentation for the selected models was described. Consequently, the screening process put forward in the following section was established on generalized precepts of the selected models.

5.3.3 Ranking of Selected Models

The approach taken in ranking the models was designed as a more subjective evaluation than ranking by internal hydrologic component capabilities of each model. This involved a generalized screening process in which selected models could be filtered out for a more constructive evaluation. The screening process used seven categories to assign a score to each model. Table 5-4 describes the seven categories, the weighted values for each category as well as the assignable range of scores.

Weighted values were assigned to each category on a scale from 1 to 5. This effectively assigned a level of importance to the subjective evaluations within each category. Greater weights were assigned to the categories reflecting time independence and overall model structure since these categories qualify the flexibility of a model to adapt to the physical nature of the basin. The cost category was assigned a low weight factor because a significant portion of cost in using any forecast model is in data acquisition, and information available on most models can only allow a subjective comparison.

The selected models were divided into three groups:

(Group A) Fully distributed grid models.
(Group B) Multi-watershed models.
(Group C) Single watershed models.

The fully distributed grid models presently use remotely sensed

TABLE 5-4: MODEL SCORING SYSTEM

CATEGORY	WEIGHT FACTOR	MODEL TYPE	SCORE
1. Model structure or modelling subject	4	Watershed	10
		Component	5
		Global	1
2. Role of time factor	5	Dynamic	10
		Static	2
3. Cognitive Value	3	Physical Based	10
		Physical-Conceptual	8
		Conceptual	7
		Conceptual-Trend	5
		Trend	2
4. Character of Results	3	Deterministic	9
		Stochastic	3
5. Operator Properties	2	Non-stationary	8
		Stationary	3
6. Ease of Application	1	Easy	8
		Moderate	6
		Complex	4
7. Model Cost	1	Low	8
		Moderate	6
		High	4
		Very High	2

data or can very easily be adapted to use remotely sensed data without compromising resolution capabilities.

Multi-watershed models can be divided by sub-watersheds in such a manner as to adapt to the resolution requirements of remotely sensed data. Single watershed models require considerable changes to their internal structures in order to be adaptable to the resolution prerequisites for remotely sensed data.

A model was not scored for the group in which it was classified, and was not penalized for its lack of adaptability to remotely sensed data. This evaluation is performed in a subsequent review process (Chapter 6). Table 5-5 shows the division of models by groups, and the subsequent scores accumulated by each model in the evaluation process.

It is apparent from the scoring results in Table 5-5 that the regressional models scores were considerably low. This reflects the weight given to the temporal flexibility of the models.

The range of scores for the deterministic models is quite small, with models being clustered into families of results. One conclusion drawn from the low variability in score among models is that given adequate calibration each model could be recommended. Therefore, additional information has to be applied to the selection process. Chapter 6 will set the criteria for comparing models and their applicability to remotely sensed data. The emphasis will be on identifying candidate models within the higher scoring clusters. The most promising models are:

- Group A: SHE, CEQUEAU, HBV
- Group B: STANFORD-IV, HSP-F, UBC, HYMO-VUH, SWMM-III, SASK6, FLOCAST, USGS, TANK, HEC-1, SSARR-4, USDAHL-74, SCS-BSM, NWSRFS, LSBR
- Group C: MOEHYDR2, SLURP, SIMFLO

TABLE 5-5: RANKING OF SELECTED MODELS

MODEL	CAT 1	CAT 2	CAT 3	CAT 4	CAT 5	CAT 6	CAT 7	TOTAL
<u>GROUP A</u>:								
SHE	40	50	24	27	16	4	4	165
CEQUEAU	40	50	21	27	16	4	4	162
HBV	40	50	21	27	16	4	4	162
MARTINEC	20	50	21	27	16	4	4	142
<u>GROUP B</u>:								
STANFORD-IV	40	50	30	27	16	6	6	175
HSP-F	40	50	30	27	16	4	4	171
UBC	40	50	24	27	16	6	6	169
HYMO-VUH	40	50	24	27	16	6	6	169
SWMM-III	40	50	21	27	16	6	6	166
SASK6	40	50	21	27	16	6	6	166
FLOCAST	40	50	21	27	16	6	6	166
USGS	40	50	21	27	16	6	6	166
TANK	40	50	21	27	16	6	6	166
HEC-1	40	50	21	27	16	6	6	166
SSARR-4	40	50	15	27	16	6	6	160
USDAHL-74	40	50	15	27	16	6	6	160
SCS-BSM	40	50	15	27	16	6	6	160
NWSRFS	40	50	15	27	16	6	4	158
LSBR	40	50	15	27	16	6	2	156
QFORECAST	20	50	21	27	16	6	6	146
PREVIN	4	10	6	9	6	8	8	51
VOLCAST	4	10	6	9	6	8	8	51
<u>GROUP C</u>:								
MOEHYDR2	40	50	30	27	16	6	6	175
SLURP	40	50	21	27	16	8	8	170
SIMFLO	40	50	21	27	16	6	6	166
MANTHORN	4	50	6	9	6	8	8	91
QUFM	4	50	6	9	6	8	8	91
MANAPI	4	10	6	9	6	8	8	51

Note: Categories defined in Table 5-4

6.0 MOST PROMISING METHODS FOR FURTHER STUDY

The objectives of the study are to investigate the interfacing of hydrologic models with remotely sensed data. The two preceding chapters addressed data aquisition and modelling techniques separately. This chapter examines the interfacing - or marrying - of the two techniques, and covers topics such as Canadian watershed model applications, unit costs for two forecasting centres, and interfacing issues. Finally, the most promising methods will be discussed taking into consideration all study findings.

6.1 Accuracy of Known Canadian Flow Forecasting Modelling

The accuracy of various models applied in Canadian basins are presented in the next paragraphs. This will provide a perspective on Canadian applications.

There are many measures of model output accuracies: some indicate how well computed flows compared with observed flows; others measure how well computed flows of one model compare with computed flows from another. Moreover, in modelling flows it is not only important how well a model simulates or forecasts observed flow volumes, it is also important how well the simulated or forecasted hydrograph matches an observed hydrograph both in rate and timing.

In comparing computed flows with observed flows, it must be borne in mind that recorded flows are always in error. One never knows the actual flow in a stream, only an estimation of it!

Appendix D describes some of the commonly used measures, or statistics, of modelled flow accuracy.

There are a number of basins in Canada where deterministic forecasting modelling has been carried out and analyses of numerical accuracies completed. The accuracy of the SSARR model and QUFM models have been analyzed with data from the Saint John River. Similar analyses have been initiated by Hydro Quebec with seven major basins. Kite (1978) reported on numerical accuracies of four models applied to the Magpie River in Northern Ontario. The Great Lakes Hydromet Network Work Group (1980) did a comparative analysis for two models in a Lake Ontario sub-basin and analyzed a model application to both Lake Ontario and Lake Michigan sub-basins. The Manitoba Flood Forecast Centre recently has carried out an extensive review of many deterministic hydrologic models. The SSARR and Hydro Quebec models were tested and compared on large tributary basins of the Ottawa River.

There are many other models used for flow forecasting and there are other comparisons of simulated versus observed flows; however, only the previous cases used rigorous accuracy calculations.

When applied to basins draining into Lake Superior the LSBR model gave the measures of accuracy listed in Table 6-1 (Croley, 1983).

TABLE 6-1: ACCURACY MEASURES OF LSBR MODEL

Forecast Period	Correlation Coefficient	RMSE (mm)
Day	0.92	0.25
Week	0.93	0.16
Monthly	0.90	7.0
Value for Perfect Accuracy	1.00	0.0

Kite (1978) compared four models applied to the Magpie River Basin in the northeast portion of the Lake Superior Basin and found the following degrees of accuracy.

TABLE 6-2: ACCURACY MEASURES FOR MAGPIE RIVER HYDROLOGIC MODELLING

	Nash's Coefficient	
Model	Calibration	Validation
SSARR	0.97	0.59
NWSRFS	0.83	0.61
SASK6	0.67	0.65
WRB(SLURP)	0.98	0.77
Value for Perfect Accuracy	1.00	1.00

Manitoba's Water Resources Branch (Canada-Manitoba, 1985) has evaluated eighteen hydrologic models for suitability and ease of use as river forecasting models. Only four models were applied to data pertaining to the Boyne River. These models are the SSARR, SLURP, HSP-F and MANAPI. This organization (Warkentin, 1985) obtained the following measures of accuracy in their modelling of two tributaries of the Boyne River.

TABLE 6-3: MODELLING ACCURACY MEASURES FOR BOYNE RIVER AT STEPHENFIELD

Model	Performance Score
HSP-F	0.75
SSARR	0.60
SLURP (WRB)	0.53
Manapi	0.65
Value for Perfect Accuracy	1.0

* - Refer to Appendix D for clarification.

In the SSARR modelling of the Saint John River Basin the following accuracy values were obtained.

TABLE 6-4: ACCURACY OF SSARR MODELLING OF SAINT JOHN RIVER

Accuracy Criteria	Perfect Score	Fort Kent Station	Mactaquac Station
C_n	1.00	0.98	0.98
C_p	0.00	0.20	0.24
C_v	0.00	0.02	0.01
C_f	0.00	0.43	0.51

C_n = Nash Coefficient
C_p = Peak flow criterion
C_v = Volume criterion
$C_f = (1-C_n)+2C_p+C_v$

Hydro Quebec (Bisson & Roberge, 1983) in reporting on the analysis of accuracies of its forecasting model, has given Nash coefficient values of modelling in seven basins for five years. The results are summarized below.

TABLE 6-5: ACCURACY STATISTICS OF HYDRO QUEBEC MODEL

	Nash's Coefficient		
Forecast Period (days)	Range	Average	Standard Deviation
1	0.58-0.98	0.85	0.11
3	0.52-0.92	0.78	0.14
5	0.34-0.95	0.69	0.19
10	0.00-0.77	0.49	0.26
Value for Perfect Accuracy	1.00	1.00	0.00

The Great Lakes Basin Hydromet Work Group (1980) modelled the Genesee River, a New York State tributary of Lake Ontario. They compared the root mean squared error of the LSBR (then called the CLERL large basin runoff model), the SSARR, and NWSRFS (snow) model. The results are given in the following table.

TABLE 6-6: MODEL ACCURACY COMPARISONS OF GENESEE RIVER

Forecast Period	Root Mean Squared Error#		
	LSBR	SSARR	NWSRFS
Month	1.25	1.26	1.22
Annual	1.30	2.02	3.50
Value for Perfect Accuracy	0.00	0.00	0.00

centimetres over the drainage area

In applying the LSBR model to twelve Lake Ontario sub-basins (Croley, 1983), the ranges of correlation coefficient and RMSE are given in the following table.

TABLE 6-7: ACCURACY STATISTICS OF LAKE ONTARIO SUBBASIN MODELLING

Forecast Period	Correlation Coefficient	RMSE(cm)
Week	0.71-0.93	0.26-1.02
Month	0.54-0.96	0.95-2.78
Value for Perfect Accuracy	1.00	0.0

Considering the Lake Ontario drainage area as a whole, correlation coefficients of 0.93, 0.95 and 0.97 were obtained for weekly, monthly and annual forecast horizons, respectively.

The Martinec, or Martinec-Rango, model can simulate and forecast daily streamflow using remote sensing techniques in mountainous basins where snowmelt is the major runoff component. A WMO study (Rango, 1983) reported on the accuracies obtained using two numerical measures of accuracy. They are:

1. Coefficient of determination on daily flow modelling - NTD
2. Ratio of differences between observed and computed runoff volume to observed runoff volume - PD.

Results of application to four basins are given in the following table.

TABLE 6-8: WMO SNOWMELT MODELLING TEST RESULTS USING MARTINEC-RANGO MODEL

			Statistical Measurement		
Basin	Drainage Area km2	Number of Years	Accuracy Parameter	Snowmelt Season	Total Year
Dischma	43	10	NTD	0.84	0.87
			PD	0.03	0.06
Durance	2120	5	NTD	0.85	0.86
			PD	0.87	0.05
W-3	8.4	10	NTD	0.80	0.77
			PD	0.08	0.13
Dunajec	680	1	NTD	0.76	0.75
			PD	0.05	0.01

The model was also applied to two small mountain basins in Colorado: the South Fork of Rio Grande and the Conejos River. The percentage of areal snow cover is a main variable, with the degree-day index representing energy inputs. Over a seven-year period, the model accounted for an average of 89 percent of the variance for the South Fork River and 87 percent on the Conejos. In the former basin, for individual years, the model accounted for between 69 and 97 percent of the variances while in the latter basin between 60 and 95 percent. Seasonal streamflow volumes have an average error of 1.8 percent on the South Fork and 1.1 percent on the Conejos for the seven year period (Rango, 1983).

In an attempt to synthesize the preceding model accuracy reports it is noted:

1) From Kite's work (1978) on the Magpie River Basin (one of the Lake Superior subbasins) the ranking of the four deterministic hydrologic models is from best to worst:

   1. WRB (SLURP)
   2. NWSRFS (snow)
   3. SSARR
   4. SASK6 (UBC)

2) Initial results of the Boyne River study indicate the following ranking:

   1. HSP-F
   2. SSARR
   3. SLURP (WRB)
   4. MANAPI

3) Similarily, the Genesee River Study gave the ranking:

1. LSBR
2. SSARR
3. NWSRFS (snow)

4) In a comparison between the Hydro Quebec modelling results and the SSARR on the Saint John River, it appears that SSARR modelling gave better results (as measured by the Nash coefficient).

The above model accuracy results are inconclusive in terms of establishing the more promising models. In the above tabulations, the SLURP model was the superior simulator in Kite's work but the second worst model in the Boyne River study. The NWSRFS also showed similar contradictory accuracy behaviour. The accuracy of any model is directly proportional to the efforts put toward calibration and the compatibility between the model's algorithms and the watershed being studied. It is therefore expected that certain models will perform better than others on certain types of watersheds. The limited permutations of model and watershed types previously described makes final conclusions on model accuracy impossible. However, several comments can be made:

1. None of the eight reported Canadian applications used remotely sensed data. Several forecast centres are nevertheless currently incorporating in "varying degrees", remotely sensed data (Lockhart, personal communication, 1985; Fox, personal communication, 1985). Although streamflow forecasting accuracies should increase with the usage of distributed data, there is no available proof of this in the reviewed literature.

2. A general cross correlation between the reported model accuracies and the selected model rankings (Table 5-5) was

ascertained. The Group B models, multi-watershed models, generally have higher accuracy potential than the lumped models of Group C. The accuracy spread among models within each of the groups is smaller than the accuracy spread amongst the three groups. Models with physically-based components generally outperformed trend or conceptual models. The Canadian applications provide some support for the model ranking of Table 5-5.

3. Canadian applications and comprehensive accuracy measurement programmes were not reported for models in Group A (distributed models).

6.2 Forecasting Costs

It is difficult to determine costs of collecting hydrometric and meteorologic data, transmitting them to a forecasting center, carrying out data reduction, model calibration and validation, model updating operations, and flow forecasting. The cost of individual sensors and hardware can be precisely estimated; however, the costs of installation and maintenance, technical manpower, support staff and other administration cannot be estimated nearly as well since it is case specific.

In order to provide cost estimates for potential forecasting centres, unit costs of various components will be presented in this section. The following tabulation shows unit costs for various data components required in the operation of a forecast center. These costs were derived from conversations held with authorities at two forecast centers, the New Brunswick Flood Forecast Center and the ALCAN Corporation flood forecast center for the Saguenay-Lac St. Jean basin in Quebec, as well as personnel at Atmospheric Environment Services. Economic cost, as opposed to financial costs were tabulated, therefore, normal overhead of 100% is included on any labour item. Where equipment is listed capital and operational costs are tabulated seperately.

TABLE 6-9: UNIT COSTS FOR VARIOUS COMPONENTS OF A FLOOD FORECASTING CENTER

Item Description		Estimated Unit Cost Capital	Estimated Unit Cost Operation
1) Meteorological Data			
i) Climatic Stations:			
	Manual	600.	1,300.
	DCP	15,000.	5,000.
ii) Class A Stations		35,000.	5,000.
iii) Synoptic Stations:			
	Manual	20,000.	75,000.
	DCP	70,000.	5,000.
iv) Radar			500./month
2) Hydrometric			
i) Telemark		40,000.	10,000.
ii) DARDC		40,000.	10,000.
iii) DCP		49,000.	10,000.
3) Snow Surveys			
i) Field Snow Courses		$ 500./day	
ii) Aircraft		$ 338./20 km flight lines	
iii) LMAS Satellite Analyses		$ 300./image	
4) Land Cover/Use			
i) LandSat		$1,000.-$2,000./image	

Unit costs for hydrological model setup, calibration and validation, computer resources and center administration are not provided due to high variability. Typical forecasting center costs could vary from a low of $50,000 to a high of $1,000,000. annually depending on the system's sophistication and size.

The above estimates are approximate only, and it is believed that the modelling costs should increase with the basin size - although not linearly. There are no Canadian studies, as of yet, that model type, model output characteristics and forecasting costs have been analyzed for a particular basin. In fact any comparisons of past and current modelling characteristics may be futile since, except for using DCS's and some data from weather radar, forecasting has until now been with non-remotely sensed data. Hence the costs and usefulness of models that are going to utilize some of the remote sensing techniques covered in Chapter 4 have yet to be assessed. Due to the lack of information and incompleteness of data, costs could not be used as a selection criterion for final recommendations.

6.3 Interfacing Remotely Sensed Data with Hydrologic Models

All hydrologic models can be interfaced with remotely sensed data. The levels of effort required to complete such tasks are generally high, since most models are not readily designed to accept spatially distributed data. Apart from the few recent models in Group A, such as CEQUEAU and SHE, all models are structured to accept point source information.

From Table 5-5 in Chapter 5 only four models were designated Group A type, eighteen Group B and six Group C. The Group A type models are part of a new generation of models that are structured to directly accept the spatially distributed databases generated from modern sensing techniques. Models that utilize only point source data can still take advantage of the distributed data; however, only as point averages.

This section will present interfacing issues that will be faced when marrying the currently operational remotely sensed parameters, discussed in Chapter 4 and the selected hydrologic models, discussed in Chapter 5.

6.3.1 Interfacing Issues

The variables given in section 4.3, which can be remotely sensed on an operational basis, can be divided into three categories as shown in Table 6-10. The table consists of a first group of variables that can be measured from maps which have been obtained by areal photography or by satellite spectral analyses. These variables are usually sensed once, normally for model calibration or parameter optimization purposes.

The second category are variables that can be measured at a point and transmitted to a flow forecasting centre via DCSs. They are usually used as model inputs or as state variables.

The last, or third category, are variables that are monitored by airborne or satellite-mounted sensors, ground-based radar, and they represent spatial statistics over a geographic unit - ie. a grid square or subbasin.

TABLE 6-10: OPERATIONAL REMOTELY SENSED VARIABLES

Variables Obtained from Mapping	Point Variables*	Areal Variables
Channel Dimensions	Lake & River Stages	Precipitation
Drainage Area	Waves & Seiches	Snow Area Extent
Land Cover		Snow Albedo
Overland Flow Lengths		Snow Water Equiv.
Surface Slope		Snowline
Impervious Areas		

* - Includes all meteorologic and hydrologic parameters that are measured at points in a basin or other geographic unit.

The variables from the preceding table comprise the following types: input variables, model parameters and state variables. The variables obtained from mapping can be used in any hydrologic models directly without algorithm modifications. The advantages of remotely sensing these variables are, they may be obtained more cheaply and in a more timely manner. The cost effectiveness of remotely sensing these variables increase with basin size.

The variables in the second category are obtained by DCS and have the disadvantage that they sense point rather than areal statistics. As with the variables in the first category, variables in this second group can also be incorporated directly into the models.

Variables in the third category represent spatial statistics over an area. When measured in a conventional manner by point reading, they are not as accurate as areal average values. An example is rain gauge versus weather radar data. Since the values of the third category variables are more accurate and because they are more representative basin averages, they are preferred to point measurements. Their use in hydrologic models designed to use point- and non-remotely sensed data will improve the models representation of meteorology, physiography and hydrology of a basin and, in turn, should improve accuracy and lower the overall modelling costs. How the variables in this category can be married with the top ranking models in each of the three model categories given in Chapter 5 will now be addressed.

As previously stated, interfacing hydrologic models with the first category of variables in Table 6-10 requires little or no effort since users currently calculate these variables from maps. Assuming the model algorithms currently use these variables, then no interfacing work is required. Techniques are currently being developed by A.J. Robinson & Associates Inc. using video-digitization of hard-copy material that will automate geographic database calculations. They are commonly obtained manually using planimeters, map wheels and scales.

The parameters under the second category are point type data and require no special processing and interfacing requirements. Under the assumption that a given hydrologic model uses some of these variables, the point source data could be directly incorporated or subjected to conventional preprocessing such as a Thiessen Polygon analyses. The distributed models of Group A have the advantage of potentially automating such preprocessing analyses. The CEQUEAU model, for example, has Thiessen Polygon routines.

The use of this second variable category is only limited by the individual model parameter requirements. As a rule, physically-based models such as HSP-F require the largest number of parameters. This fact has discouraged potential users because of the lack of available data and somewhat accounts for the low model popularity. The applicability of the second category of variables is not limited because of interfacing issues but rather model requirements.

Unlike the first two categories, the third category can involve extensive interfacing tasks depending on the compatibility between data and model input requirement types. The task of interfacing remotely-sensed data to Group A models requires a small level of effort; however, a significantly larger effort is required should Group B and C models be selected. According to the grouping of models described in Chapter 5, Group A models utilize spatially distributed data; therefore, this data can be passed into the model directly without spatial averaging. The other two groups would require areal averaging into essentially point data before introduction into the model.

Line type data such as gamma-ray snow survey data must still be processed into spatial averages before incorporation into the various models.

A technique of combining remotely sensed and other measurements such as point and line data for hydrologic areal averages is described in detail in an interim NASA report (Johnson et al, 1982). The technique is known as the Correlation Area Method (CAM).

The previous discussion addressed the first interfacing issue - point versus distributed databases. This issue can involve significant data processing; however, programming efforts should be very small unless fully automated processing and complex data networks are required. The second interfacing issue pertains to the time mismatch between sensing interval and model computational time step. Unlike the first issue, which can be resolved without modifications to the hydrologic model, this issue can lead to substantial programming efforts depending on whether or not the data are state variables or inputs.

Model input data usually has to conform to a specific time interval to suit the internal algorithms. Data with a high sampling frequency can be averaged over a longer duration to satisfy the model requirements. The opposite case of having a lower data sampling frequency than the model's requirement can be a potential problem if the model structure is inflexible. This problem can only be assessed on a case-by-case basis and is a function of data availability and model requirements.

State variables, such as snow water equivalent, are usually updated on an infrequent basis and are usually used for re-initialization. They would not represent interfacing problems unless the duration of sampling interval increases to a point where they would impede the model operation.

6.4 Model Selection

The selected models should maximize the benefits and capabilities of the remotely sensed data and offer a flexible internal structure. The latter characteristic will ensure ease of program adaptation for future enhancement in the sensing and measurement fields as well as improvements in computational hydrology. Two most promising models were selected from Table 5-5, one from Group A and one from Group B. No model was selected from the single basin or lumped group, since this group can only marginally benefit from spatially distributed data.

Group A Model: Distributed Models

This group represents the new generation of models. They are compatible with the distributed nature of basin parameters and they can reflect the rapid changes in parameter values with time. They are also directly compatible with modern sensing techniques which offer spatially varying values.

Models of Group A can maximize the benefits from remotely sensed data and are therefore strongly recommended. Within this group, the Canadian CEQUEAU model ranked a close second to the European SHE model. The CEQUEAU model was selected for testing over the top ranking model because the model has been developed for Canadian basins.

Group B Model: Multiple Basin Models

This large group of models include the physically-based and conceptual multi-watershed models. They can be adapted to use remotely-sensed data and therefore can take advantage of most pertinent remote sensing techniques. By defining the sub-basins small enough a "quasi-distributed" model can be numerically constructed; however, enormous computational inefficiencies will result. The selection of the physically-based HSP-F model provides comprehensive algorithms and complete hydrologic simulation options. Since the HSP-F model is well documented, has been successfully applied on Canadian basins, and offers more simulation options, it was selected instead of the marginally higher-ranked Stanford-IV model. The top three models in Group B are all of the same parent - Stanford-IV.

The CEQUEAU model of Group A and the HSP-F model of Group B are selected as the most promising models of the reviewed group of 60 models. The following chapter will deal with the selection of a test basin, while recommendations on a test programme for Phase II of this study will be described in Chapter 8.

7.0 TEST BASIN SELECTION

7.1 Selection Criteria

In order to study the costs, difficulties, advantages and benefits of marrying remote sensing techniques with hydrologic forecasting modelling applicable to hydroelectric flow forecasting, one or two models will be applied to one basin. This basin should have the maximum amount of pertinent ground and remotely sensed information available that can be used for model input as well as output variables, model parameters and state variables. This information should have been collected for a sufficiently long enough period of duration that model calibration and validation can be undertaken and be both complete and precise. The basin should be large enough that it is representative of basins in which hydroelectric generation is carried out in Canada and yet small enough that there is climatic homogeneity. If there is a hydroelectric development or developments on the river, it should not have a reservoir with a relatively large amount of storage, since the upstream watershed runoff ratios are usually difficult to accurately calculate in these cases.

In reviewing candidate basins where hydroelectric generation occurs, remotely sensed data availability was an important factor. Candidate basins could be selected from the following:

1) A tributary of the Saint John River;
2) A tributary of the Saguenay River in Quebec;
3) A tributary of the Ottawa River either in Quebec or Ontario;
4) A Lake Superior basin tributary;
5) The Boyne River, a tributary of the Red River, in Manitoba;
6) A headwater tributary of the Saskatchewan River that drains the eastern slope of the Rocky Mountains;

7) A basin that is located in the interior mountains of British Columbia.

Since a distributed model is recommended to be tested, data acquisition savings could be achieved by selecting regions where physiographic databases are available. This would eliminate the tributaries around Lake Superior.

Another selection consideration is using a basin that is covered by archived weather radar. If such a basin is selected, then areal statistics of basin precipitation can be calculated for the various intervals used in the models. Those weather radar stations that have archived data, with the exception of the Newfoundland station, are located in the Great Lakes/St. Lawrence River Basin east of London. Unfortunately, these areas do not contain basins in which gamma ray surveys are currently being undertaken. Hence, in selecting a basin on which to test hydrological models, a decision has to be made between using data from a basin that has gamma ray surveys of snow and soil moisture content and a basin containing good spatial precipitation statistics.

Should gamma ray snow equivalent analyses be selected then the following regions are recommended.

1) Saint John River Basin in New Brunswick;
2) Canadian tributary basin that drains into Lake Superior; and
3) Boyne River, a tributary of the Red River Basin in Manitoba.

7.2 Candidate Basins

Forecasting modelling is currently being carried out on the basins surrounding Lake Superior and in the Saint John River Basin. Gamma ray surveys have been carried out on the two previous sets of basins for at least two years. It is suggested that the forecasting hydrologic modelling be carried out on one of the tributary basins from one of these geographic regions.

Seven tributary basins in the Canadian portion of the Saint John River Basin and twenty-two basins on the Canadian portion of the Lake Superior watershed were considered as candidate basins. For the Saint John River Basin, suitable basins have been narrowed to the Tobique and the Nashwaak. Some pertinent statistics of these basins are given below.

Tobique: Drainage Area - 4370 km2
- Three hydrometric stations
- Four meteorological recording stations in and around the basin.
- Two small hydroplants
- Seven Gamma Ray Flight Lines (2-years)
- NOAA Snow Cover Statistics (2-years)

Nashwaak: Drainage Area - 1780 km^2
- Two hydrometric stations
- Four meteorological recording stations
- Two Gamma Ray Flight Lines (2-years)
- NOAA Snow Cover Statistics (2-years)

There are twenty-two major subbasins forming the land portion of the Lake Superior basin. On the Canadian portion, which comprises 54 percent of the total land drainage area, there are 23 hydrometric stations. Those major Canadian subbasins that have hydrometric stations on the main river stem and over which gamma ray surveys have been made since the fall of 1983 are listed in the following table.

TABLE 7-1: CANADIAN SUBBASINS OF LAKE SUPERIOR BASIN

Basin	Drainage Area Sq. Km.	Hydrometric Station Location	GammaRay Flight Lines
Pigeon	1550	Middle Falls	LS400
Black Sturgeon	2980	Near Highway 17	LS293, LS284
Little Pic	1320	Near Coldwell	LS450, LS253
Pic	4270	Near Marathon	LS252, LS251 LS236, LS234
Black River	1980	Near Marathon	LS241, LS235 LS251
White	4170	Below White Lake	LS429, LS428 LS234
Magpie	1930	Michipicoten	LS226
Michipicoten	5130	High Falls	LS224, LS225 LS471
Montreal	2880	Near Harbour	LS223, LS231 LS416, LS415

These basins are well represented with gamma ray survey flight lines, each of which is 20 to 30 km long and have 300 metre wide swaths over which the snow and soil moisture content are sampled. The suitability of these Lake Superior watersheds for hydrologic model testing will not only depend on the basin characteristics and the hydrometric record length, but it will also depend on whether the basins are covered by gamma ray survey flight lines, and by meteorological recording stations located in or in the vicinity of the watershed. There are ten active Canadian synoptic, or first-order, stations in the Canadian portion of the Lake Superior basin. All these stations measure precipitation and temperature and most stations also measure wind, radiation, and humidity.

It appears that the two best Lake Superior basins to model with regard to gamma ray survey data are the Pic and the Montreal.

One major factor that weighs in the selection between the two geographical areas is the relative importance of soil moisture data and meteorological data. The Lake Superior tributary basins not only have gamma ray data collected during the winter but are also surveyed once a month during the remainder of the year. Thus, soil moisture content statistics are well known. The two Saint John River tributary basins only have gamma surveys for the snowmelt period. Thus little data is available on soil moisture for the Saint John basins. The converse is true for meteorological data. The two Saint John River tributary basins have meteorological recording stations both in and in the vicinity of the watersheds. Neither of the two recommended Lake Superior tributary basins have meteorological recording stations in its watershed and the average distance between recording stations in the geographical region is 170 km. Thus, soil moisture will be better quantified for the Lake Superior subbasins but more importantly, meteorological variables will be better documented for the Saint John tributary basins. Furthermore, the Saint John basins offer remotely sensed snow cover data.

The selection of the geographic region and the test basin will be decided jointly by the study team and the technical advisory committee.

8.0 CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

The objective of Phase I of this study is to carry out a literature review and assessment of contemporary remote sensing techniques and hydrologic methods that can be used to enhance Canadian hydroelectric generation, with the aim of interfacing the two so that the cost of hydroelectric flow forecasting can be made more accurate or less expensive, or both. It is noted that a significant portion of the review on remote sensing techniques is based upon U.S. literature and that some operational remote sensing techniques have yet to be applied in Canada.

The following paramount findings were made:

1. Data Collection Systems are well developed and the technology is available for use in hydrologic forecasting.

2. Precipitation monitoring by weather radar is presently operational in a number of Canadian locations. The techniques for using this data for hydrologic analysis - hindcast - are well founded and give results of reasonable accuracy. The techniques for using weather radar in a precipitation forecasting mode are not as clear and well known. The precipitation forecasts are not as accurate as accuracies obtainable in hydrologic analyses.

3. Although there are some advantages to remote sensing techniques replacing conventional ground-based means of measuring modelling variables, the best advantages are in new remote sensing techniques that provide more accurate and better basin-wide variable values (areal rather than point values).

4. Currently, there is considerable research being carried out on measuring areal values of surface soil moisture, surface temperature and radiation statistics. Although economically feasible methods of remotely sensing these variables on a basin-wide basis are not operational as yet, they could be in the near future. When this occurs, it is possible that great improvements in operational hydrologic modelling will materialize, particularily in the determination of basin-wide statistics of evapotranspiration and probably also soil moisture content.

5. Research is underway to develop precipitation forecasting techniques in Canada; weather radar cannot as yet provide accurate precipitation forecasts while satellite techniques using cloudtop temperatures for frontal storm assessments are currently in the research and development stage.

6. Snowline, snow cover extent and snow albedo can be monitored by satellite sensing techniques.

7. The snowpack water equivalent can be operationally monitored in Canada by airborne gamma ray surveys. Research and development into satellite-mounted microwave sensing techniques is progressing.

8. Landcover types can be accurately delineated by Landsat data analysis with either a 79 or a 30-metre resolution; however, at most Canadian locations it can be accurately determined from 1:50,000 topographic maps. The major advantage to the use of Landsat obtained data in most of Canada is to provide current land use/cover statistics.

9. Modelling costs could not be used as a model selection criterion due to incomplete model information or lack of input data, or both.

10. Modelling difficulties arise when various data types (areal, line and point) of the same variable are used concurrently in algorithms. The correlation area method provides a means of resolving this problem.

11. By the criteria adopted in this study, deterministic models ranked higher than stochastic ones. Furthermore, physically-based models ranked higher than conceptual and trend models.

12. Comparative accuracies of known Canadian hydrologic model applications prove inconclusive; however, general tendencies, which supported the model scoring results could be observed. Physically-based models performed better than conceptual and conceptual models better than trend models.

13. Twenty nine selected models - deterministic and stochastic - that are applicable to Canadian conditions were divided into three categories according to model types and internal characteristics. From these categories, two models (CEQUEAU and HSP-F) are being recommended for study and testing in Phase II.

14. Two regions of Canada, New Brunswick and northwestern Ontario, were selected as prime candidates for a basin where the models could be tested and evaluated for cost, accuracy, time, and ease of application.

8.2 Recommendations

There are two potential advantages to using remotely sensed data as an integral part of hydrological forecasting modelling: one is to improve the accuracy of existing modelling; the other is to obtain the same degree of modelling accuracy but at a lower modelling cost. Hence, in phase II of the study both possible advantages should be investigated. For the same degree of modelling accuracy, the economic benefits can be obtained in measuring model parameters by remote sensing techniques rather than using ground-based measurements. Another aspect is the optimization of economic benefits derived from cheaper sampling techniques and improved modelling accuracies.

1. Either the CEQEAU or HSP-F models should be studied and tested in Phase II in either of the selected sub-basins of the Saint John River or the Lake Superior basins.

2. The test basin should be discretized for a full range of grid sizes. This process will quantify accuracy for various degrees of resolution.

3. The correlation area method should be applied when different measurement technologies are available for the same hydrological parameter in order to obtain areal averages.

4. For the modelling, the remote sensing of snow cover extents, snow water equivalent and snow albedo are recommended.

5. Land cover statistics should be determined by Landsat analysis.

9.0 REFERENCES

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APPENDIX A

TERMS OF REFERENCE

APPENDIX "A"

STATEMENT OF WORK

1. Background

Hydroelectric power generation, both large-scale and small-scale, is governed not only by the demand for power and generating capacity, but also by the availability of streamflow from year to year. Seasonal variations of streamflow within the year make it difficult at times to generate the rate of hydroelectric power required. This problem is at least partially overcome by a storage reservoir. Excess streamflow is stored in the reservoir during periods of high runoff and released later for power generation during periods of low flow. However, optimum power generation from existing hydroelectric power plants is rarely, if ever, achieved. The primary reason for this failure is a lack of accurate forecasts of reservoir inflows. Both over-estimation and under-estimation of inflows result in a waste of generating potential, incurring additional back-up system expenses. As well, flooding the related damage could occur downstream of the dam as a result of unnecessary of ill-timed releases.

There is a need to develop a cost-effective methodology for long-term and short-term flow forecasting which will provide accurate forecasts and, therefore, help to maximize power output. In view of recent and ongoing research, it is possible that data acquired via modern remote sensing techniques - both aerial and satellite-based - can improve the performance of conventional flow forecasting methods at a reasonable cost. Before this statement can be fully evaluated, however, applicable remote sensing and forecasting techniques must be identified, and the latter must be modified to accept the remotely-sensed input.

2. Objectives

The objectives of this project are to modify conventional methodologies of short-term and long-term streamflow forecasting by incorporating the use of data acquired via contemporary remote sensing technologies, and to apply these methodologies to a pre-selected Canadian watershed.

3. Requirements

In order to meet the above objectives, a detailed documentation is required of modern methodologies of streamflow forecasting which incorporate the use of data acquired via contemporary remote sensing technologies. The documentation must include:

a) The identification and assessment of proven contemporary remote sensing techniques which may now be considered to be fully operational and which have application to hydrologic forecasting.

b) The identification and assessment of hydrological forecasting models - conceptual and stochastic - applicable to the Canadian conditions, which have been designed for or are adaptable to modern remotely-sensed input.

c) The selection and modification of the most promising forecasting methodologies on the basis of a) and b).

d) The application of each methodology to a pre-selected Canadian watershed, emphasizing information sources and acquisition and step-by-step approach to its application.

e) Presentation and evaluation of results of each application and recommendations for further possible improvements.

APPENDIX "A"

STATEMENT OF WORK
(Cont'd)

4. Tasks

Expanding upon the five basic requirements outlined in the preceeding sections:

a) A literature search and review is to be made of proven contemporary remote sensing techniques - both aerial and satellite-based - which may now be considered to be fully operational and which have application to hydrologic forecasting. Applicable remote sensing techniques include those which can be used to assess the various components of the hydrologic cycle, such as streamflow, precipitation, evaporation and snowpack; to assess geomorphological characteristics of watersheds, such as land-cover, topoography and drainage networks; and to transmit and relay hydrometeorological data. Table 1 lists surface-type observational requirements for hydrology as suggested by the World Meteorological Organization/Committee of Hydrology (WMO/CHy) Working Group on Hydrological Data Collection, Processing and Transmission Systems. All of the parameters contained in this table are to be considered, with the exception of the water quality parameters, if they are relevant to flow forecasting. Each technique is to be clearly described and assessed in terms of accuracy, cost, time and ease of application.

b) A literature search and review is to be made of hydrological forecasting methods which are applicable to Canadian conditions and which have been designed for or are adaptable to modern remotely-sensed input. Both stochastic methods, such as regression models, and deterministic methods, such as conceptual runoff models and routing models, are to be considered. Each model must have application to long-term streamflow forecasting, wherein the forecast period can extend from one to several months, or short-term forecating, wherein the forecast period is in the order of 10-15 days. Each technique is to be clearly described and assessed in terms of accuracy, cost, time and ease of application.

c) On the basis of the reviews carried out in Sections a) and b), the most promising forecating methods are to be selected for further study. At this time, a draft report is to be prepared and submitted to the Technical Advisory Committee presenting the work performed under Sections a) and b) and making recommendations as to the selection of forecasting methods for further study. A final decision will be made jointly by the Committee and the Contractor as to which methods are to be pursued during the remaining portion of the contract.

   Once selected, each forecasting method is to be modified to accept the applicable remotely-sensed inputs. A complete description is to be provided of each methodology thus developed.

d) Each methodology developed under section (c) is to be applied to a pre-selected Canadian watershed. Each application is to be fully documented using a step-by-step approach. All aspects of data acquisition and analysis and modelling procedures are to be fully explained. Any computer programs developed are to be included and documented.

e) The results of each application are to be presented and an assessment made of each methodology in terms of accuracy, cost, time and ease of application. Recommendations are to be made regarding further possible improvements and future work.

The work performed in accordance with section a) to e) inclusive is to be published in a high-quality final report.

APPENDIX B

PAPER: COMPATIBILITY OF PRESENT HYDROLOGIC MODELS
WITH REMOTELY SENSED DATA

COMPATIBILITY OF PRESENT HYDROLOGIC MODELS WITH REMOTELY SENSED DATA*

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ABSTRACT

The state-of-the-art in hydrologic modeling has evolved as part of a constant struggle and interaction with parallel advancements in measuring and computing capabilities. Model sophistication and accuracy have increased in almost direct proportion to the ability to provide input data and to make meaningful computations. Today a wide variety of techniques exist, some are remnants of the past such as correlative relations between basic watershed parameters and peak runoff, and some are in a relatively embryonic stage such as continuous simulation models employing distributed data bases. Remote sensing techniques, both aerial and satellite, continue to offer new incentives for innovation in hydrologic modeling. While these techniques are being applied, their full potential is far from realized.

This paper summarizes some of the current uses of aerial and satellite remote sensing in hydrologic modeling and discusses their level of success. This is followed by an assessment of the compatibility of current and emerging model concepts with the types of data that can be derived from remote sensing techniques. Finally, concepts are presented for enhancing hydrologic modeling capability through integration of model structure and remote sensing capabilities.

INTRODUCTION

Background

1. Hydrologic simulation models have become an integral part of almost all aspects of hydrology. For example, existing and forecast weather conditions are input to models to estimate future flood discharges for emergency operations, flood fighting, and reservoir regulation. Models are used in planning studies to evaluate the benefits and impacts of alternative land use plans or flood control measures. In design studies, models are used to assist in developing specifications for engineering structures to solve specific flood control, navigation, or water supply problems.

2. The capabilities of a particular model are determined by its structure and the quality of the data input to the model. Model structure and associated inputs can be separated into three categories: meteorological phenomena, physical description of the watershed, and hydrologic processes. Meteorological phenomena concern the sources of water such as rainfall, snowfall, and snowmelt. The physical description of the watershed includes parameterization of the watershed boundaries, the stream channel network, topography, land cover, surface geology, and subsurface geology. Hydrologic processes include those processes such as infiltration, interception, depression storage, interflow, evapotranspiration, and groundwater recharge that influence the runoff and streamflow processes.

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3. The required model input data are directly tied to the complexity of model structure. It is important to note that model inputs can be complex for two reasons: because a model considers individually numerous hydrologic processes to arrive at a streamflow estimate, or those processes that are considered are described in a complex manner such as spatially distributed throughout the watershed.

4. Hydrologic model structure and associated inputs have evolved through parallel developments in concept, measurement capability, and computational capability (Fleming, 1975). Advanced model concepts seldom become operational until the inputs can be provided and the calculations executed in a timely manner. Recent advances in computational (computer) and measurement (remote sensing) technology have provided an opportunity for implementing new model concepts that could significantly enhance our hydrologic modeling capability.

5. Remote sensing is a relative newcomer to the arsenal of methods for acquiring hydrologic data. Aerial photography has been used for determining the physical limits and surface characteristics of watersheds for some time. Photogrammetry has commonly been used to acquire topographic information and stream channel geometry. With the coming of satellites such as Landsat, considerable attention was focused on the use of spacecraft imagery for describing land cover and land use conditions. Both old and new remote sensing techniques have demonstrated potential as valuable and cost effective methods for acquiring input data for hydrologic models. Engman (1981) pointed out, however, that the potential for application of remote sensing in hydrology is considerably greater than the applications addressed so far. Remote sensing can provide distributed data as opposed to the point data (e.g., rain gauge and pan evaporation) that most models have been designed to use and continuous or repetitive coverage of an area giving feedback on the state of dynamic processes or changes in watershed characteristics. Current models are not configured to take advantage of these capabilities, thus remote sensing remains a largely untapped resource for hydrologic modeling data provided by remote sensing systems.

Objective and Scope

6. The objective of this paper is to explore the compatibility of existing and emerging hydrologic models with the data acquisition capabilities of modern remote sensing techniques. The general evolution of hydrologic models is presented to set the stage for a synopsis of the current applications of remote sensing relevant to hydrologic modeling. Anticipated advances in remote sensing capabilities are discussed with respect to their potential to enhance hydrologic modeling. Concepts and strategies needed to make hydrologic models more compatible with remotely sensed data are discussed and endorsed.

Model Evolution

7. A summary of some major developments in hydrologic modeling is given in Table I. Model developments are separated into general concepts or structure, description of meteorological processes, physical description of watershed, and relations for hydrologic processes.

8. Hydrologic models have evolved from simple empirical relations to very sophisticated multi-component models. While initial emphasis was focused on observation and measurement, simple relations that are still in wide use emerged in the 1800's. Examples include time of concentration and the rational formula by Mulvaney, the exponential flood formula by Dickens, and the Manning Formula for flow in natural channels. Hydrologic developments in the 1800's were also stimulated by the modern concept of the

hydrologic cycle leading to numerous advances in the understanding of the roles of the various components of the hydrologic cycle.

9. The early and mid-1900's saw an increase in sophistication in both models and description of the individual processes that comprise the hydrologic cycle. A major advance was the development by Sherman of the unit hydrograph method followed by the development of the synthetic unit hydrograph, a bastion of many currently operational runoff models. Horton and later Phillip made significant advances in describing infiltration, McCarthy described the Muskingham routing method, and Lighthill and Whitman introduced the kinematic wave theory.

10. Major research programs in hydrology and the coming of the computer age occurred simultaneously in the 1950's. These efforts resulted in the first major integrated models that considered most or all of the land based components of the hydrologic cycle. The computer, perhaps more than any other single technological advance, has dramatically changed the emphasis in hydrologic modeling from simplicity to sophistication. The sophistication is evident in both the relations used to describe hydrologic processes and the descriptors of the meteorological conditions and watershed characteristics used as inputs to the models.

11. Meteorological conditions were initially characterized by simple storm totals. As forecasting interests turned from peak discharges to the entire hydrograph, rainfall intensity and duration gained importance as did the ability to estimate snowmelt rates and volumes. The ability to use data from more than one gauge led to the Theissen polygon and isohyetal techniques for describing storm distribution. Energy budget data such as solar energy, relative humidity, air temperature, and wind speed became important for the water budget models.

12. Inputs describing physical characteristics of watersheds were initially limited to very simple area, average slope, and flow length values. Other descriptors such as soils and vegetation cover or land use were included but models remained "point" oriented. Parameter values were "lumped" or averaged over the watershed area. Watersheds were later divided into subwatersheds and the lumping done over smaller areas to more realistically preserve the major spatial variations in watershed surface conditions. The idea that only some areas contribute to runoff was initiated. Finally, completely distributed data bases were developed and even greater attention was paid to spatial distribution of conditions, a major emphasis today.

13. Hydrologic processes were first considered very crudely and primarily with early systems techniques. The simple runoff coefficient and later the unit hydrograph and linear reservoir developed by Dooge are examples. Mathematical relations for individual processes such as interception, evapotranspiration, infiltration, and runoff evolved and matured with the advent of water balance models.

CURRENT REMOTE SENSING APPLICATIONS FOR HYDROLOGIC MODELS

General Applicability

14. While the potential for future applications of remote sensing in hydrology is great and researchers have documented feasibility in numerous areas, the actual applications to date have been somewhat limited. Anderson (1979) expressed that initial studies with satellite data have been limited to doing conventional things, not necessarily the optimum use of satellite data. Aircraft remote sensing products have enjoyed broader operational use but again for the most part as a substitute method for collecting data previously acquired by ground-based techniques.

Constraints

15. As previously discussed, hydrologic models currently in use were structured for ease of use based on available data acquisition methods. In most cases remote sensing was not considered as a data acquisition alternative except perhaps for geometric data through photogrammetry. Model inputs rely heavily on ground measurements, empirical indices, or parameters derivable from maps. Common practice remains establishing the best data base possible using available data and then modifying index values until a known input of rainfall (and snowmelt if appropriate) reproduces the associated measured output (discharge). This is referred to as calibration if simple methods are used and parameter optimization if sophisticated methods are used. For these reasons very few inputs for current hydrologic models can be obtained directly by remote sensing techniques. For example, upper and lower soil zone water storage capacities, parameters needed for popular continuous streamflow simulation codes, cannot be directly estimated from image data. At best, approximate values may be inferred based on other parameters extracted from images. Perhaps the one major exception to this is the acquisition of land cover information for use in the models that utilize the U. S. Department of Agriculture Soil Conservation Service (SCS) curve number procedure. Even in this case operational applications of the Landsat technology are not widespread.

16. A summary of current applications of remote sensing to hydrologic modeling is provided in Table II. The information presented in the table relates most closely to the fundamental data required to derive model inputs as opposed to the actual derived indices and parameters accepted by most of the models. A vast majority of the remote sensing applications to date have involved acquiring inputs to models.

Remote Sensing of Meteorological Conditions

17. Cloud cover, snow cover, and precipitation monitoring are the principal ongoing remote sensing applications for meteorological conditions. Cloud cover is monitored routinely by the National Weather Service using visible and infrared imagery from the Geostationary Operational Environmental Satellite (GOES). The 30-minute frequency coverage in the visible provides good estimates of cloud cover with an approximate 1 km resolution. The thermal imagery allows estimates of cloud heights through cloud top temperatures. Cloud cover and type can also be interpreted from the Advanced Very High Resolution Radiometer (AVHRR) imagery obtained from the NOAA-6 and NOAA-7 satellites. Coverage is only two times per day, but the AVHRR provides a four-channel multispectral capability with bands in the visible, near infrared, intermediate infrared, and far infrared.

18. Since 1973 NOAA polar orbiting satellites have been used to produce snow cover maps for selected watersheds in the western United States (McGinnis et al. 1980). Currently NOAA monitors snow cover in 30 basins primarily with the NOAA6/7 and GOES satellites. Photointerpretation methods using zoom-transfer scope equipment are routinely used to estimate the extent of snow cover. The presence of rough terrain and tree cover can significantly alter the snow cover signature making completely automated interpretation difficult.

19. Bowley and Barnes (1979) and Rango (1980) have reported successful application of Landsat MSS imagery for snow cover mapping. Band 5 Landsat imagery showed striking differences in snow cover extent in the Sierra Nevada in both normal and drought years. Barnes et al. (1974) showed that in areas such as Arizona and the southern Sierra Nevada, the extent of the mountain snowpacks can be mapped from Landsat in more detail than is depicted in aerial survey snow charts. Weisnet (1974) compared Landsat and

NOAA Very High Resolution Radiometer (VHRR) imagery (1.0 km resolution) and found that the snow cover mapped from the VHRR imagery was consistently less than that mapped from Landsat. Studies by Rango and Martinec (1979) and Rango (1980) have shown that snow cover information can be used to help estimate snowmelt runoff using hydrologic models. Landsat data for a basin in Wyoming was used to estimate snow cover extent for input to the Martinec snow melt model resulting in estimated snowmelt runoff within 5 percent of measured seasonal values.

20. Cloud cover information has been used to estimate precipitation using both GOES and TIROS-N AVHRR imagery. One of the most popular methods of estimating rainfall from GOES visual and infrared imagery is the Scofield and Oliver (1979) technique. It was primarily developed for convective storms and involves a decision tree structure used by analysts to estimate point precipitation intensity. None of the visible/IR satellite techniques are applicable for all precipitation types and climatic regimes (Atlas and Thiele 1982); there is particular concern for stratiform precipitation.

21. In general, cloud indexing techniques used with GOES imagery can provide reliable estimates of areas having no rainfall and intense rainfall. Areas of light rainfall are not reliably determined. Procedures such as the Scofield and Oliver technique used with GOES imagery can provide point rainfall intensity estimates for some storm types. Cloud indexing methods developed by Barrett (1970), Follansbee (1973), and Follansbee and Oliver (1975) provide weekly or monthly average rainfall estimates over large areas.

Remote Sensing of Watershed Physical Descriptors

22. Classification of Landsat MSS imagery for land use/land cover information has been the most widely investigated application of space remote sensing in hydrologic modeling. The bulk of these efforts have centered on using the land use information to estimate SCS runoff curve number values for streamflow forecasting and flood studies. Slack and Welch (1980) used Landsat I data to estimate SCS curve numbers for the 125-mi^2 Little River watershed, Georgia. Average SCS curve numbers were computed for each of six subbasins and compared to conventionally derived values. Agreement was within 2 curve numbers. They reported land use classification accuracies of 88 percent for agricultural lands (vegetated and bare soil), 87 percent for woodlands, and 27 percent for open water.

23. Webb et al. (1980) used Landsat to acquire land use data by unsupervised classification techniques for six watersheds across the United States. In four of these basins the Landsat classifications and simulation results were compared to those from conventionally acquired data. In the Rowlett Creek (24.6 mi^2) Landsat data provided nearly the same lag time as the conventional data and flow-frequency curves derived from simulations using Landsat and conventional data were very close. While the average basin parameters derived from Landsat and the resulting simulation results were determined to be within acceptable error limits for hydrologic modeling, individual cell classification accuracies were relatively poor. In general, at the grid cell level Landsat land use was in error about one-third of the time. By aggregating land use over large areas, the average percentage of area covered by each major land use class reduced to less than 8 percent.

24. Taylor et al. (1980) compared the use of Landsat derived and conventional land cover data for six watersheds. The cost effectiveness of Landsat was proven for areas greater than 26 km^2 (10 mi^2). Their analyses showed Landsat and conventional methods to be nearly equally effective in producing land cover data for hydrologic studies.

25. Jackson et al. (1977) used the Hydrologic Engineering Center model STORM and the WREM model to assess land use data from Landsat for hydrologic modeling. Landsat bands 5 and 7 were used to classify Forest, Residential, Grass, Highly Impervious, Moderately Impervious, and Bare Soil. Agreement between air-photo and Landsat estimated land cover classes decreased as the size of the area over which values were lumped decreased. The WREM model was used to model 179 subcatchments with Landsat providing input on the percent impervious area for each. The error in this estimate was very substantial for small subcatchments, confirming the relationship observed for land cover.

26. Bondelid et al. (1981) compared Landsat and conventionally derived SCS curve numbers for three watersheds in Pennsylvania. The results showed that in general the curve number estimation was not highly sensitive to the land cover data source, although Landsat was not able to identify land cover at the same level of detail as is normally used in the SCS procedure. The study also showed that while Landsat-derived and conventional curve numbers may agree well over an entire watershed, there may be large differences for individual subwatersheds.

27. Channel and valley cross section data and the drainage network in a basin are critical to most modeling efforts. While general slope and valley section data have been provided by photogrammetry, it is an expensive method for large areas. Airborne laser mapping systems have significant potential for cross section mapping in both open and wooded areas (Link and Collins, 1981). A pulsed laser system, the NASA Airborne Oceanographic Lidar, produced profiles over 2 km length flightlines that had a root-mean-square difference of from 12 to 27 cm in unforested areas and less than 50 cm in forested areas. The same system is also applicable for bathymetric measurements in relatively clear water bodies for depths up to 10 m (Link et al., 1982).

28. Drainage networks can be delineated reliably on side-looking airborne radar imagery, even in vegetated terrain. The radar imagery must be acquired from two directions to ensure that the channels on both sides of ridges are mapped. Landsat can be used to delineate drainage in rough terrain at a resolution comparable to the information shown on a 1:62,500 scale topographic map. However, in moderate and flat terrain, the drainage network is usually not as obvious. Accurate stream channel delineation is only possible for large rivers that have lateral dimensions larger than one pixel.

Remote Sensing of Hydrologic Process Parameters

29. Individual process parameters such as infiltration or interception index are not normally directly sensed remotely. The state of the system can be monitored, however, by sensing such things as soil moisture and streamflow throughout the basin. The status of these variables can provide valuable feedback on the state of individual processes.

30. Schmugge et al. (1979) outlined the properties observed in each spectral region that could be used to estimate soil moisture as follows:

Wavelength Region	Property Observed
Reflected Solar	Soil albedo/index of refraction
Thermal Infrared	Surface temperature
Active Microwave	Backscatter coefficient, dielectric properties
Passive Microwave	Microwave emission/dielectric properties and soil temperature

The use of reflected energy in the form of tone or color on aerial photographs is useful for qualitative estimates of wet or dry conditions. Since spectral reflectance of dry soil, surface roughness, and other factors influence the spectral signature of wet soils, Landsat has not provided a reliable quantitative tool for soil moisture mapping. Thermal and microwave techniques appear to have the most potential.

31. Thermal methods rely on measurement of the diurnal range of surface temperature or measurement of crop canopy temperature (Schmugge, 1978). Thermal IR provides relatively high resolution (1 km or less). Limitations include the inability to sense moisture content in areas of cloud cover and interference from partial vegetation cover and surface topography. By coupling topographic data with the thermal imagery, some influences of topography can be normalized. Heilman and Moore (1979) demonstrated the potential of the HCMM thermal imagery for detection of near surface soil moisture. Thermal inertia values were shown to relate reasonably well to soil volumetric water content for areas in South Dakota. The thermal band on the NOAA-6 AVHRR has similar potential for soil moisture sensing.

32. Active microwave sensors rely on changes in soil dielectric properties (Lundien, 1971) or backscatter coefficient (Batlivala and Ulaby, 1977) with changes in soil moisture content. Feasibility has been established by aircraft and ground measurements; however, sensor systems with reasonable resolution are not currently available for spacecraft. The synthetic aperture radar (SAR) system on SEASAT was the first system with good resolution (25 m); however, the incidence angle employed was not optimum for soil moisture determination and there is difficulty in calibrating such a system with enough precision to extract soil moisture data.

33. Passive microwave provide some advantages over thermal systems but suffer from poor resolution. McFarland (1976) did show a close correlation between the 21 cm passive microwave (Skylab) brightness temperature and the Antecedent Precipitation Index for areas of Texas and Oklahoma. Since passive microwave systems sense emitted energy, they are sensitive to both temperature and emissivity.

34. Streamflow cannot be sensed directly but the width of a river or area of a lake, which can be correlated to streamflow or outflow, can be determined from numerous types of imagery including aerial photographs, radar, and Landsat. The primary constraints are the contrast between water and land signatures and the sensor spatial resolution. The inundation caused by flooding has been monitored using Landsat by many including Williamson (1974), Kruus et al. (1979), and Kalensky et al. (1979). A favorite method is to compare a flood scene with a normal water scene to map flooded area. Wiesnet et al. (1974) studied the 1973 Mississippi River flood with the NOAA-5 VHRR infrared sensor. They concluded that large floods could be delineated for large river systems. Also, flood maps could not be prepared for streams whose valley widths were less than 3 km. Berg et al. (1979) showed that TIROS-N AVHRR data could be used to approximately delineate flooded areas for small rivers with wide floodplains. Lowry et al. (1979) demonstrated the use of X- and L-band SAR for mapping floods on the Red River in Manitoba, Canada. The SAR imagery was flown at steep depression angles in a pseudo satellite mode and required considerable interpretation to generate flooded area maps.

ENHANCING HYDROLOGIC MODELING THROUGH REMOTE SENSING

Current Trends

35. To date, remote sensing has been used chiefly to map general watershed characteristics from which conventional model input parameters are derived. A more significant contribution could be gained if the unique

capabilities offered by remote sensing were integrated into hydrologic modeling methods. Table III provides a overview of the current, near-term, and potential future remote sensing advances that could significantly impact hydrologic modeling. The following paragraphs discuss briefly the general ideas outlined in the table. This discussion is followed by an outline of concepts for making hydrologic models more compatible with remotely sensed data.

Opportunities through
Advances in Remote Sensing

36. Meteorological Conditions: Meteorological data are critical to any hydrologic modeling effort. The highly variable and dynamic character of the weather make it very difficult to provide accurate inputs to a model. Barrett (1970) argued that rainfall was the most highly varible meteorological element in both space and time and inadequately measured by conventional means. Beven and Hornberger (1981) pointed out that errors in estimated precipitation volume and intensity over a catchment are likely the limiting factor in runoff simulations in many cases.

37. In addition to rainfall, snow cover has been portrayed as the most difficult and complicated hydrologic parameter to measure. Snow extent, distribution, depth, water equivalent and density are all important. A distributed precipitation and snow cover mapping capability a critical component for accurate hydrologic modeling.

38. Perhaps the most immediate capability that could be put into operational use is the extrapolation of point rainfall (gauge) data using existing weather radar and satellite capabilities. The resulting distributed rainfall data would enhance flood forecasts and provide more accurate inputs for model calibration for planning and design studies.

39. The 1.55 to 1.75 μm band on the Thematic Mapper (TM) is expected to provide an enhanced capability to separate snow cover and clouds and will provide much enhanced resolution over the GOES System. Coupled with other TM channels, some additional information on areas where snow melt is occurring may be possible.

40. Continued development of microwave and multiple channel IR/microwave systems could provide a truely distributed rainfall mapping technique. Current passive microwave systems are limited in resolution and do not perform well over land. Radar systems are limited to low earth orbits but concepts such as the frequency agile rainfall radar (Atlas et al., 1981) show considerable potential. Combining visible and near-IR channel snow albedo may provide a means to estimate the entire snow albedo curve.

41. Watershed Physical Descriptors: The most immediate advantage that remote sensing offers in the area of watershed physical descriptors is the ability to provide distributed data on the character of the watershed such as land use/land cover, valley and channel hydrogeometry, and the drainage network. Calabrese and Thome (1979) projected that improved resolution such as that provided by the TM and SPOT would provide improvements in land cover classification, but hydrologic models were not currently capable of using this improved information. Use of radiance, spectral, spatial (texture), and temporal analyses will lead to much improved pixel by pixel land cover classification accuracies and more accurate delineation of impervious areas.

42. Valley and stream hydrogeometry mapping will be enhanced by operational airborne laser mapping systems. The airborne profiling of terrain system (APTS) currently under development and testing by the USGS will provide a space-age positioning capability with a conventional laser profile system to provide accurate channel slope and cross-section information with

a significantly improved capability over photogrammetric techniques for mapping in forested areas. Advances in on-board positioning systems less reliant on ground reference stations (Link et al., 1982) will lower the cost of laser mapping hardware and expand the capabilities available through commercial firms. Ultimately, laser mappers in spacecraft such as the shuttle (Kobrick and Elachi, 1981) will provide general elevation mapping over large areas sufficient for small scale slope and drainage divide delineation.

43. The ability to map drainage networks will be enhanced through the increased resolution of spacecraft imagery such as that acquired by the TM and SPOT systems. Coupling enhanced drainage delineation with digital topographic data will provide the opportunity for automated definition of basin and subbasin boundaries in accordance with criteria suited to particular study objectives.

44. Hydrologic Process Parameters: Soil moisture has been identified as the greatest single variable that consistently causes trouble in NOAA river level forecast (Rodda, 1976). Point sampling does not provide the necessary information on the true distribution of surface soil moisture conditions at any given time. The ability to estimate the true distribution of surface soil moisture conditions and the changes in the distribution with time is a critical capability for improving hydrologic forecasts.

45. Currently, soil moisture conditions are considered on a lumped-index basis such as the antecedent moisture index. Remote sensing can be used to grossly map the general wetness of the surface, but operational techniques are not available to accurately quantify surface soil moisture conditions with time. Since changes in surface moisture conditions are very dynamic, aircraft sensing is not practical. Satellite sensing on a daily basis has promise to provide suitable regional information.

46. Microwave sensors, both passive and active (Hickman et al., 1981) have shown considerable potential for reliably mapping surface soil moisture particular for relatively damp or wet soils. The effects of vegetation are difficult to eliminate for moisture values below 50% of field capacity. In the range of 50 to 150% of field capacity, radar soil moisture is dominated by the soil contribution, and estimates within ±15 percent of field capacity are possible. Using field capacity reduces the impact of soil texture on radar backscatter. Perhaps the most immediate use of proposed microwave soil moisture mapping systems would be for extrapolating point source ground measurements when they are available.

47. Current spacecraft sensors can provide regional information of water body geometry by delineating the land-water boundary. The current capability using Landsat is both resolution and time limited. The TM and SPOT systems will enhance the spatial resolution considerably, but temporal resolution will not be adequate for many flood monitoring applications. The existence of synthetic aperture radar systems with steep incidence angles in spacecraft will provide more accurate delineation of flooded areas on forested floodplains. Only aircraft can currently provide the necessary time and resolution capabilities needed for flood fighting operations. In the future, polar orbiting satellites with pointable sensor packages could provide the necessary capability for near-real-time flood mapping.

48. Evapotranspiration (ET) cannot be directly sensed; however, by combining information on the distribution and character of vegetation cover, meteorological observations, and surface moisture conditions, a methodology for estimating ET is feasible. This capability will be enhanced as higher spatial resolution systems provide more information on surface characteristics, and advancements in multi-channel meteorological satellite sensor packages allow more refined sounding of available moisture in the atmosphere.

Opportunities Through Modeling Concepts and Strategies

49. The Dilema: Remote sensing has not significantly increased the accuracy of the land phase models of the hydrologic cycle primarily because of the dissimilarity and hence incompatibility of the time and spatial averages as used in hydrologic models, as exists in the real world, and as measured by remote sensing systems (Peck et al., 1983). Advances in remote sensing will result in the capability to provide distributed data on static watershed descriptors, dynamic meteorological conditions, and hydrologic process parameters far beyond the fidelity required in current models. The key to more effective use of remote sensing in hydrologic modeling is to increase the compatibility of the models with these data. It is paramount of course that these changes in modeling concepts or strategies provide enhanced accuracy or more cost effective modeling capabilities.

50. Distributed data, for example, can potentially enhance the accuracy of runoff estimates from individual subbasins and increase the sensitivity of models to changes in watershed response within the time frame of individual storm events or surface conditions over long periods. Distributed data also represent an additional computational burden that any derived benefits must justify. Distributed models are most practical when their inputs can be directly measued or developed from directly measurable parameters.

51. An Approach: A model that could utilize distributed data to the degree necessary for specific applications and watershed conditions, utilize periodic "status reports" on the state of the watershed during an event or over a period of numerous events to update the state of process algorithms, and utilize more detailed historical information to effect more realistic model calibration suitable for a wider range of event magnitudes would be more compatible with emerging remote sensing capabilities. While these are only a few of the more obvious model characteristics needed to optimize the utility of remote sensing for hydrology, they can serve as examples for the general concepts and strategies that need to be evaluated.

52. Distributed Data: The advantages and need for distributed meteorological inputs were fairly well established in the previous discussions presented herein. The use of temporal and spatial varying rainfall, for example, can only provide maximum payoffs if the model can realistically translate the variations in rainfall into spatial and temporal variaions in runoff and streamflow with respect to the distribution of watershed surface and subsurface characteristics. This does not necessarily dictate the need for a fully gridded multi-dimensional consideration of all hydrologic processes. Conversely, it points to the need to consider the spatial variations in the watershed at the level of sophistication needed to describe watershed response.

53. A distributed data base describing watershed physical characteristics and criteria for establishing the relative sensitivites of major processes (e.g. infiltration, ET, depression storage) could lead to a simplistic means to specify the individual subbasins or portions thereof that will critically impact basin response. The ability to draw boundaries around these units by an automated procedure is not unreasonable. Models that can accommodate various levels of basin subdivision exist and the extension of these concepts to a design that more fully considers the distributed data available from remote sensing appears both logical and feasible.

54. Model Updates: Timely data on the state of hydrologic processes during and between individual events could provide a mechanism for updating hydrologic process algorithms. This is analogous to providing a check on the actual position of a vessel to remove inherent drift in position

estimates provided by an on-board navigation system. This concept could first be applied to initialize a model (i.e., antecedent conditions) and periodically to ensure that the model is realistically tracking the actual watershed response. The ability to determine areas where surface saturation has occurred or even various levels of surface saturation would significantly enhance the determination of runoff contributing areas. Periodic descriptions of snow cover attrition or depletion would serve to improve snow melt contributions to runoff.

55. Hydrologic models can be structured to allow periodic comparison of the distributed status of a critical process parameter (e.g., surface saturation) with a similar map derived from timely imagery products, thus, effecting a means to verify or modify the model state to match reality. The ability to accomplish this type of comparison and update is within the state-of-the-art of geographic information systems. The value of such an update capability may vary considerably for different watersheds and meteorological events and must be established through experiments and sensitivity analyses.

56. Calibration: Model calibration is usually plagued by a paucity of data. This and the character of lumped model formats also precludes at times the ability to calibrate for a wide range of event magnitudes. Historical storms recorded in a distributed manner, coupled with distributed data on watershed characteristics, and information describing the pre-event, intra-event, and post-event surface conditions would provide a capability to calibrate hydrologic models more realistically. Peculiar spatial and temporal storm and watershed response characteristics could be more comprehensively considered in modifying model parameters to match output to observed streamflow. A calibration using these enhanced data products would provide a more credible model for planning, flood forecasting, or engineering design applications.

SUMMARY

57. Advances in remote sensing capabilities are paving the way for enhanced data acquisition that can significantly impact on the capabilities of hydrologic models through distributed temporal and spatial data describing meteorologic conditions, watershed physical characteristics, and hydrologic processes. Through enhanced inputs, periodic updates of model states, and more comprehensive calibration procedures remote sensing technology can assist in upgrading model outputs. As new models emerge to take advantage of the opportunities offered by remote sensing, we will find that history will repeat itself, and hydrologic models will continue to evolve in parallel with the basic data sources available and the state-of-the-art in data collection and processing.

58. Hydrologic models that can fully utilize the distributed meteorological, watershed, and hydrologic process related data available from advanced remote sensors will significantly enhance our design, planning, and forecasting capabilities. Remote sensors can provide distributed input data on dynamic (meteorology) and static (watershed physical descriptors) factors. The potential exists to accurately determine initial watershed states (antecedent conditions) and to update hydrologic process algorithms during a period of simulation or between significant events. Remotely sensed data will have to be available in near-real time to make these enhanced capabilities possible.

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Table I. Summary of Some Major Developments in Hydrologic Models

Period	Model Concept or Structure	Description of Meteorological Conditions	Physical Descriptors of Watershed	Relations for Hydrologic Processes
1800's	Simple empirical relations, rational formula	Point observations of storm totals, evaporation theory	Use of simple descriptors such as area, length, and slope	Processes studied to establish concepts and empirical relations
Early & mid-1900's	Unit hydrograph and synthetic unit hydrograph	Point observations of intensity, duration of storms, snow measurements and monitoring, Theissen polygons concept	Lumped physical descriptors of surface vegetation soils; continued use of general area, slope, length parameters	Unit hydrograph concept, major processes such as infiltration considered as losses to obtain rainfall excess, snow melt relations based on temperature
1950's & 1960's	Multi-component water balance models, extension of unit hydrograph models, systems approach	Integration of data from multiple gauges, emphasis on energy flux measurements, consideration of full effects on meteorology on floods	Lumped physical surface descriptors coupled with additional parameters on subsurface conditions; use of partial contributing area concepts	Emergence of water balance models, all processes included by simple relations, indices, or empirical coefficients, systems approach to reduce sophistication of relations
1970's to present	Extension of multi-component models, distributed models are born. Continued use of hydrograph procedures; use of non-linear systems procedures	New rain gauge area weighting techniques, use of weather radar, emerging satellite snow and rainfall mapping, limited use of distributed data	Adaptation of distributed spatial data on such things as land cover and soils. Use of geographic information systems approaches	Optimization to obtain best parameter values based on observed data, more sophisticated process algorithms, systems approach continued

Table II. Summary of Current Remote Sensing Activities in Hydrologic Modeling

Data Type	Ongoing Applications	Assessment of Current Capability
Meteorological Conditions	Cloud cover	Cloud type and extent can be reliably mapped with the NOAA polar orbiting and geostationary satellites.
	Snow cover	Snow cover is mapped operationally by the NWS using primarily the visible band imagery of the SMS/GOES. Thermal imagery from SMS/GOES is used to help separate cloud cover from snow cover. Pixel by pixel calibration is necessary to accurately delineate the snow cover boundary in areas with considerable relief or forest cover. Snow cover has been mapped with Landsat; however, the Landsat detectors have difficulty in separating snow from other bright objects or materials because of their low albedo saturation levels.
	Precipitation	Rainfall intensity, duration, and location can be estimated from GOES imagery by the use of cloud indexing techniques such as the Scoefield and Oliver procedures. Accuracy of estimates can vary considerably for different type storms. Best results are achieved for convective storms. Areas of high intensity rainfall and areas of no rainfall can be reliably delineated best. Polar orbiting meteorological satellites can be used with relatively simple cloud index techniques to get weekly or monthly average regional precipitation estimates. Again these procedures work best for convective storms, and they are areal averages, not point estimates.
Physical Descriptors of Watershed	Land use/ land cover	Landsat has been used extensively to map land cover and land use classes. Experiments on test watersheds have shown these data to be acceptable for some hydrologic modeling applications. Problems occur in urban areas where Landsat resolution is inadequate to discriminate many classes. Not all hydrologically relevant land use classes are separable by satellite imagery. Aerial photography can be often used to fill in these gaps. Digital image processing techniques have made this a cost effective application of satellite imagery for areas greater than 25 km^2. While dominant use of the land cover information has been associated with estimating SCS curve numbers and impervious areas, estimates of evapotranspiration potential and interception storage can be inferred from vegetation types.

(Continued)

Table II. (Concluded)

Data Type	Ongoing Applications	Assessment of Current Capability
Physical Descriptors of Watershed (continued)	Valley and channel cross sections	Conventional photogrammetric techniques have provided stream valley geometry data for some time. Channel cross sections have traditionally been acquired by ground measurements, but airborne laser mapping systems have shown potential for operational use.
	Drainage network	Aerial photography and Landsat have been used effectively to delineate drainage networks. Landsat does a reasonably good job in rugged terrain but is not adequate, especially for small streams, in moderate to gentle topography because of lack of contrast and resolution.
Process Parameters	Soil moisture	NOAA polar orbiting satellites with the Advanced Very High Resolution Radiometer (AVHRR) infrared channels have shown potential for mapping wet soil areas over large areas. Landsat imagery is too infrequent for soil moisture applications.
	Area inundated, surface water	Landsat has been used to inventory all man-made waterbodies above 10 acres in size. While waterbodies can be reliably located and the water-land boundary delineated for the larger ones, difficulty occurs for long narrow rivers and streams because of 80 m pixel resolution. The NOAA polar orbiters have the advantage of much higher frequency of coverage but have relatively poor (1 km) resolution.

Table III. Summary of Remote Sensing Advances That Will Impact Hydrologic Modeling

Factor	Current Capability	Near-Term Capability Enhancement	Potential Future Capabilities
Rainfall	Satellites provide reasonable estimates of rainfall extent and duration and rough estimates of rainfall intensity based on cloud type/cover/movement	Satellite data provides means to extrapolate point rain gauge data resulting in truly distributed rainfall inputs on temporal basis for any area	Distributed rainfall extent, duration, and intensities through use of adaptive sensor pointing concepts and new sensors such as frequency agile rainfall radar
	Radar provides distributed rainfall intensities and durations	Satellite and ground based radar techniques provide rainfall inputs for flood fighting applications and more detailed input information for calibration to historical storms	Enhanced accuracy of ground based radar rainfall estimates via dual polarization and dopplar radar systems coupled with digitizing and automatic processing capabilities
Snow cover	Landsat, NOAA, VARR, and GOES systems map approximate snow cover extent and area problems exist in discriminating snow from clouds and snow in forested areas	Thematic mapper 1.55-1.75 μm channel offers higher spatial resolution and better snow-cloud discrimination for monthly snow cover mapping	Microwave and IR sensors offer possibility to sense snow depth/snow water equivalent. Corrections incorporated for topography aspect angle and vegetation cover will enhance accuracy of estimates
	TIROS-N AVHRR imagery provides 1.1 km snow cover mapping and lake ice melt monitoring capability	Regional estimates of snow extent, snow water equivalent, and snowmelt onset can be estimated from NIMBUS-7 SMRR microwave radiometer data. Large footprint (60 km) limits use for small watersheds	Multi-temporal analysis techniques using no snow and snow. Improved pixel to pixel registration capabilities will assist in multi-temporal signature comparisons for snow cover parameter mapping
Cloud cover	NOAA, TIROS, GOES satellite sensors provide	Automated mapping of cloud cover conditions	Spaceborne laser ranging could give much more

(Continued)

Table III. (Continued)

Factor	Current Capability	Near-Term Capability Enhancement	Potential Future Capabilities
Cloud cover (continued)	reliable cloud cover and cloud type information	over land will be enhanced by new multi-spectral capabilities on TIROS-N and Thematic mapper	accurate cloud height information. Multichannel microwave systems could provide total atmospheric column water equivalence values and some sounding capabilities
Land use/ Land cover	Spatially averaged land use/cover information can be acquired for simple categories using Landsat data on operational basis only lumped indices for runoff are accurately derived for model inputs	Higher resolution of Thematic Mapper (TM), SPOT, and RBV sensors provide more accurate pixel by pixel classification of land use/cover for input to distributed models	Advances in sensor technology will continue to increase spectral, radiance, and spatial resolution possible from space. Coupled with advances in computer technology, the ability to generate comprehensive geographic data bases will emerge
	Aerial photography provides operational means for acquiring detailed spatial land use/cover data bases through conventional photointerpretation. More sophisticated classifications are possible than with spaceborne imagery	Advances in use of temporal, spatial, radiance, and spectral information for automated classification enhance capability to discriminate between previously difficult to separate land cover classes. More detailed data bases can be derived from satellite imagery	Operational high resolution satellites will provide near-real-time data for determining changes in watershed cover conditions and to update geographic information systems for hydrologic model applications
Valley/stream hydrogeometry	Photogrammetric techniques provide operational capability in open (unforested) areas. Feasibility of using airborne laser systems for	Advancements in aircraft positioning, scanning laser mappers and on-board data processing will provide a fully capable airborne	Airborne laser mapping systems in space and space photogrammetry will provide regional slope and elevation data for input to distributed hydrologic models.

(Continued)

Table III. (Continued)

Factor	Current Capability	Near-Term Capability Enhancement	Potential Future Capabilities
Valley/stream hydrogeometry (continued)	mapping in forested areas demonstrated and operational capability emerging as commercial service	elevation mapping system with much enhanced cost effectiveness over conventional methods	Mapping valley cross sections may be operationally feasible
Drainage network	Aerial photography provides any scale drainage network delineation except in heavily forested areas where side-looking radars provide an alternative. Landsat provides capability for mapping major drainage ways	Higher resolution RBV, TM, and SPOT imagery provides enhanced drainage network delineation. Image processing using spatial filtering techniques combined with digital topographic data will assist in defining basin and subbasin boundaries	Additional high resolution data will enhance automated drainage network and basin delineation capabilities
Soil moisture	Surface moisture conditions can be qualitatively inferred from NOAA polar orbiting and GOES satellite imagery	Microwave sensors in aircraft or spacecraft coupled with in-situ ground sensors provide first operational distributed soil moisture mapping capability with quantified estimates based on indices such as field capacity	Active and passive microwave spacecraft borne sensors will provide daily spatial surface soil moisture distribution maps for update of process parameters, antecedent conditions, and contributing area. Advanced calibration and data analysis as well as commercial distribution will provide near-real time data
Surface water	Approximate land-water boundaries can be operationally mapped using satellite data. Difficulties occur in accurate mapping on forested floodplains	Higher resolution of TM and SPOT provide more accurate land-water interface mapping. SAR systems with 21-25 cm wavelength improve mapping flooded areas in forests	Data processing and handling advances lead to near-real-time flood mapping data for specific areas through polar orbiters with pointable sensor systems

(Continued)

Table III. (Concluded)

Factor	Current Capability	Near-Term Capability Enhancement	Potential Future Capabilities
Evapotranspiration	Simple estimates made based on cloud cover and vegetation cover from meteorological and Landsat satellite	Higher resolution multispectral systems provide more definition of vegetation cover, type, and character. Enhanced meteorological data coupled with climatology provide more accurate estimates of ET on a distributed basis	Advances in multi-channel atmospheric sounding and surface moisture condition mapping from space provide automated near-real time distributed ET estimates

APPENDIX C

EMR MAPPING ACCURACY SPECIFICATIONS

(supplied from EMR text)

TOPOGRAPHICAL SURVEY

MAP EVALUATION

INPUT

New and Revised Published maps.

Location and Type of horizontal and vertical control

ASDB Report

Docket from resource center which includes:

- Individual set-up report for each overlap
- Machine check report
- Method of revision
- Report of any problems concerning compiling, revision or tying to adjăcent maps
- Larger scale maps

PROCEDURES

The accuracy of New 1:50,000 and 1:250,000 maps is evaluated from the above information, also there is a continual evaluation of the maps as more information is obtained. The sources of this information are, additional field control, 1:250,000 maps compared with new 1:50,000 maps and 1:50,000 maps compared with larger scale maps produced form other sources usually the provinces. All information obtained from map users is considered.

OUTPUT

An evaluation and historial record of each topographical map is obtained.

This record includes a computer read out of the compilation record and accuracy evaluation of each map.

Two sets of index cards are produced. One set is used in house to record the history and also the faults of each map. The second index shows the history of each map which may be used by the public.

EXPLANATION OF THE SIX CHARACTER MAP EVALUATION CODE

(ref: STANAG 2215)

First Character - Horizontal or Planimetric Accuracy

Horizontal accuracy is coded by the letters A to F. inclusive.

A - ±0.5 mm accuracy for 90% of all points at publication scale. At various ground scales this accuracy becomes:

12.5 m for 1:25,000
25 m for 1:50,000
125 m for 1:250,000

B - ±1. mm accuracy for 90% of all points at publication scale.

C - ±1.5 mm accuracy for 90% of all points at publication scale.

D - Up to ±2 mm accuracy for 90% of all points at publication scale.

E - Over ±2 mm accuracy for 90% of all points at publication scale.

F - Map will not meet any of the standards listed above.

Second Character - Vertical or Relief Accuracy

Vertical Accuracy is coded by the digits 1 to 5 inclusive.

1 - 90% of all contours are accurate to within ±½ contour interval.

2 - 90% of all contours are accurate to within ±1 contour inverval.

3 - Contours which do not meet 1 or 2.

4 - Relief by form lines, hachuring or shading.

5 - No relief on map (i.e. planimetric map).

APPENDIX D

MODEL ACCURACY CRITERIA

MODEL ACCURACY CRITERIA

There are two categories of means to measure the accuracy of hydrologic forecasting models (Quick, 1985). They are given in the following paragraphs.

Graphical Criteria

Linear plots of simulated and observed hydrographs of daily discharges.

Plots of relative error between the simulated and observed mean daily discharges given by $\sum(y_c - y_o)$; to be plotted as a function of time.

Flow duration curves of simulated and observed daily discharges. Scatter diagrams of simulated versus observed monthly maximum daily discharges (peak flows).

Numerical Criteria

Coefficient of determination $N_T = \dfrac{\sum(y_o - \overline{y}_o)^2 - \sum(y_c - y_o)^2}{\sum(y_o - \overline{y}_o)^2}$

Seasonal volume difference: $PD = \dfrac{V_o - V_c}{V_o}$

Ratio of standard error to mean: $S = \dfrac{\sqrt{\dfrac{\sum(y_c - y_o)^2}{n}}}{\overline{y}_o}$

Ratio of relative error to mean: $R = \dfrac{\sum(y_c - y_o)}{n\bar{y}_o}$

Ratio of absolute error to mean: $A = \dfrac{\sum|y_c - y_o|}{n\bar{y}_o}$

Coefficient of persistence: $CP = \dfrac{r - \mu_r}{\sigma_r}$

Coefficient of gain from daily averages:

$$NS = \frac{\sum(y_o - \bar{y}_{od})^2 - \sum(y_c - y_o)^2}{\sum(y_o - \bar{y}_{od})^2}$$

In the above equations:

y_o = observed discharge

y_c = computer discharge

n = total number of observations

$\bar{y}_{od}$ = mean daily observed discharge for each day of the year derived from the calibration period.

v_o = observed runoff volumes during snowmelt seasons.

v_c = computed runoff volumes during snowmelt seasons.

$$\mu_r = 1 + \frac{2n_1n_2}{n_1 + n_2}$$

$$\sigma_r = \sqrt{\frac{2n_1n_2\ (2n_1n_2-n_1-n_2)}{(n_1+n_2)^2(n_1+n_2-1)}}$$

r = number of runs

n_1 = number of positive residuals

n_2 = number of negative residuals

Notes:

1. All the previous numerical criteria will be computed separately for the calibration period and the verification period.
2. In addition, they will also be computed for the snowmelt seasons during the calibration period and those during the verification periods. In this case y_o will be the mean observed discharge computed for the snowmelt seasons but separately for the calibration and verification periods.
3. PD will be computed for the snowmelt seasons only but separately for the calibration and verification periods.
4. NT will be computed both for mean daily discharges and mean monthly discharges.

These criteria were used by the WMO in its study of the intercomparison of snowmelt runoff models (WMO, 1983).

Tang and Lockhart (1983) have suggested accuracy standards for hydrologic forecasting. They combined three criteria - Nash, Point and Volume - to give a composite criterion. It is:

$$C_f = (1-C_n) + 2C_p + C_v$$

where C_n is Nash's criterion:

$$C_n = \frac{\sum(y_o - \overline{y}_o)^2 - \sum(y_o - y_c)^2}{\sum(y_o - \overline{y}_o)^2}$$

where $$C_p = \frac{[\sum(y_o - y_c)^2 \times y_o^2]^{1/4}}{[\sum(y_o^2)]^{1/2}}$$

n_2 = number of negative residuals

Notes:

1. All the previous numerical criteria will be computed separately for the calibration period and the verification period.
2. In addition, they will also be computed for the snowmelt seasons during the calibration period and those during the verification periods. In this case y_o will be the mean observed discharge computed for the snowmelt seasons but separately for the calibration and verification periods.
3. PD will be computed for the snowmelt seasons only but separately for the calibration and verification periods.
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where C_n is Nash's criterion:

$$C_n = \frac{\sum(y_o - \overline{y}_o)^2 - \sum(y_o - y_c)^2}{\sum(y_o - \overline{y}_o)^2}$$

where $C_p = \dfrac{[\sum(y_o - y_c)^2 \times y_o^2]^{1/4}}{[(y_o^2)]^{1/2}}$

$$\text{and } C_v = \frac{\sum (y_o - y_c) \times \Delta T}{y_{max} \times T}$$

For a perfect hydrograph reproduction $C_p = 0$. The volume criteria measures the quality of reproduction of the water balance and compares the observed and forecasted hydrograph volumes.

The suggested accuracy standards are in the following table (Tang and Lockhart, 1983).

SUGGESTED ACCURACY STANDARDS

Criterion	C_n	C_p	C_v	C_f
Perfect	1.00	0.00	0.00	0.00
Objective	0.90	0.20	0.02	0.50
Acceptable (upper limit)	0.80	0.50	0.05	1.25

Another numerical criteria of model accuracy is the root mean squared error.

$$RMSE = \sqrt{\frac{\sum (y_o - y_c)^2}{n}}$$

Manitoba Flood Forecast Centre (Warkentin, 1985) has developed two measures of accuracy. They are:

$$a = \frac{\sum |Q_c - Q_o|}{2 \sum Q_o}$$

and

$$b = \frac{|P_c - P_o|}{P_o}$$

where P is peak flow rate and Q is flow volume.

They are combined into a performance score which is equalled to 1-(a+b). A perfect simulation would give a performance score of one.

APPENDIX E

LIST OF PUBLICATIONS REVIEWED

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