EVALUATION OF SNOWMELT MODELS FOR APPLICATION IN PERMAFROST ENVIRONMENTS

P.G. Landine, R.J. Granger and D.M. Gray

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by

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EXECUTIVE SUMMARY

The study examines existing models used for synthesizing and forecasting streamflow from snowmelt in respect to their application in permafrost environments of northern Canada. Emphasis is placed on input data requirements; the manner a system treats the process of snow accumulation, snowmelt, water storage, transmission, and refreezing within a snowcover; infiltration to frozen soil; and the modularity or flexibility of a system to modifications and changes.

Based on the results of studies on model comparisons, published in the literature and model documentation; discussions with the developers (architects) of different systems; and communications with users of different systems, five models were selected for intensive evaluation. These are: (a) CEQUEAU - Institut National de Recherche Scientifique; (b) SSARR (Streamflow Synthesis and Reservoir Regulation) - U.S. Army Corps of Engineers; (c) TANK - Japanese National Disaster Prevention Center; (d) NWSRFS (National Weather Service River Forecast System) - U.S. National Weather Service and (e) HSP-F (Hydrologic Simulation Program-F) - U.S. Environmental Protection Agency. It is concluded that in their present form it is unlikely that any of the five systems would give reliable predictions of snowmelt runoff in Arctic environments without either extensive calibration of model parameters or major modifications or revisions to the simulation routines. Thus, the structure of the model and the ease with which program changes can be made are important factors in deciding the choice of a system.

Two models are superior to the others in terms of their flexibility and modularity. They are CEQUEAU and the HSP-F and both are recommended to NHRI for consideration of future use and development. Although each has its'
advantages, it is premature, without a line by line appraisal of the programs or a direct attempt to modify and introduce changes, to conclude which one of the two will best satisfy the needs of NHRI. In the short term, the performance of each model (in respect to its' application to northern permafrost basins) would benefit from revisions to selected algorithms based on recent research findings. However, full development of a practical, reliable system can be expected only with additional knowledge and a better understanding of the processes and parameters affecting snowmelt-runoff relationships in premafrost regions. It is suggested that the requirements of the model should play an important role in the planning and direction of future research investigations directed to this goal.
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INTRODUCTION

A snowmelt-runoff model must consider or simulate the following processes (once the snowcover has been determined): melt, storage, movement and refreezing of meltwater in the snowpack, infiltration, and movement of water in overland and channel flow. These processes are not always distinct, but interrelated and the nature and complexity of each can vary depending on the particular situation. A number of snowmelt-runoff models have been produced and are in use today. Some are physically-based, but most rely on simple indices to calculate or estimate melt. It might be said that in general the approach used by modellers has been one of seeking the simplest algorithm which adequately represents (or reproduces) the process in the given situation. The result has been a series of "different" models, each of which is most reliable in the area where it was developed and which usually requires extensive "calibration" when applied elsewhere. For the most part these models have been developed and tested in temperate climates.

When selecting a model for use in a "new" environment, or when preparing to develop one, it should be kept in mind that modelling has been, and will probably continue to be, an exercise in the art of compromise... between simplicity and reality. An examination of the methods used to model the various processes reveals this to be the case.

Snowmelt models

Snowmelt is governed by the transfer of energy at the snow surface and the snow/soil interface (U.S. Army Corps of Engineers, 1956; Kuz'min, 1961). The major energy fluxes generally involved in the melting of the snowcover are the radiative exchange and the turbulent transfers (Male and Granger, 1981).
Various models available for estimating the process can be classed according to the simplicity, or complexity, with which they simulate these energy transfers, either collectively or individually. In existing systems four categories can be identified:

(1) Single variable indices of melt,

(2) Single variable indices of the major energy transfers,

(3) Multiple variable indices of the major energy transfers, and

(4) Complete energy balances.

Index models require few inputs, generally only air temperature; however, their reliability can depend on the physical characteristics of the site and can vary seasonally. They also generally require a greater calibration effort, which must be repeated for each new basin. Under "normal" climatic conditions index models may give good results, but can produce significant errors when conditions are extreme. Roberge et al. (1988) point out that the more complex energy balance models generally provide good results under all conditions and are easily transposable from one area to another; however, they require a large number of input data which may be rarely available or difficult and expensive to measure.

The simplest snowmelt model is the degree-day melt index (U.S. Army Corps of Engineers, 1956) which uses the daily mean air temperature as a direct indicator of melt. Air temperature is related to the melt of the snowcover through the use of a melt factor, which can be site specific and usually varies seasonally. The degree-day approach for estimating melt can work well in situations where temperature is a reliable index of the net or total energy exchange, for example in areas dominated by maritime climate and in forested areas. According to Anderson (1976) a forest cover restricts the
penetration of wind and solar radiation, so that long-wave radiation dominates
the energy exchange at the snow surface and, air temperature, with which the
long-wave exchange is closely correlated, becomes a good indicator of the
whole of the energy transfers. This observation was the basis for the
development of the SNOW-17 model, a temperature-based model in which each of
the major energy transfers affecting melt is represented. The model is the
basis of the snowmelt routine in the National Weather Service River
Forecasting System (NWSRFS); the HBV model of the Swedish Meteorological and
Hydrological Institute that is used extensively in Nordic countries; the
Streamflow Synthesis and Reservoir Regulation model (SSARR) of the U.S. Army
Corps of Engineers and the CEQUEAU model recently developed at the Institut
National de Recherche Scientifique.

As suggested above there are situations where air temperature is not a
reliable indicator of the net energy transfer to the snow surface. Peck and
Anderson (1977) provide "extreme" climatic conditions under which a
temperature index will not work. Male and Granger (1978) showed that in open,
unforested areas the short-wave radiation exchange, which is poorly-correlated
with air temperature, is the dominant melt-producing energy flux to complete
snowcovers. For these areas it might be preferable to use multiple variable
indices for estimating the major energy fluxes; for example, temperature (and
wind) for the turbulent exchanges and the sunshine ratio for the radiative
contribution to the melt.

All the above methods assume that some of the energy fluxes (latent heat
transfer, soil heat flux) contribute little to the melt, and are thus ignored.
A complete energy balance accounts for all the energy transfers. Each transfer
is calculated using a physically-based formula or empirical expressions. This
approach of course requires a larger number of input variables (humidity, wind speed, soil temperatures, etc.). In spite of the complexity of a complete energy balance model it has been incorporated into snowmelt-runoff models (ie. Institute of Hydrology Distributed Model (IHDM), Systeme Hydrologique Europeen (SHE) Snow Model). These have been used primarily as research tools and have not been applied as operational forecasting systems.

Storage and Movement of Liquid Water in the Snowpack

The effect of storage by the snowpack on the movement of meltwater is important in the evaluation of both the volume and the time distribution of runoff. In order to evaluate the storage potential of the snowpack it is necessary to consider the "cold content" of the snowpack, its liquid water holding capacity and water transmission rates (U.S. Army Corps of Engineers, 1956). The movement of water through snow has been the object of much study (Colbeck, 1972, 1975, 1978, 1979; Wankiewicz, 1978). Despite the advances in theory of meltwater movement, virtually all the existing operational snowmelt runoff models handle this process in a relatively simple manner similar to that described by the U.S. Army Corps of Engineers. That is, melt produced at the snow surface is used initially to raise the snowpack temperature (overcome the cold content) and satisfy its liquid water holding capacity, after which the total melt produced is made available to surface runoff or infiltration. These models were all developed and tested in temperate climates where it can be assumed that the soil surface is at 0°C and that a positive soil heat flux is contributing to the advancement of the melt; in this situation the simple approach seems to work well.

The situation can be significantly different in colder climates. Marsh and Woo (1984 a,b; 1985), in studies of meltwater movement in an arctic
snowpack, show that when the soil remains frozen a large negative soil heat flux can exist throughout the melt period. Under this condition warming of the snowcover is delayed, meltwater entering the soil is refrozen, a basal ice layer is formed and runoff (and infiltration) is limited even after the snowcover becomes isothermal at 0°C. Only when basal ice growth ceases will meltwater be available for runoff. They developed a model for the wetting front advance and release of meltwater from these snowpacks and showed that it is important to include the effects of the heat flux at the snow-soil interface and the development of the basal ice layer in calculating snowmelt runoff.

**Modelling the Effects of Frozen Ground on Snowcover Runoff**

Most operational snowmelt runoff models use some form of soil moisture accounting routine in which the meltwater produced by the snowmelt routine is the major, or sole, input. These accounting routines are designed for unfrozen soil conditions and they generally distribute meltwater input into some or all of the following "components": upper zone storage, percolation, interflow and groundwater recharge. Soil parameters, or transfer coefficients, are used to control the quantities of water distributed to each component. These parameters are changed to allow calibration of the model for various soil conditions.

The presence of frozen soil greatly affects the amount of runoff produced from snowmelt. It has been shown (Gray et al., 1984; Gray et al., 1985a) that snowmelt runoff models which neglect the effects of frozen ground are subject to serious prediction errors when frozen ground is present. Several approaches for including frozen ground effects in soil moisture accounting routines have been suggested. These include:
(1) Modification (or calibration) of soil parameters in existing routines (Sand and Kane, 1986),
(2) A frost index to identify the presence of frozen ground (Molnau and Bissell, 1983; Neuman, 1983; Anderson and Neuman, 1984).
(3) An infiltration model for frozen soil (Gray et al., 1986), and,
(4) Solutions of the combined heat and mass transfer equations (Kuchment et al., 1986).

The first approach involves essentially the calibration of an existing model for conditions of frozen ground. Sand and Kane (1986) used the Swedish HBV-3 runoff model for simulating runoff during snowmelt periods in the Chena River Basin in Alaska. They calibrated the model for frozen (early melt) and unfrozen (late melt) soil conditions by adjusting the maximum soil moisture storage capacity, the limit for potential evaporation, and the infiltration rate and percolation rate coefficients. The improvement in model simulation achieved by accounting for the "seasonal variation" of the soil parameters is demonstrated. Further improvement in model performance is expected if a gradual transition between frozen and unfrozen conditions is used in place of an abrupt change.

To identify the presence of frozen ground the concept of a frost index has been introduced. Molnau and Bissell (1983) developed a continuous frozen ground index (CPGI) which they incorporated into the SSARR model for use in the Pacific Northwestern United States. Neuman (1983) and Anderson and Neuman (1984) introduced frost index equations into the Sacramento soil moisture accounting model of the NWSRFS. A preliminary version of the modified system was used to model runoff in the Minnesota River basin in 1981-82. The frozen ground index attempts to simulate the occurrence of frozen ground and its
effects on percolation and runoff, (accomplished by modifying different parameters of the soil moisture accounting routine).

The frost index is similar to a degree-day factor; it has units of temperature and is limited to temperatures below the freezing point. It is computed continuously from air temperature data, and is affected by snow cover (insulating effect), the daily thaw rate from ground heat (thawing from below), and the meltwater entering the soil. The soil parameters modified by the frost index are the parameters used in the unfrozen soil moisture accounting routine. These must be "calibrated" for each basin as well as a function of the frost index. The major advantage of the frost index over the "seasonal variation" method used by Sand and Kane (1986) is that it allows continuous simulation of the occurrence and disappearance of frozen ground and provides a basis for the seasonal adjustment of the soil parameters in the moisture accounting routine. This approach is probably most useful in areas where seasonally-frozen ground does not occur every year.

An infiltration model for frozen soils may be preferred over a frost index in areas where the soil freezes annually to depths greater than 1 metre. In this situation the processes of upper zone storage, percolation, interflow and groundwater recharge will differ significantly from those in unfrozen ground so as to render the "calibration" of soil parameters impractical. However, the use of some index may still be required to detect the disappearance of frozen soil. Granger et al. (1984) and Gray et al. (1984) describe the development of a simple physically-based model describing snowmelt infiltration to Prairie soils. The model assumes frozen soils can be grouped into three broad categories according to their infiltration potential: Unlimited - cracked or highly porous soils capable of infiltrating all the
snow water; Limited - the infiltration potential of a soil depends on the snowcover water equivalent and the ice content of the soil layer, 0-300 mm at the time of melt; and Restricted - a soil containing an impermeable layer at the surface that inhibits infiltration. Computer programs were written to interface with the NWSRFS and SSARR (Gray et al., 1984, 1985a, 1985b, 1986). It is demonstrated that the model markedly improves the performance of both systems in simulating streamflow from snowmelt on Prairie watersheds.

Kuchment et al. (1986) describe a system of physically-based hydrological models used to predict components of the water balance for river basins in the USSR. Infiltration from snowmelt is obtained from the solution of combined heat and moisture transfer equations in which the calculated heat flux at the bottom of the snowpack and the snow water yield are used as upper boundary conditions. (No mention is made, however, of partitioning snow water yield between infiltration and runoff.) Although the method is physically correct, it is difficult to implement since a great deal of information must be known about the soil physical properties, i.e.: soil porosity, density, maximum hydrosopicity, field capacity, saturated hydraulic conductivity, and thermal conductivity. The authors also recognize that spatial variability of these parameters can be a major source of error, and that some estimate must be made of the distributions of the parameters. Although visual inspection of the hydrographs presented by the authors suggests that the model works well, no indication is provided as to the importance of accounting for the frozen soil parameters on the reliability of the model.
MODEL SELECTION AND EVALUATION

Recently, two major studies comparing snowmelt models were reported by MacLaren Plansearch (1984) and the World Meteorological Organization (1986). Although these studies did not specifically examine the effects of frozen soil or discuss the applicability of the models to northern permafrost environments, they provide substantial information about the character of different models. Taken together the studies represent examination of 21 different models. The WMO study was a very controlled investigation involving eleven models using data sets from six different basins. Although visual inspection of model output suggests there is little to choose between systems, the numerical assessment provides useful information in respect to the effects of different physical characteristics, for example basin size, relative elevation range, percent forest cover and others, on model performance. For example, the TANK model (Sugawara et al., 1984) is strongly affected by forest cover (the model does not consider this parameter); SSARR (U.S. Army Corps of Engineers, 1975) appears to work less well on watersheds with a relatively large range in elevation; and the reliability of CEQUEAU (Morin et al., 1981) tends to decrease with watersheds larger than 2000 km² because of the limited number of grid points.

It is postulated that any model adopted for northern permafrost watersheds should be able to account for: spatial variability in snowcover accumulation patterns, hence snowcover properties; temporal and latitudinal variations in the radiative regime; the heterogeneous nature of permafrost and peat and mineral deposits; and other pertinent parameters affecting snowmelt and runoff. Four common methods of distributing processes and parameters used by modellers are:
(a) Lumping parameters and processes,
(b) Dividing basins according to elevation bands
(c) Prorating processes according to a percentage of vegetative
cover or land use, for example forest cover, impermeable surfaces, etc., and
(d) Distributing parameters and processes according to topographi-
cal and physical features and relative position.

The first method simply treats a watershed as an uniform area in which
there is no accounting for areal variability. NWSRFS treats snowmelt in this
manner. SSARR, TANK, HBV and others divide basins according to elevation
bands. This is a convenient approach where the relationships between elevation
and precipitation (snow accumulation) and elevation and temperature
(snowmelt) are known.

Several models recognize that physical characteristics other than
elevation are important. For example, snow accumulation and snowmelt processes
differ in forested and open areas; hence, a different melt rate is calculated
for each and the "net" melt is prorated according to the percentage of the
gross area of the basin represented by each. Also, infiltration may be
adjusted according to the percentages of pervious and impervious areas. The
HSP-F model (Johanson et al., 1980) falls into this category.

Fully-distributed models attempt to handle all processes and parameters
in time and space by dividing a watershed into discrete, quasi-uniform units
or linked sub-basins. Snowmelt is calculated independently on each unit and
meltwater is routed systematically by transferring water from one area to the
next downstream. CEQUEAU is a distributed model.

During the course of the investigation, information was obtained about
systems that are currently being applied in forecasting in the northern region and those being considered for future application. Discussions with Dr. Douglas Kane, University of Alaska suggested that at the present time there was no new or original work being undertaken in the State towards the development of a snowmelt runoff model. Apparently, some effort is being made to determine whether the Swedish HBV can be calibrated for frozen soils, without re-writing any part. Dr. K. David Harvey, Water Resources Branch, Inland Waters Directorate advised that they are working with the TANK model and that the Calgary Regional Office is involved in the application of TANK to several basins in Alberta. Note, the HBV is similar to the TANK model in the manner it simulates different processes. Dr. E. Anderson, U.S. National Weather Service advised that the NWSRFS had been modified but that the updated version does not include a "frost Index" nor provision for accounting for heat and mass fluxes in frozen ground. Discussions were held with Professor Guy Morin, INRS, Ste Foy, was consulted about the algorithms, modularity and availability of the CEQEAU model.

Based on information such as that presented above, the personal experience and knowledge of personnel of the Division of Hydrology on snowmelt and infiltration processes in open, cold climate environments, the availability of different systems and their present and potential use in North America, the results of studies reported in the literature and other factors it was decided to focus the evaluation on the following systems:

(1) CEQEAU of the Institut National de Recherche Scientifique,
(2) U.S. Army Corps of Engineers Streamflow Synthesis and Reservoir Regulation (SSARR),
(3) TANK model of the Japanese National Centre for Disaster Prevention,
(4) U.S. National Weather Service River Forecast System (NWSRFS), and
(5) HSP-F of the U.S. Environmental Protection Agency.
These models are reviewed with respect to the following criteria:

(1) The physical integrity and framework of the algorithms used to simulate different processes, specifically: snow accumulation; snowmelt; water transmission, refreezing and storage in a snowcover; snowmelt infiltration; the effects of permafrost on runoff, and their application to northern environments.

(2) Data requirements (use of standard network data inputs is considered a positive attribute),

(3) The modularity of the system in terms of:
   (a) Accounting for spatial and temporal variability of different parameters and processes, and
   (b) Adding and/or modifying subroutines and algorithms.

(4) Availability of a PC version,

(5) Model structure and documentation, and

(6) Current or projected use of the model by other groups of Environment Canada.
CEQUEAU

1. Model Name:

CEQUEAU

2. Developer:

Universite du Quebec
Institut National de Recherche Scientifique
Ste Foy, Que.

3. Documentation:

INRS-Eau, rapport Scientifique No. 93, 449 p.

4. General Description:

CEQUEAU is a conceptual, water balance model with distributed parameters. It accounts for spatial variations in the physical characteristics of the watershed through the use of a square grid system. The area of each square is divided into percentages covered by forest, lakes and marshes, and by impervious surfaces and further divided into "partial areas" according to sub-basin drainage divides.

Mass balance and snowmelt calculations are made for each whole square and downstream routing is carried out by systematically calculating flow from one partial area to the next. Discharge can be calculated at any point in the drainage network and the distributed approach allows the model to follow streamflow development in both time and space. Thus, it can be used to evaluate the effects of engineering works on the flow regime in the basin.
5. Snowmelt and Snowcover Depletion Algorithms:

The basic equations used for calculating snowmelt are described by the U.S. Army Corps of Engineers (1956). Identical expressions, but with different parameters, are used for both open and forest-covered areas. A temperature index, based on the mean daily air temperature, is used to represent the mean snowpack temperature (cold content). A second index is used to represent the snowpack ripening, or the saturation of the snowpack with liquid water.

"Potential melt" (TECp) is calculated using a modified temperature index approach from the equation:

\[ TEC_p = TFC \times \max(0, \text{TJE} - \text{TSC}) \times \text{HEURE}, \]  

where:

- TFC = melt factor,
- TJE = mean daily air temperature,
- TSC = threshold temperature for melt, and
- HEURE = a factor designed to account for the potential insolation.

TECp and the liquid precipitation are routed through to the soil surface only if the snowpack temperature and ripening indices have reached their threshold values. If the snowpack temperature index hasn't reached the threshold, the liquid water may be held in the pack. If the ripening index hasn't reached its threshold, the liquid water reaching the soil is some fraction of the potential melt calculated as a function of the ripening index.

The snowcover mass balance is calculated as:

\[ SNC_i = SNC_{i-1} + PJN_i - TFC_i \]  

where \( SNC_i \), \( SNC_{i-1} \) are the snowcover water equivalents for days \( i \) and \( i-1 \),
respectively. $P_{JNi}$ is the snowfall for day $i$, and $T_{FCi}$ is the liquid water reaching the soil surface.

6. Input Data Requirements:

(a) Meteorological
- daily solid and liquid precipitation, and
- daily maximum and minimum air temperatures.

(b) Snowcover
- initial snowcover water equivalent.

(c) Physiographic
For each whole square the information required are:
- elevation of the south-west corner,
- area in forest cover,
- areas in lakes and marshes, and
- area with impermeable surfaces.

7. Snow-Soil Interactions:

As shown in Fig. 1, liquid water produced on each square area and reaching the soil surface may:

(a) Run off from impervious surfaces,

(b) Enter the Upper Zone and:
  - Evaporate,
  - Runoff, if storage is satisfied,
  - Leave as Interflow (2 levels) and become available for streamflow when appropriate storages are satisfied,
  - Percolate to a Lower Zone, where it may:
    - Evaporate,
    - Leave as Baseflow (2 levels) and become available for
Figure 1. Diagram of the production function (CEQUEAU model).
streamflow when appropriate storages are satisfied. Liquid water produced on each square that reaches lakes and marshes may: evaporate or, if storage is filled, run off.

8. Flow Routing:

CEQUEAU systematically routes runoff from one partial area to the next (see Fig. 2). The water produced on the partial area (output of the production function) plus the inflow of water from the partial area(s) immediately upstream represents the amount of water available for routing to the next partial area downstream.

The flow from each partial area is controlled by its routing coefficient which is related to the hydraulic characteristics of the partial area and to the relative storage capacity of the drainage network. The routing coefficient is determined by the expression:

\[
XKT_i = 1 - \exp(EXXKT*SA_i*100/SL_i/CEKM2),
\]

where \(XKT_i\) is the daily routing coefficient for the partial area, \(EXXKT\) is a calibration parameter, \(SA_i\) is the area of the basin upstream of the partial area, \(SL_i\) is the area of surficial water on the partial area, and \(CEKM2\) is the area of each whole square.

9. Calibration:

The model uses a large number of parameters which must be optimized with calibration of these parameters being achieved by trial and error.

(a) Eighteen parameters are determined by trial and error (eg. drainage coefficients, storage thresholds),

(b) Twelve parameters are derived from physical characteristics of the phenomenon (eg. temperature and precipitation lapse rates), and

(c) Three "constants" are determined from hydrological and
Figure 2. Diagram of the routing function (CEQUEAU model).
physiographical characteristics of the basin (eg. time of concentration).

10. Other Remarks.

(a) The distributed approach to modelling provided by the model should prove advantageous in areas where physiographical characteristics vary significantly, for example spatial variations in permafrost and in peat and mineral deposits.

(b) The distributed approach (grid system with appropriate scale) allows for the correlation of results with observed satellite data (ie. snow cover).

(c) The model, as presently constituted, calculates snowmelt (using a temperature index) on whole squares and carries out a mass balance on partial areas. In areas where radiative exchange processes are important to ablation, both melt and mass balance calculations should be performed on the partial areas.

(d) The modular construction of the model (with thirty subroutines used to compute various processes) allows a high degree of flexibility. For example, a snowmelt routine could be modified or replaced or a routine for routing melt quantities within the snowcover could be inserted with relatively little programming effort.

(e) The model is available on diskette for use on a PC.

(f) Input data requirements are minimal (max/min temperatures, precipitation). However these would be expected to increase with the development of other algorithms.

11. Application to the Arctic and Permafrost Areas

CEQUEAU would require some modifications before it could be applied
with confidence to a northern environment. Initially:

(a) The temperature index approach of calculating snowmelt should be replaced by an energy balance,

(b) The routine for partitioning meltwater between runoff and infiltration should be modified to include the effects of frozen soil and permafrost. As a first approximation, the "tank" approach for simulating soil moisture reserves may be applied by simply closing the transfers to the lower tanks. Eventually, however it is preferable to generate an algorithm which employs a physically-based approach.
1. Model Name
SSARR (Streamflow Synthesis and Reservoir Regulation)

2. Developer
U.S. Army Corps of Engineers
North Pacific Division
Portland, Oregon.

3. Documentation


4. General Description
SSARR was developed for the North Pacific Division, U.S. Army Corps of Engineers, to provide mathematical hydrological simulations for the planning, design and operation of water control works. It has been further enhanced for operational river forecasting and management activities.

It is a mathematical hydrological model of a river basin system used throughout which streamflow from snowmelt and rainfall can be synthesized.

The system has two main components:
(a) The Watershed Model
Simulates rainfall-runoff, snow accumulation, and snowmelt
runoff. Algorithms are included for modelling the snowpack cold content, liquid water content, and seasonal conditioning for melt. The processes of interception, evapotranspiration, soil moisture storage, baseflow infiltration and movement of runoff into the stream channel are also modelled by the system.

(b) The River System and Reservoir Regulation Model

Routes streamflows from upstream to downstream points through channels, lakes and reservoirs under free flow or controlled-flow modes of operation. Flows may be routed as a function of multi-variable relationships which include backwater effects from tides or reservoirs. Diversions and overbank flows may be simulated.

5. Snowmelt and Snowcover Depletion

(a) Snowmelt

(i) Temperature Index Method

Melt during clear weather is calculated by:

\[ M = MR \times (T_a - T_b) \]  \hspace{1cm} [4]

where MR is a melt rate factor, a function of antecedent temperature index, \( T_a \) is the air temperature and \( T_b \) is the base temperature, usually 0°C.

Melt during rain is calculated as:

\[ M = (RMR + .007P)(T_a - T_b) \]  \hspace{1cm} [5]

where RMR is the rain melt rate, and P is the rainfall depth. Equation 5.

(ii) Generalized Snowmelt Equation.

The expression is a semi-empirical energy budget equation developed by the U.S. Army Corps of Engineers for partly-
forested areas of the U.S. Pacific Northwest. This procedure is not normally used on an operational basis, but rather for design flood derivations and reconstitution studies, when adequate data are available.

(b) Snowcover depletion

(i) Snowcover depletion curve model

The depletion curve option simulates the catchment as an entity and depletes the snow-covered area as a function of accumulated generated runoff expressed as a percent of the seasonal total. At the beginning of a simulation, the initial snow-covered area, total seasonal generated runoff and initial generated runoff must be specified by the user.

This option is appropriate for simulation of the active melt season in regions where snowmelt runoff is the dominant process. During the melt season, runoff from rainfall on snow free areas is normally negligible and new snow is not significant. In the event that rain on bare ground during melt is significant, the split watershed option can be used, to model snow-covered and snow-free areas separately.

(ii) Integrated Snow Band Option

The Snow Band Option allows a more quantitative appraisal of the distribution of snowcover. With this option, a basin is subdivided into one or more (up to 20) bands of equal elevation. An inventory of snow accumulation and melt is maintained on each band. Variations in temperature, precipitation and other parameters with elevation are taken
into account. Simulation of snowpack conditions and moisture input for runoff routing is independently accomplished for each band. This approach is particularly suited for mountainous basins where snow depth is a function of elevation.

6. Input Data Requirements

(a) Meteorological

For the index methods of snowmelt only daily air temperatures and precipitation are necessary. In the case of the generalized snowmelt equation daily values of air temperature, precipitation, dew point temperature, windspeed and global solar radiation are required.

(b) Snowcover

The snowcover data required is the basin average snowpack water equivalent or for the Snow Band option, the snow water equivalent (SWE) on each elevation band at the beginning of the simulation.

(c) Physiographic

The elevation of all hydrometeorological stations, lakes and reservoirs; the total basin area and area vs. elevation curve, forest cover ratio and storage volume of lakes and reservoirs.

7. Snow-Soil Interactions

Infiltration Algorithm (soil structure)

SSARR makes use of a soil moisture index (SMI) to control infiltration and runoff. SMI is an indicator of the relative soil wetness, when the soil moisture is depleted (only by evapotranspiration) SMI is small, if the soil is wet SMI achieves a maximum value. Runoff is computed using tables of SMI versus runoff percent. Baseflow and
subsurface flow are handled separately by infiltration indices, which allow a certain percentage of runoff to be routed through a series of cascading reservoirs with varying time constants.

There is no facility for, or method of, treating a soil differently when it is frozen or snow is present. Rainfall and snowmelt are regarded as identical inputs to the infiltration and runoff algorithms. This seriously limits the application of the model to cold regions.

8. Output Flow Routing

Melt occurring at the air-snow interface is processed by the snow conditioning algorithm. The "cold content" and "liquid water deficits" of the snowpack must be satisfied before any water is available to runoff. When meltwater is released from the pack it is processed in the same way as rainfall.

SSARR simulates the entire river system with routines for channel routing, lake routing and reservoir routing and regulation. The time step of the output hydrograph is 6 hours.

9. Other Factors

(a) A IBM-PC compatible version of the model is available (U.S. Army Corps of Engineers, 1986).

(b) The model is relatively easy to calibrate, a well-written manual with examples is supplied with the software.

(c) It can be applied to basins of various sizes ranging from approximately 1 km² to several thousands of km².

(d) It can not be subdivided to account for different land use factors within a basin.

(e) The program code is, by modern standards, poorly written. Because it
is unstructured it is very difficult to enter the program and try to modify old code or insert new code.

10. Positive Features

Two methods of snowmelt modelling are provided, the temperature index method and the generalized snowmelt equation.

The model can simulate all hydrological aspects of the river system from rainfall and snowmelt to streamflow and reservoir storage, from upstream to downstream points.

SSARR is widely used on an operational basis by several agencies in North America.

The program, with documentation, is readily available at minimal cost from the developer.

11. Negative Features

Serious concerns are related to the program code itself. The system is very large and therefore requires considerable computer memory and the programming style is archaic because it is poorly structured and organized.

The snowmelt equations are for mountainous, forested or partly-forested areas.

There is no provision in the model to account for the presence or the effects of frozen ground on hydrological processes.

The snowcover depletion curve method is very difficult to use operationally and the integrated Snow Band option is designed for areas of high relief.
TANK

1. Model Name
   Tank Model

2. Developer
   Japanese National Centre for Disaster Prevention
   3-1, Tennodai, Sakura-Mura, Nihari-Gun,
   Ibaraki-Ken, 305

3. Documentation
   Tank Model With Snow Component
   M. Sugawara, I. Watanabe, E. Ozaki and Y. Katsyama
   Japanese National Centre for Disaster Prevention

4. General Description

   TANK is classified as a deterministic, lumped-parameter model. It is
   a simple model, composed of four tanks (see Fig.3). Rainfall and
   snowmelt are input to the top tank (A), evaporation is subtracted from
   the storage of tank A. Water in each tank is depleted by discharge to
   the stream channel from the side outlet(s) and infiltration to the next
   tank through the bottom outlet.

   Tank A has three types of soil moisture storage, the first, S1 is
   the primary soil moisture, S2 is the secondary. The third type of
   storage is called free water, this occurs if the depth in tank A is
   greater than S1. When the water depth is greater than S1 + HA2,
   discharge will occur from A0, A1 and A2 at a rate proportional to the
   hydraulic head. Similarly, in Tank B discharge will occur from B1 if the
   water depth is greater than HB and likewise for Tank C when the depth is
greater than HC. Precipitation will fill the primary storage in Tank A first and as it fills water gradually moves to the secondary storage S2 via a transfer function.

Evaporation depletes the primary storage and when the level in S1 drops below the level of S2, water is moved from the secondary to the primary storage. The rate of movement is proportional to the difference in their respective heights. One other type of transfer is allowed, when the primary storage is not full, water is moved up from the free water of Tank B,C or D, whichever has a supply of water available.

5. Snow Accumulation and Ablation

A simple temperature model is used to distinguish the form of precipitation and to calculate snowmelt. When the air temperature is less than or equal to 0°C, precipitation is assumed to be snow and is added to the existing snowpack. If the air temperature is above 0°C, precipitation is assumed to be rain, and snowmelt occurs. The amount of snowmelt is given by:

\[
\text{Melt} = \text{SMELT} \times T + \frac{(P \times T)}{80},
\]

where SMELT is a coefficient whose value may vary from 4 to 6 depending on region, \( T \) is the air temperature in °C, and \( P \) is precipitation in mm.

Elevation bands are used to delineate zones of snow accumulation and depletion. Snow accumulation and melt are computed for each zone independently. Precipitation and air temperature are assumed to be uniform over each zone, both are lapsed with elevation. In most cases 4 to 6 elevation zones are sufficient.

The model also includes an option to simulate liquid water storage in and percolation through the snowpack. It is represented by another
Figure 3. Pictorial representation of the TANK model (after Sugawara et al., 1984).
tank (see Fig. 4) which is located between the snow model and the first soil tank. In Fig. 4, XSN is the snow water equivalent and W0 is a constant that determines HSN, the position of the upper tank outlet. When the snowpack is dry, (HSN is below W2) and the amount of water supplied to the soil is low; when the pack is wet, W2 and W1 both contribute to the soil.

6. Input Data

(a) Meteorological

Daily precipitation at one or more stations in or near the basin, daily max/min air temperature or mean air temperature and daily or monthly mean of potential or actual evapotranspiration.

(b) Snowcover

An initial value of snow water equivalent for each elevation band.

(c) Physiographic

The physiographic data requirements are: total basin area, an area vs. elevation curve and the elevation of hydrometeorological stations.

Figure 4. Pictorial representation of a Snowpack Tank (after Sugawara et al., 1984).
7. Snow - Soil Interaction

Frozen soil is not mentioned in the documentation. However, because of the simplicity and modularity of the model it may be possible to introduce another tank, between the snowpack tank and the first soil tank, to simulate the infiltration characteristics of frozen soil. This new tank would exist only if snowcover was present, which would allow the model to function normally at other times.

8. Output Flow Routing

River discharge is simply the sum of flows from the side outlets of the tanks. No routing from upstream inflows is provided.

9. Other Factors

(a) Micro-computer Compatibility

It is not known whether there is a micro version available. However, because the model is small and simple, there should be little difficulty in making it micro-compatible.

(b) Ease of Calibration

Calibration is essentially a trial and error process, but it must be preceded by very careful selection of the initial parameters. The documentation manual outlines a procedure for calibration, as well as providing numerous step by step examples. An automatic calibration procedure is also described in the manual. It appears that both methods, manual and automatic, require some informed subjective judgement on the part of the operator.

(c) Basin Size Range
The model has been used on basins as small as 8 km² and as large as 4000 km², but in theory there is no upper or lower limit in size.

(d) Subdivision by Land Use Category

Subdivision is not possible directly, but may be accomplished by running basins with different calibrations in parallel.

10. Positive Features

The main positive feature of the TANK model is its simplicity. The model is easily set up and calibrate for any watershed.

11. Negative Features

The greatest strength, simplicity, of the TANK model is also its greatest weakness. The simple temperature index model for calculating snowmelt would be inadequate for any open-terrain region.

A channel and reservoir routing algorithm would need to be added.

The model does not consider seasonally frozen soil or permafrost.
U.S. NATIONAL WEATHER SERVICE RIVER FORECAST SYSTEM

1. Model Name

U.S. National Weather Service River Forecast System (NWSRFS)

2. Developer

Office of Hydrology W23
National Weather Service, NOAA
8060 13th St.
Silver Spring, MD. 20910 U.S.A.

3. Documentation


4. General Description
The NWSRFS contains models and procedures for a variety of river forecasting applications which include historical data processing and model calibration, operational river forecasting and extended streamflow prediction. It is designed for use at River Forecast Centres throughout the United States. Operationally, it can receive on-line data from up to 1000 precipitation stations, 250 river gages, 75 reservoir sites, plus hundreds of stations reporting temperature, snow depth and evaporation. The system is used by the U.S. National Weather Service for flood forecasting, water supply prediction, continuous forecasting for water management and low flow forecasting.

Soil moisture accounting is by the Sacramento sub-model, which is a deterministic, lumped-input, lumped-parameter type. It converts moisture input (snowmelt or rainfall) to a hydrograph of channel discharge at the outlet of the catchment. Snow accumulation and ablation are modelled by a temperature index method. Routing models translate and attenuate a flood wave as it moves between two points in a channel.

5. Snowmelt and Snowcover Depletion

The snow accumulation and ablation model use air temperature as the sole index of the energy exchange across the snow-air interface. The flow of this sub-model is illustrated in Fig. 5. In the figure, PXTEMP is the temperature delineating whether the precipitation is rain or snow. If snow, the snowpack depth is updated, as well as the areal extent of snowcover and snowpack heat storage.

Heat exchange at the snow-air interface is handled in one of three ways: (a) If the air temperature is greater then 0°C and there is no rain (or light rain), melt is assumed to be the product of a seasonally
Figure 5. Flow chart of NWSRFS snow accumulation and ablation model (after Anderson, 1973).
varying melt factor and the difference between the air temperature and a base temperature; (b) If the rainfall intensity is greater than 2.5 mm/6h and the air temperature is above 0°C, melt is governed by a semi-empirical, temperature-based energy equation; and (c) If the air temperature is less than 0°C, the energy exchange can be positive or negative and the direction of heat flow depends on whether the air is warmer or colder than the surface of the snowpack. An antecedent temperature index is used to index the temperature of the surface.

Areal extent of snowcover is modelled by a snowcover depletion curve, a plot of the areal extent of snowcover versus the ratio of mean areal water equivalent to an index value. This curve must be calibrated for each basin.

The model keeps a continuous accounting of the heat storage of the snowpack. Sufficient heat must be added to bring negative heat storage to zero before melt can begin. The liquid water holding capacity of the snowpack is established by the user. Transmission of meltwater through the snowpack is calculated by equations developed at the Central Sierra Snow Laboratory in 1955 (U.S. Army Corps of Engineers, 1955).

The U.S. National Weather Service in its report to the World Meteorological Organization (WMO, 1984) indicated that an energy budget option for snowmelt was planned. Dr. E.A. Anderson (personal communication, March, 1988) indicated that the energy budget option had not been implemented, nor is it being actively pursued.

6. Input Data

(a) Meteorological

The model has a 6-hour time step, therefore input data must
also have the same time interval. The required elements are air temperature and precipitation. Because most available data are inputted as daily maximum and minimum air temperature and total daily precipitation, the model has internal routines for converting daily values to 6-hour values. The internal routines for temperature conversion are a combination of empirical equations developed in California and Vermont (Anderson, 1976). They are not likely to be applicable in open terrain or the Arctic environment.

Mean monthly or daily potential evapotranspiration is also required.

(b) Snowcover

The basin average snowpack water equivalent at the beginning of a simulation period is required.

(c) Physiographic

The following data are required: total basin area, an area vs. elevation curve, percent impervious area, areas of lakes, marshes and rivers, and hydrometeorological station elevations.

7. Infiltration Algorithm

The soil moisture model of the NWSRFS is illustrated in Fig. 6. Two soil moisture zones, Upper and Lower are defined. The Upper zone represents the upper soil layer and interception storage while the lower zone represents the bulk of the soil moisture and long term groundwater storage. Each zone stores water in two forms. Tension water, or water closely-bound to soil particles, which is filled by infiltration and depleted by evapotranspiration. Free water is depleted by horizontal movement, percolation and evapotranspiration. For pervious areas, the
Figure 6. Schematic of the NWSRFS soil moisture model (after Peck, 1976).
upper zone storages must be completely satisfied before runoff will occur. Part of a basin can be defined as impervious to infiltration and runoff occurs directly from these areas.

The model does not include a procedure for freezing a soil or modifying infiltration and percolation rates when snow and/or frozen ground is present. Anderson and Neuman (1984) attempted to introduce an algorithm to the system for determining whether or not frozen ground is present so that the calibrated runoff coefficients could be changed for the frozen soil condition. However, this algorithm has not been implemented in the operational model.

8. Output Flow Routing

The stream discharge time step is 6 hours. An entire river system can be simulated, with routing routines for channels, lakes and reservoirs. There is also a routing routine for extended streamflow prediction, based on historical data.

9. Other Factors

(a) Presently there is not a micro-computer version of the complete NWSRFS available. It operates only on a central computer facility in batch mode. With effort it may be possible to separate individual modules of interest for implementation on a micro-computer.

(b) Calibration of the model is not difficult, several examples are provided in the manuals. However a complete manual for the current NWSRFS version could not be found, nor is one referenced in the literature.

(c) The model will operate over a full range of basin sizes, from a point to several thousands of km$^2$. 

(d) Complete redesign, re-coding and testing of the NWSRFS was completed in 1984 (Anderson, 1986). The new version is highly flexible and modular, allowing the user to incorporate virtually any combination of the sub-models in a simulation. Not only is it easy to add new operations to the system, but the procedure for adding an operation does not require an understanding of the data base or control structure, except in the case of a modification that requires additional input data.

10. Positive Features

The conceptual soil moisture routine is designed with a strong physical base. Thus initial parameter estimation and calibration of the soil structure is easily accomplished.

The model is in operational use and is part of a large, well-established system.

11. Negative Features

There are several limitations of the model in respect to its potential use in northern, permafrost environments, namely: (a) the lack of a method for dealing with the effects of frozen ground, (b) the absence of a melt option employing a complete energy budget, (c) the equations for storage and transmission of meltwater through a snowpack are for deep, mountainous snowpacks, and (d) the program is so large (230,000 lines for the full system), that unless it can be subdivided, it would not be feasible for an agency not involved in operational forecasting to implement.
HYDROLOGICAL SIMULATION PROGRAM

1. Model Name

Hydrological Simulation Program - Fortran (HSP-F)

2. Developer

Environmental Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Athens, Georgia.

3. Documentation


4. General Description

The HSP-F is a set of subroutines that can simulate the hydrological and associated water quality processes on pervious and impervious land surfaces and in streams and well-mixed impoundments.

Major components of the energy balance for snowmelt are accounted for by empirical formulae rather than physical equations.

5. Snowmelt and Snowcover Depletion

The algorithms used for snowmelt are based on work by the U.S. Army Corps of Engineers (1956), Anderson and Crawford (1964) and Anderson (1968). Empirical relationships are employed when physical ones are not well known.

The snow algorithms use meteorological data to determine whether precipitation is rain or snow, to simulate an energy balance for the
snowpack and to determine the effect of the heat fluxes on the snowpack.

The model simulates net radiation, convective sensible heat flux due
to condensation, sensible and latent heat from rain and heat transfer to
or from the soil. The thermal quality of the snowpack is accounted for by
a negative heat storage term. All energy fluxes are computed as an
equivalent depth of melted or frozen water. Negative heat storage must be
reduced to zero before meltwater is released.

Routines exist for estimating:

(a) The fraction of a land segment covered by snow. It is estimated
by dividing the depth of the snowpack by a cover index. It is
essentially an areal depletion curve method.

(b) The density of new snow. Snowpack density is revised downward
when new snow occurs and then is compacted daily until a
maximum is achieved.

(c) The fraction of clear-sky radiation.

(d) Albedo by a dullness index which is based on the depth of new
snow and the time elapsed since snow last occurred.

(e) Heat fluxes due to atmospheric condensation and convection from
empirical relations that inherently assume a positive or zero
heat flow to the pack.

(f) Net short-wave radiation from the solar radiation flux (input
data) and semi-empirical relations for albedo and shading.

(g) Long-wave radiation, by equations based on Stefan's law of
black body radiation, which are linear approximations of curves
given in Snow Hydrology (U. S. Corps of Engineers, 1956).

(h) Liquid water holding capacity from the density of the snowpack.
There is also a routine to simulate re-freezing of liquid water in the pack. The ice created is assumed to be at the bottom of the pack or frozen in the ground.

6. Input Data

(a) Meteorological

Precipitation, air temperature, global solar radiation, dewpoint temperature and wind velocity. These must be in the same time step as the requested output, i.e., if hourly streamflow forecasting is requested, hourly input data is necessary.

(b) Snowcover

The initial snowcover water equivalent for the basin at the beginning of a simulation.

(c) Physiographic

The data required for each land segment in the basin are: area, mean elevation, latitude, forested area and shade factor. Other factors associated with soil erosion and water quality simulation are optional.

7. Infiltration Algorithm

The infiltration algorithms simulate both the continuous variation of infiltration rate with time as a function of soil moisture and the areal variation of infiltration over a land segment. The equations representing the dependence of infiltration on soil moisture are based on the work of Philip (1957).

The infiltration capacity, the maximum rate at which infiltration occurs, is a function of both fixed and variable characteristics of the watershed. The primary fixed characteristics are soil permeability and
land slopes, while variable characteristics are soil surface conditions and soil moisture content.

There is a factor to reduce infiltration and upper zone percolation when the ground is frozen; soil temperature is simulated by a separate subroutine. For frozen ground, the mean infiltration rate and percolation for unfrozen soil are multiplied by the factor:

\[ \text{INFFAC} = 1.0 - \text{IWE} \]  

where IWE is the ice water equivalent of the ice portion of the snowpack. The minimum value of INFFAC is 0.1, thus infiltration and percolation can be reduced up to 90%.

8. Output Flow Routing

The time step for output flow routing is the same as the time step of the input data.

9. Other Factors

(a) A micro-computer program of the HSP-F is available at low cost.

(b) Calibration of HSP-F would require considerable effort due to the large number of processes which are simulated. However, these simulation procedures are based on physical principles which make the initial selection of parameters relatively easy.

(c) HSP-F can be applied over a full range of basin sizes. Difficulty may be encountered on large basins and heterogeneous units because of the extrapolation of point data and the large number of parameters which would need to be estimated.

(d) The model allows a watershed to be divided into pervious and impervious land units. Several of each are allowed, the actual number depending on the user's needs and the variability of the
basin. Each unit requires its own parameter set.

(e) The HSP-F is a complete system that was designed from the top down in an orderly fashion with clearly defined objectives. Every level was planned before being written in pseudo-code and then translated into structured FORTRAN. Uniform data structures, logic figures and programming conventions are used throughout. Modules are separated according to function so that they contain only those activities which are unique to them. New modules can be inserted or old ones modified with little disruption to the existing code.

10. Positive Features

The most important feature of the HSP-F is the modularity and flexibility within a well-defined framework. Virtually any modifications that a user may wish to make could be accommodated with little effort.

The model is nearly complete in a physical sense. It simulates soil temperature, infiltration to frozen ground, snowmelt (by the energy equation), re-freezing of meltwater during pauses in the melt sequence, the hydraulic behavior of reaches and reservoirs and host of other processes associated with water quality. The water quality subroutines could be replaced by "dummy" routines to reduce program size.

The program documentation (Johanson et al., 1980) is well written, with an overall description of the program, flow charts of the entire system and a detailed description of each of the 500 subroutines.

11. Negative Features

The HSP-F requires more meteorological input data than temperature-index systems.

The sample runs provided in the user's manual are not complete, they
show the input but not the output from the system.
EXPERIMENTAL MODELS

There are many new models and improved versions of old models in the literature. These models and their components could best be viewed as experimental or research tools. They do not form part of an operational system, and for most, complete documentation or indeed program copies are impossible to obtain. However, it would be possible to introduce some of these routines into any operational system that has considerable flexibility and modularity.

Gray and Landine (1984) demonstrated that the performance of both the NWSRFS and SSARR in simulating streamflow from snowmelt on the Prairies can be substantially improved by including a frozen-soil, infiltration routine. This model is based on the results of field studies reported by Granger et al. (1984) which suggest that frozen soils can be grouped into three classes according to their infiltration potential, namely: Restricted, Limited and Unlimited. Areas of a watershed classed as "Restricted" are considered impervious; those classed as "Unlimited" are capable of absorbing all water originating from the snowcover. For soils having "Limited" Potential the amount of infiltration can be estimated from the snowcover water equivalent (SWE) and the soil moisture content (ice/water) of the upper (0-30cm) soil layer, at the time of melt. The routine may serve as a basis for the development of an infiltration algorithm for permafrost areas.

In another study, Gray and Landine (1986) developed a model for calculating snowmelt by the energy equation and incorporated it in SSARR. The energy budget snowmelt model (EBSM) consists of semi-empirical relationships for estimating short-wave radiation, albedo, long-wave radiation, net
radiation, sensible and latent energy, advected energy and internal energy changes based on standard climatological observations of air temperature, vapor pressure, sunshine hours, snowfall and snow depth. They demonstrated that the EBSM is workable and when interfaced with a streamflow forecasting system (e.g. SSARR) provides information on discharge rates of at least equivalent accuracy to that obtained by a temperature index approach. They also provide evidence to suggest that the estimates of the time-of-start and magnitude of snowcover runoff quantities may be better. Conceivably, this routine could be used as a starting point towards the development of a melt routine for the open, tundra regions of the north.

In a major review of hydrological models commissioned by the Ontario Conservation and Water Management Branch, (McLaren Plansearch, 1984) the HSP-F was applied to several research basins in Ontario. Some of the subroutines required modifications for Ontario conditions. For example, long-wave radiation was underestimated and this problem was corrected by introducing a different offset constant into the equation. The albedo decay routine was altered slightly to change the rate of decline. An absorption factor was put into the short wave radiation equation to account for energy passing through the snowpack and being absorbed by the ground, thus unavailable for melt. The negative heat storage algorithm was found to underestimate the accumulated negative balance. It was replaced by a simple accumulation of negative net radiation. The deficit is dissipated by absorbed net radiation when the energy balance at the snow surface becomes positive.

Snowmelt due to latent and sensible heat exchange is modelled in the HSP-F by linear empirical functions of temperature, vapour pressure and windspeed developed in the 1950's by the U.S. Army Corps of Engineers (U.S.
Army Corps of Engineers, 1956). Price (1977) has indicated alternative approaches for calculating latent and sensible fluxes based upon physically-derived equations relative to the stability of the air masses are more appropriate. A simplified version of these theories was incorporated in the model.

Each modification produced an incremental improvement in the model output. All were accomplished with little difficulty in terms of programming and with no additional data requirements.
SUMMARY AND RECOMMENDATIONS

In the early stages of the evaluation, it became evident that none of the models evaluated, nor others reviewed in the literature, would satisfy all the evaluation criteria. It is unlikely that without major revisions any of the systems would provide adequate, reliable simulations of those processes such as snowcover accumulation, snowmelt, meltwater transmission within snow, refreezing of meltwater, infiltration to frozen soils, and the effects of the permafrost active layer on the melt and meltwater release patterns which are important to snowmelt runoff in the Arctic. This is not to say that some may prove successful for synthesizing streamflow from a watershed after extensive calibration. Such being the case, the lack of physical integrity will likely severely limit its' transposability throughout the region.

Assuming that any system selected will need to be modified for northern regions, less weight is given to the physical constraints of a particular model than on the ease with which it can be modified. In this respect the important criteria are: (a) the program must have a well-organized structure, (b) it must be modular, and (c) the code must be well-documented so that new subroutines can be easily introduced to the system. Two models meet these criteria, HSP-F and CEQUEAU. The HSP-F is a very large and comprehensive system that meets all criteria; CEQUEAU model is a smaller less comprehensive system that is also well-suited to modification. Working programs of both systems are available in microcomputer form at minimal cost. The HSP-F is technically superior to CEQUEAU in a number of ways; (a) the program code in CEQUEAU, though modular, is not written in structured FORTRAN, (b) the routines used by HSP-F have a stronger physical base, and (c) HSP-F simulates
other processes (erosion, sediment transport, pollutant movement, etc), which may become important in future applications.

Both models require a significant amount of detailed information on physiographical characteristics of a basin as input together with a number of calibrated parameters. However, the meteorological data requirements for HSP-F are greater than for CEQUEAU due to the use of the energy budget snowmelt calculation.

Assuming that a primary mandate of NHRI is directed to research required to satisfy long-term operational needs it is recommended that both HSP-F and CEQUEAU be considered for future development and revision. Using the results of research reported in the literature it is believed that many of the subroutines and parameters in these systems could be modified or adjusted to improve their application for simulating snowmelt-runoff relationships on northern, permafrost watersheds. Work on these adjustments should be given high priority in any project towards the development of an operational model. These investigations would also provide information on the flexibility of CEQUEAU and HSP-F for modification.

Full development of a reliable operational model will require not only time, but a major research effort directed towards gaining an understanding of important physical processes and identifying the pertinent parameters and data required for simulation. In these respects, the model should serve as the central focus or tool in planning future research needs and goals.
REFERENCES


