APPLICATION OF SLURP HYDROLOGICAL MODEL TO A SUB-ARCTIC BASIN

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ABSTRACT

The SLURP model developed at NHRI, is a distributed conceptual model which simulates the behaviour of a watershed by carrying out vertical water balances for each element of a matrix of land covers and subareas of a watershed and then routing the resulting runoff between subareas. The model is able to simulate snowpack accumulation and depletion, groundwater response of watersheds, and rainfall and snowmelt generated streamflow. This study describes an approach of applying the SLURP hydrological model to a mountainous sub-arctic streamflow of Wolf Creek Basin. In this sub-arctic region, annual peak flow is generally dominated by snowmelt. As a research basin, the Wolf Creek basin has been equipped with instruments to measure the snow depth and density. A procedure to convert snow data time series into winter precipitation required by SLURP is developed. The generated winter precipitation data, together with other related climate data from three meteorological stations within the basin were used for both model calibration and model verification. Two years of streamflow data were tested with good results obtained for the calibration period 1994-1995 and somewhat lesser for the verification period 1995-1996.

INTRODUCTION

The great majority of the hydrological simulation modeling systems used in practice today belongs to the simple lumped conceptual type (Refsgaard et al., 1996). For simulation or forecasting of a streamflow hydrograph, one of the many simple lumped models will often suffice (Kite, 1997). However, for scientific research for the north, such as the Wolf Creek basin, these models are not readily applicable to high latitudes, as they do not adequately take account of such cold-regions hydrologic processes as snowmelt, permafrost interactions, and evapotranspiration. To determine the types, intensities, and locations of runoff production requires an accurate, explicit representation of the relationships between hydrology, vegetation, and climate (Wigmosta et al., 1994).

We describe here a distributed conceptual hydrological model, SLURP, applied to a mountainous sub-arctic streamflow of Wolf Creek Basin. The SLURP model fits somewhere between the lumped basin models and the fully-distributed physically-based models (Kite, 1997). The major advantage of models in this middle ground of detail is that they can incorporate the necessary physics while retaining simplicity of operation. The SLURP model is able to simulate the behavior of a watershed at many points and in many variables, but avoids the data and computation-hungry excesses of the fully-distributed models. In practical applications, the users of both lumped and physically-based fully-distributed models may also tend towards this middle ground. For example, users of lumped models may imitate the use of a distributed model by successively applying a lumped model to subwatersheds, and from the other end of the scale, Jain et al. (1992) describe the need to use area-averaged variables when applying the fully-distributed SHE model in practical situations.

SLURP uses remotely sensed data and image analysis. Climatological inputs such as precipitation and temperature are particularly critical for hydrological models. Depending on the type, quality, and record lengths of site-specific data, model can be run either using data from an observation network, or using the output from other (e.g. atmospheric and numerical weather prediction) models (Kite, 1996 and 1994). The SLURP model is able to simulate snowpack accumulation and depletion, groundwater response of watersheds, and both rainfall and snowmelt generated streamflow.

This study describes an approach of applying the SLURP hydrological model to a mountainous sub-arctic streamflow of Wolf Creek Basin. In this sub-arctic region, annual peak flow is generally dominated by snowmelt. As a research basin, the Wolf Creek basin has been equipped with instruments to measure the snow depth and

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density. Investigation of a procedure to convert snow data (snow depth and density) into winter precipitation is also one of the objectives of this study.

SLURP HYDROLOGICAL MODEL

SLURP is a daily time step conceptual distributed hydrological model in which the parameters are related to land cover (vegetation type). The SLURP model divides a watershed into a number of hydrologically-consistent subareas known as Aggregated Simulation Areas (ASAs). Each ASA contains a number of different land covers. The basic requirements of an ASA are that the distributions of land covers and elevations within the ASA are known and that the ASA contributes runoff to a definable stream channel. The subdivision of watersheds is best done using a Geographic Information System (GIS) to collate the areal data from different sources and present them in a form suitable for the model. If the model is to be calibrated, then at least some of the ASAs should have streamflow gauges at their outlets. Input data required by SLURP are shown in Table 1. All the parameters and coefficients used in the model are listed in Table 2.

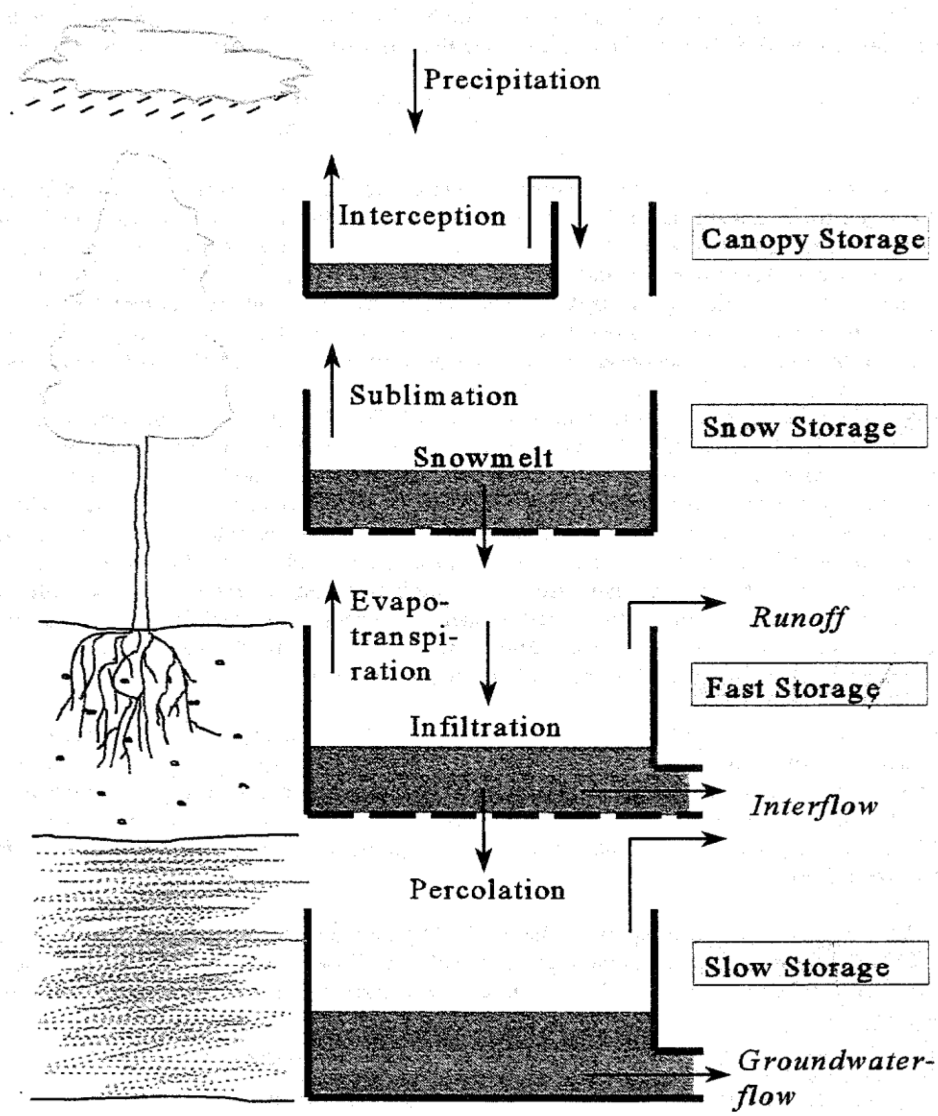


Figure 1. Schematic of the SLURP Hydrological Model

The SLURP model applies a vertical water balance to each element of the matrix of ASAs and land covers (Kite, 1997) using four reservoirs (Figure 1), one for the canopy, one for snowpack, one for a rapid response store (may be considered as a combined surface storage and top soil layer storage), and one for a slow response store (may be considered as groundwater). The model routes the precipitation through the appropriate processes and generates outputs (evaporation , transpiration and runoff) and changes in storage (canopy interception, snowpack and soil moisture). Runoffs are accumulated from each land cover within an ASA using a time/contributing area relationship for each land class and the combined runoff is converted to streamflow and routed between each ASA.

The SLURP model was designed to make maximum use of remotely sensed data. A GIS is used in an analysis of the land cover data and the streamflow network to yield a distribution of distances from each land cover to the nearest stream and distances down the stream network to the ASA outlet. Runoff from each land cover is first routed to the nearest stream and then routed down the stream channel to the ASA outlet. After the runoffs from all the land covers within a ASA have been routed, they are combined into an ASA streamflow which is routed from one ASA to the next ASA down the stream system to the watershed outlet. Depending on data availability, this routing may be carried out using non-linear reservoirs, Muskingum-Cunge or by accessing an external user-written procedure.

In its present version the model is written in FORTRAN 90 which provides for dynamic allocation of memory. This means that the program is no longer restricted to a certain number of ASAs or a certain length of data file. The only restriction now is the size of the computer RAM and hard disk. Details of the structure of the hydrological model are given in Kite (1997).

STUDY AREA

Wolf Creek Basin

The Wolf Creek basin is located at approximately 61 degrees north latitude and 135 degrees west longitude and 15 kilometres south of Whitehorse, the capital city of Yukon Territory. With a northeasterly aspect (Figure 2), the basin occupies a 220 km^2 areas with elevations ranging from 800 to 2250 metres in the southern Yukon headwater region of the Yukon River. Coal Lake, situated at an elevation of 1300 metres, is the major surface water storage element. The stream length (from the headwaters to the Highway site) is approximately 41 kilometres with a main channel slope of 0.015. Geologically, the area is primarily sedimentary consisting of glacial till varying from a thin layer to a depth of one to two metres. Soils are primarily poor forest and tundra types with relatively good drainage. The basin is located within a discontinuous/scattered permafrost zone. Three types of vegetation are found within the basin: low bush tundra, high bush taiga and boreal forest consisting of mixed spruce, pine and poplar (DIAND, 1995).

The sub-arctic continental climate of the basin is characterized by a large variation in temperature, low relative humidity and relatively low precipitation. The summer climate ranges from 5° to 20° Celsius and the winter range is from -5° to -20° Celsius with a mean annual temperature of -3° Celsius. Summer and winter extremes of 25° Celsius and -40° Celsius are not uncommon. An Arctic inversion occurs frequently during the winter months, causing air temperature to increase with elevation. Annually, precipitation ranges from 300-400 mm, with approximately 40% falling as snow (DIAND, 1995).

Basin response is typical of a mountainous sub-arctic stream. Streamflow response during snowmelt (late May, early June) is characterized by peak flows ranging from 10 to 20 m^3/s. Due to the significant lake storage and the proximity of Wolf Creek to the Gulf of Alaska, minimum winter flows are relatively high around 0.4 m^3/s. In the summer, the basin is subject to intense rainstorms which produce secondary peaks (DIAND, 1995).

Meteorological Stations and Hydrometric Stations

The study area has been instrumented with three meteorological stations and three hydrometric stations. The three meteorological stations were established within the three elevation-vegetation zones: the Black Spruce Forest, the Alpine Tundra and the Buckbrush Taiga. These stations monitor air temperature, rainfall, snowfall,

Table 1. Input Data Required by SLURP

Data Type	Examples	How Derived
Physiographic	Areas, distances and elevations	Measured from GIS
Time series	Precipitation, air temperature, dewpoint temperature, net radiation and streamflow	Measured
Parameters and coefficients	See Table 2	Estimated, Calibrated, or Measured

Table 2. Parameters and Coefficients of the SLURP Model

No.	Parameter and coefficients	How derived	Sensitivity
1	Initial contents of snow store*[1]	Measured/ Estimated	medium
2	Initial contents of slow store*[1]	Estimated	low
3	Maximum infiltration rate*[1]	Estimated	low
4	Manning roughness surface*[1]	Estimated	low
5	Retention constant fast store*[1]	Estimated	high
6	Max. capacity fast store*[1]	Measured/ Estimated	high
7	Retention constant slow store*[1]	Estimated	high
8	Max. capacity slow store*[1]	Measured/ Estimated	medium
9	Precipitation factor*[1]	Estimated	high
10	Snow melt temperature*[1]	Estimated	medium
11	Temperature lapse rate	Measured/ Estimated	medium
12	Precipitation lapse rate	Measured/ Estimated	low
13	Initial contents of canopy store	Null	low
14	Initial contents of fast store	Null	low
15	Max. capacity of canopy store	Estimated	medium
16	Albedos (surface, snow)	Measured/ Estimated	medium
17	Leaf area index	Measured/ Estimated	medium
18	Interception coefficients a, b	Estimated	medium
19	Soil heat flux	Estimated	low
20	Areas of the land covers	Measured (GIS)	medium
21	Elevations of the land covers	Measured (GIS)	medium
22	Distances to steam	Measured (GIS)	medium
23	Distances downstream	Measured (GIS)	medium
24	Changes in elevation to stream	Measured (GIS)	medium
25	Changes in elevation downstream	Measured (GIS)	medium
26	Snow melt rates and radiation coeff.	Estimated	high
27	Between ASA routing coeff. α, β	Estimated	low
28	River geometry	Measured/ Estimated	low
29	Priestley-Taylor Coefficients*[2]	Estimated	medium
30	Windspeed function*[2]	Estimated	low
31	Fieldcapacity and wilting point*[2]	Measured/ Estimated	medium

*[1] can be included in calibration procedure
*[2] are optional

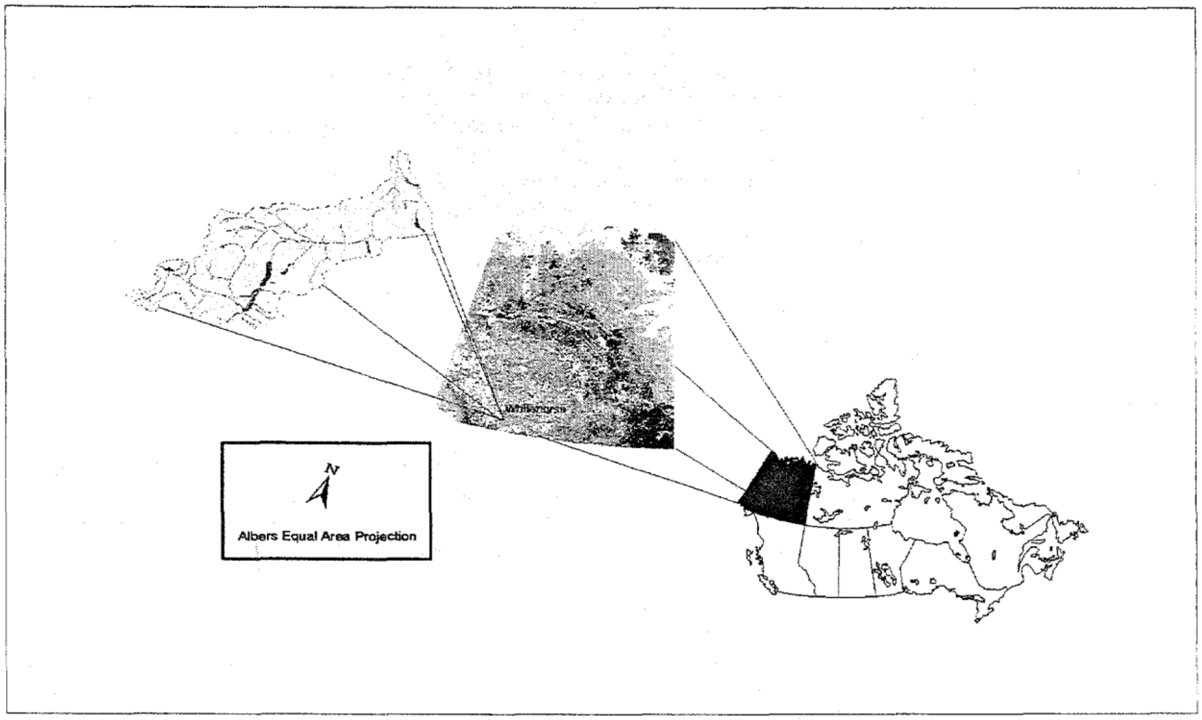


Figure 2. Location of Wolf Creek Basin, Yukon

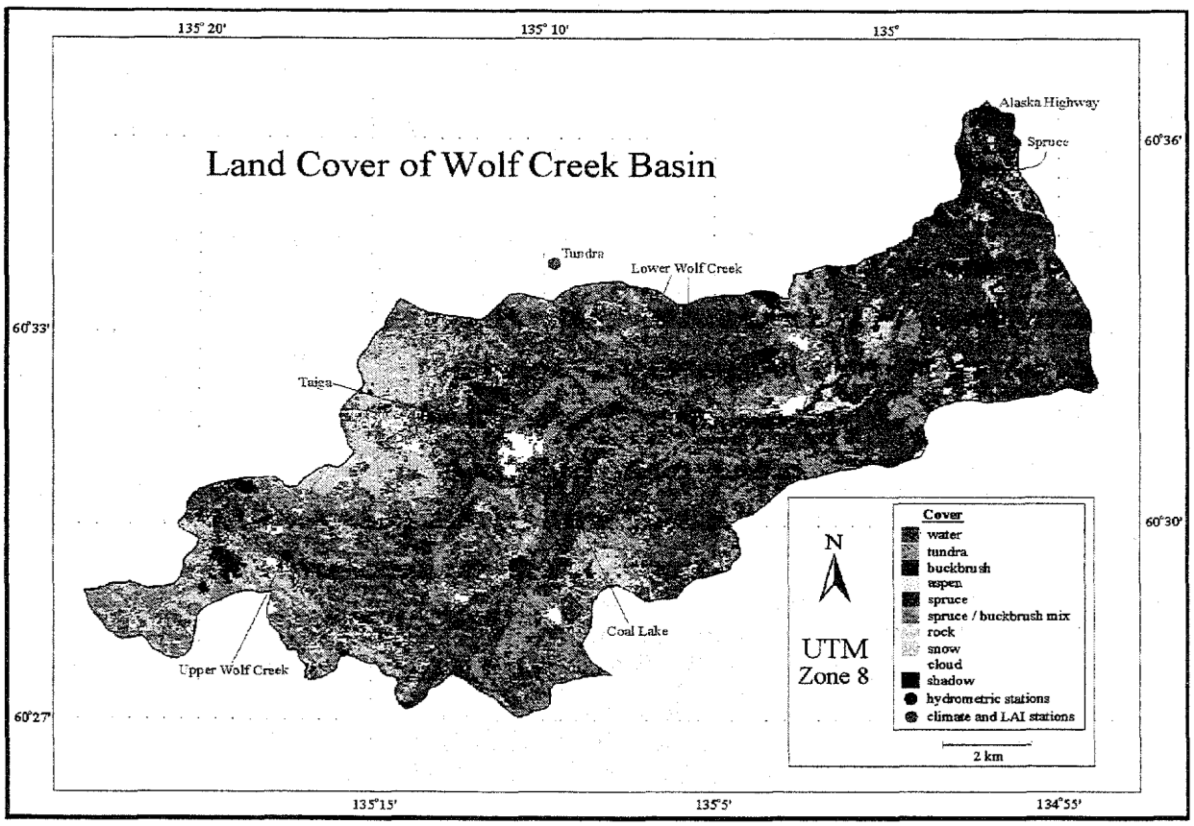


Figure 3. Land Cover of Wolf Creek Basin

wind speed, humidity, incoming and outgoing short-wave radiation, net radiation, barometric pressure, snow depth, blowing snow transport, soil temperature and soil heat flux. Twenty-five point snow courses were sampled monthly throughout the winter at the three meteorological station sites to provide snow density measurements.

The first hydrometric station was established in the spring of 1993 at the Wolf Creek basin outlet into the Yukon River (Figure 2). Its drainage area covers the whole basin area (220 km^2). Two additional hydrometric stations were established in the summer of 1994 at the outlet of Coal Lake and the mouth of North Fork Creek, respectively. The Coal Lake station has a drainage area of approximately 95 km^2 and is largely controlled by Coal Lake while North Fork Creek has an approximate drainage area of 25 km^2 and contains no surface water storage.

APPLICATION OF SLURP TO THE WOLF CREEK BASIN

Data Analysis and Pre-processing

Time series of climate data in Atmospheric Environmental Service (AES) standard format required for SLURP include precipitation, air temperature, dewpoint temperature, and net radiation. Related available data from three above-mentioned meteorological stations are half-hourly measured air temperature, net radiation, relative humidity, snow depth and tipping bucket readings. Both air temperature and net radiation can be directly converted into daily data in AES format.

Dewpoint temperature was derived from air temperature and relative humidity. For both over water (when air temperature is greater than 0 °C) and over ice (when air temperature is not greater than 0 °C) conversions, vapour pressure was first computed from air temperature and relative humidity. Dewpoint temperature was then calculated from vapour pressure. A final check made sure that dewpoint temperature doesn't exceed air temperature.

There were no winter precipitation measurements within the basin, therefore, more effort was needed to prepare precipitation data from snow depth and tipping bucket readings, and monthly-measured snow densities, each of which was averaged from 25 measurements at three snow courses nearby the three meteorological stations. Figure 4 shows a flow diagram of converting snow data and tipping bucket readings into precipitation time series. In winter months or when air temperature was below 0, all tipping bucket readings were regarded as 0. A positive increment of snow depth in a daily time-step multiplied by the mean snow density calculated from 25 measurements within that month gives snow water equivalent (SWE). For summer months (July, August and most of June & September) all snow depth readings were regarded as 0. The precipitation time series were then generated by adding both SWE (for winter months) and tipping bucket readings (for summer months) and were all converted to AES standard format.

Daily mean areal precipitation, air temperature, dewpoint temperature and net radiation data for the period September 1, 1994, to August 31, 1996, were computed for each ASA using Thiessen polygons. Daily maximum evapotranspiration rates were computed for each ASA with the CRAE model (Morton, 1983) using measured screen air temperature and net radiation, and dewpoint temperature. Daily streamflows at the three hydrometric stations were obtained for the same period from Indian and Northern Affairs Canada at Whitehorse.

Simulation Results

In this application, the Wolf Creek Basin was divided into 19 sub-basins or ASAs based on the expected hydrological similarity. A GIS was used to extract the land cover data for the Wolf Creek Basin from a one-kilometre resolution NOAA AVHRR dataset covering western and northern Canada. The areas of each category within each ASA were measured using the area cross-tabulation functions within the GIS.

The hydrological model was applied to the 19×8 matrix of ASAs and land cover classes, calculating evapotranspiration and runoff from each land cover area within each ASA, converting to streamflow for each ASA and routing the flow down the stream network. The simulated streamflows were then compared to the observed

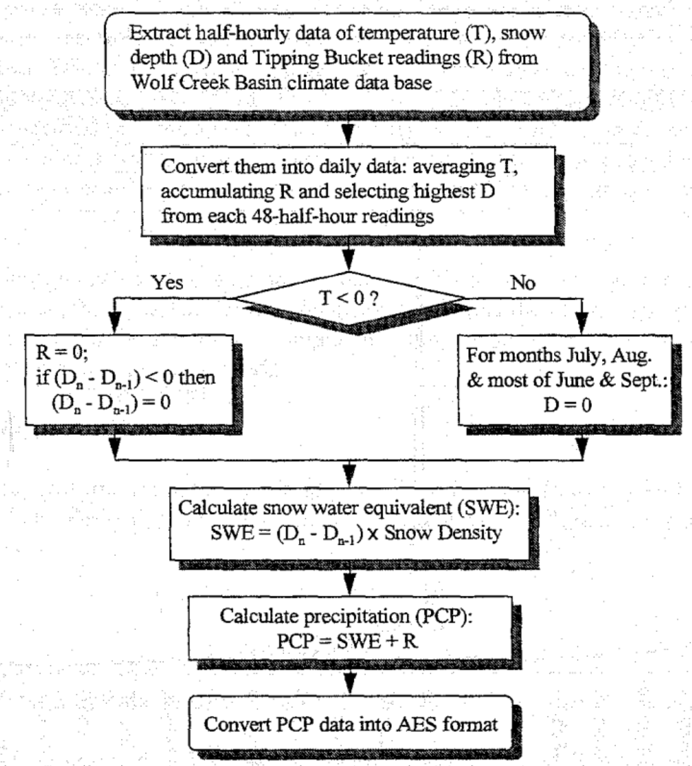


Figure 4. Procedure of converting snow data and tipping bucket readings into precipitation for SLURP model

streamflows and the parameters of the model were calibrated to provide the best least-squares fit. The model was calibrated for the Wolf Creek Basin for the period September 1, 1994 to August 31, 1995. During the calibration, parameters included in Table 2 were first manually estimated on the basis of experience in similar basins, then a built-in Shuffled Complex Evolution (SCE-UA) Global Optimization Method (Duan et al., 1994) was used. The model was verified by running it for the period September 1995 to August 1996 for which streamflow data were available.

Figure 5 compares the results of the SLURP simulation with the recorded flows at the outlet of Wolf Creek River, for both the calibration period and the verification period. The daily precipitation and temperature averaged over the last ASA where the basin outlet is located are also shown on the figure. The model simulates the recorded flows well for the calibration period, but not as good for the verification period. The model does not respond to the first peak of hydrograph in late April 1996. The flows for this spring event were estimated by Jasek and Ford (1997) and were caused by the failure of an ice dam (sending a significant flood wave downstream) in late April at the outlet of Coal Lake. The ice dam was created by unusually cold January of 1996 (Jasek and Ford, 1997).

Table 3 lists the statistics of model application for the total (calibration and verification) period. The commonly used Nash/Sutcliffe criterion has a value of 0.83 compared with a perfect fit value of 1.0 and the water volume over the 2 years is less than 6% in error.

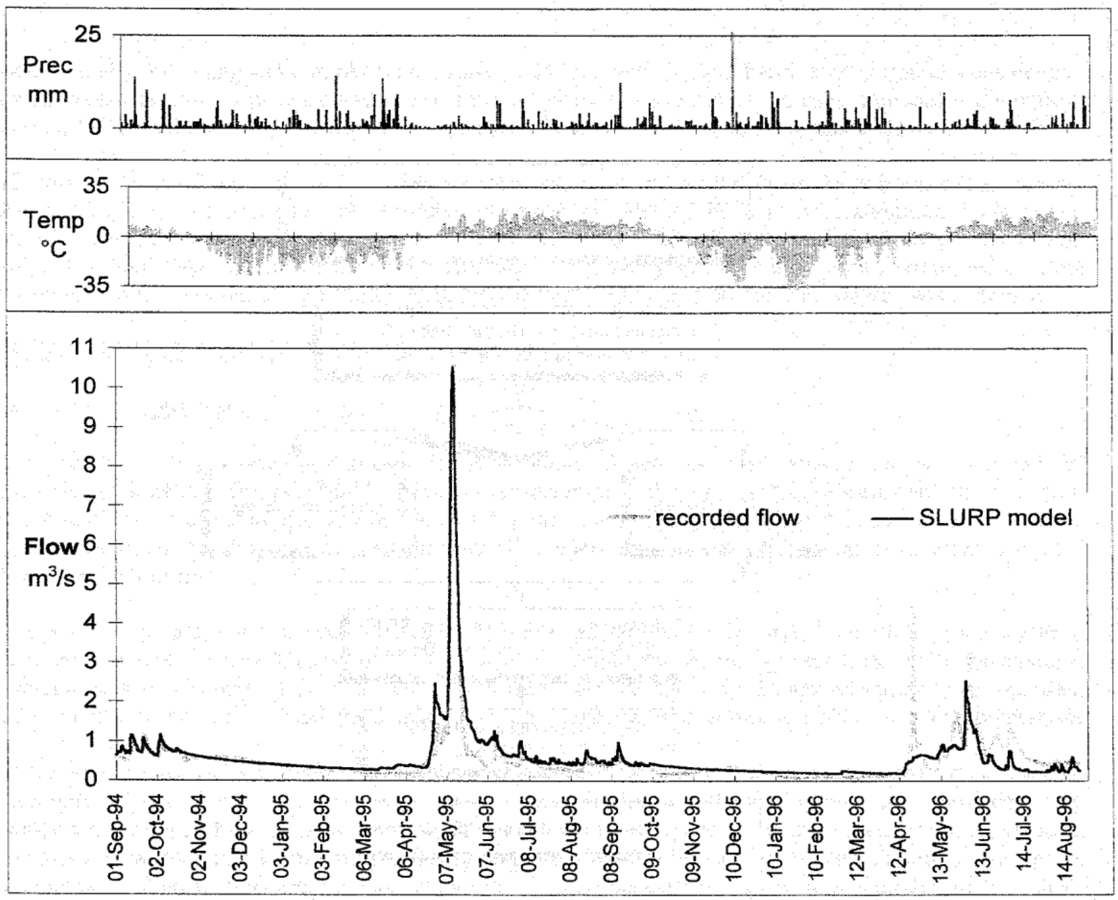
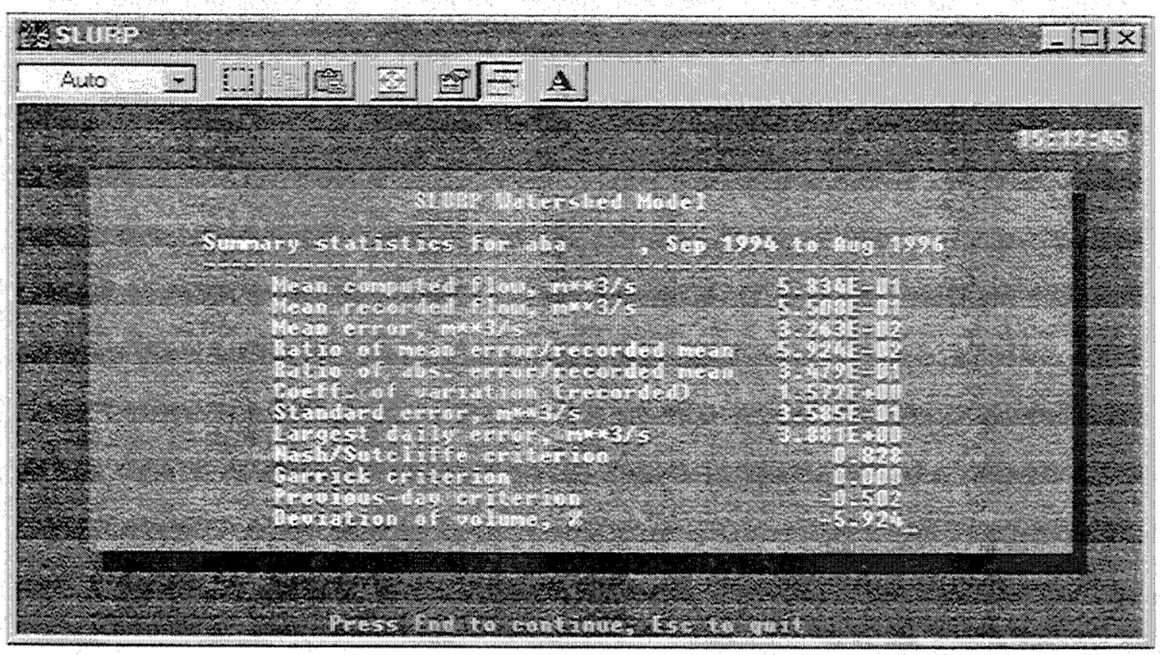


Figure 5. Application of SLURP Model for Wolf Creek Basin, September 1994-August 1996

Table 3. Statistics Summary of Application of SLURP Model for Wolf Creek Basin


SLURP Watershed Model

Summary statistics for aba , Sep 1994 to Aug 1996

Mean computed flow, m**3/s	5.834E-01
Mean recorded flow, m**3/s	5.508E-01
Mean error, m**3/s	3.263E-02
Ratio of mean error/recorded mean	5.924E-02
Ratio of abs. error/recorded mean	3.479E-01
Coeff. of variation (recorded)	1.572E+00
Standard error, m**3/s	3.585E-01
Largest daily error, m**3/s	3.881E+00
Nash/Sutcliffe criterion	0.828
Garrick criterion	0.000
Previous-day criterion	-0.502
Deviation of volume, %	-5.924

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CONCLUDING REMARKS

We have described a continuous simulation distributed hydrological model that includes canopy interception, evaporation, transpiration, snow accumulation and depletion, infiltration and percolation as well as runoff generation. The parameters for each of four storage reservoirs are related to land cover (vegetation type). The SLURP model was successfully calibrated and verified for the Wolf Creek Basin using recorded hydrometeorological data. Winter precipitation data, converted from snow data by using the described procedure, were used as one of the main distributed inputs to the hydrological model. The resulting hydrograph was found to compare well with the recorded streamflow for the calibration period. Simulation results, considering that this is a remote sub-arctic basin without winter precipitation data, are acceptable. The procedure of converting snow data into winter precipitation may provide an alternative solution for simulating ungauged (without winter precipitation measurements) basins.

For future research, more years of data are needed for this ongoing research to fully assess the accuracy of the model to simulate the north region sub-arctic streamflows. Climate data from nearby Whitehorse airport station, when available, may be used in the model for comparison study. Incorporation of NHRI's Blowing Snow Model (Pomeroy et al., 1993) with SLURP will be made.

ACKNOWLEDGMENTS

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