

Sub-grid runoff processes and hydrological modelling in the subarctic Canadian Shield

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Abstract This paper discusses the application of a semi-distributed physically based hydrological model to the 16 000 km² Yellowknife River basin. The model was calibrated, but attempts at validation failed. Errors in the vertical water budget and river routing portions of the model were not large enough to account for the differences between observed and modelled streamflow. Field studies suggest the model structure did not adequately simulate the effect of storage capacity differences between land cover types on the sub-grid transfer of runoff to the stream. Runoff is delayed or prevented from reaching higher order streams because of seasonal changes in hillslope and headwater lake storage capacities, while the model structure implies that any excess water from the hillslope vertical water budget is immediately transferred.

Key words Canadian Shield; SLURP model; Yellowknife; runoff generation; hydrological modelling; water balance

INTRODUCTION

A key problem in coupling atmospheric and hydrological models is accurately accounting for hydrological processes at the sub-grid scale. This is crucial in a heterogeneous landscape such as the subarctic Canadian Shield. Testing of models in conjunction with field programmes is vital to ensure that model structures represent crucial processes. The objective of this study was to identify hydrological processes important at the sub-grid scale in the subarctic Canadian Shield using both field investigations and hydrological models.

STUDY AREA

The Yellowknife River (Fig. 1) occupies a 16 000 km² basin draining south to Great Slave Lake. It lies within the Canadian Shield physiographic region where Precambrian bedrock is exposed or is at shallow depths from the surface. Irregular bedrock surfaces formed by glacial erosion result in surface water, accounting for 25% of the basin. Vegetation is dominantly open black spruce forest with tundra dominating the extreme northern reaches. The climate is characterized by a July daily average temperature of 16°C and a January daily average temperature of -29°C. The region averages about 280 mm of annual precipitation with approximately 55% of that falling as snow. Permafrost is widespread and discontinuous, varying with position on the landscape and soil type and depth.

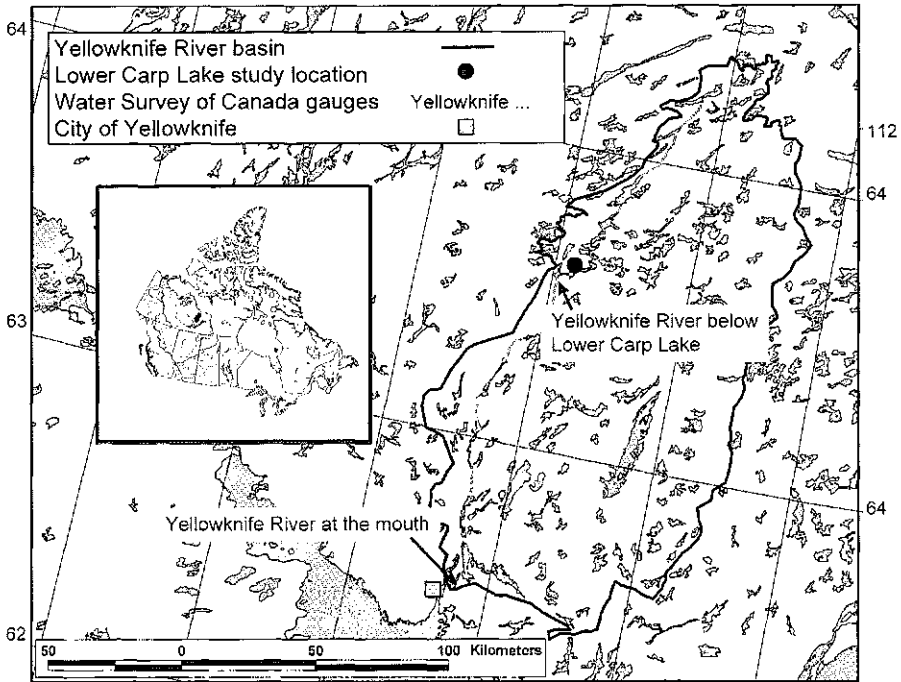


Fig. 1 Location of the Yellowknife River basin.

MODEL APPLICATIONS

The SLURP model is a conceptual semi-distributed hydrological model in which variables and parameters are related to land cover type. The structure and application methods are described in Kite (1995). The source of climate inputs was an Environment Canada climate station at the City of Yellowknife (Fig. 1). Topographic data were derived from Canadian National Topographic System 1:250 000 mapsheets. Land cover was derived from Landsat TM satellite imagery. Measured streamflow data were from Water Survey of Canada stations (Fig. 1). The results from the March 1995–October 1995 calibration run are shown in Table 1. The similarities between measured and computed streamflow were considered acceptable enough to proceed to a validation run which simulated streamflow from March 1996 to October 1996. The results (Table 1) were less accurate than the calibration.

Table 1 SLURP results for Yellowknife River at the mouth.

Specification and dates	Calibration: March–October 1995	Validation: March–October 1996
Mean computed streamflow ($\text{m}^3 \text{s}^{-1}$)	17.16	16.75
Mean measured streamflow ($\text{m}^3 \text{s}^{-1}$)	17.77	23.49
Mean error ($\text{m}^3 \text{s}^{-1}$)	-0.61	-6.73
Largest daily error ($\text{m}^3 \text{s}^{-1}$)	12.5	48.6
Nash-Sutcliffe criterion	0.509	-0.406
Deviation of volume (%)	3.4	28.664

FIELD STUDIES

To determine why there was such a large difference in the quality of the calibration and validation, an additional model run using the same parameters and variables was completed for March 1997–October 1997 to compare with field measured water budget and streamflow data from August 1997–October 1997. The field site was a headwater basin near Lower Carp Lake (Fig. 1). Field instrumentation is described in Spence (2000). Modelled river routing times of runoff event peaks between the Yellowknife River below Lower Carp Lake and at the mouth were compared to those measured at Water Survey of Canada hydrometric stations. Field water budget and river routing results (Table 2) suggest that the SLURP vertical water budget and river routing schemes produce acceptable results with errors that do not significantly account for the large inaccuracies in the validation streamflow estimates. The largest error must be in the to-stream routing schemes of the model.

Table 2 Water budget and river routing results for 1997.

	Measured	Computed
P (mm)	54	54
E (mm)	15	9
R (mm)	10	18
ΔS (mm)	27	27
Routing time (days)	22	17

SUB-GRID RUNOFF PROCESSES

The structure of the SLURP model uses aggregated simulation areas (ASAs) to subdivide basins. Figure 2(a) shows a typical Canadian Shield ASA with different land cover types, including a lake. Figure 2(b) shows how SLURP determines runoff volume from the ASA. Storage in each land cover type increases if precipitation (P_i) exceeds evapotranspiration (E_i). If the storage (S_i) exceeds the storage capacity (S_{ci}), runoff (R_i) occurs and is immediately routed to the ASA outlet. The ASA runoff volume is the sum of the runoff from individual land covers.

Spence (2000) found that the storage capacity of headwater lakes can dampen the volume and timing of hillslope runoff in Canadian Shield headwater basins. The hydrological connection between different landscape units in the Canadian Shield is controlled by saturation conditions (Bransfield & Roulet, 1998). Because SLURP assumes that landscape units are always connected, the poor modelling results support these field studies in suggesting that storage conditions and hydrological connections between land cover types influence runoff response in the Canadian Shield. River routing will also be influenced by storage conditions because high order streams in the Yellowknife basin contain many lakes. This suggests that the river routing schemes and the positive results in Table 2 may not hold for all situations. More flexible model schemes are needed to account for storage effects. In particular, a more appropriate to-stream routing scheme may be one where vertical water budget calculations are performed for each land cover type and runoff is routed to downslope land covers when storage capacities are met (Fig. 2(c)). This structure would have to include topological relationships in order to be effective.

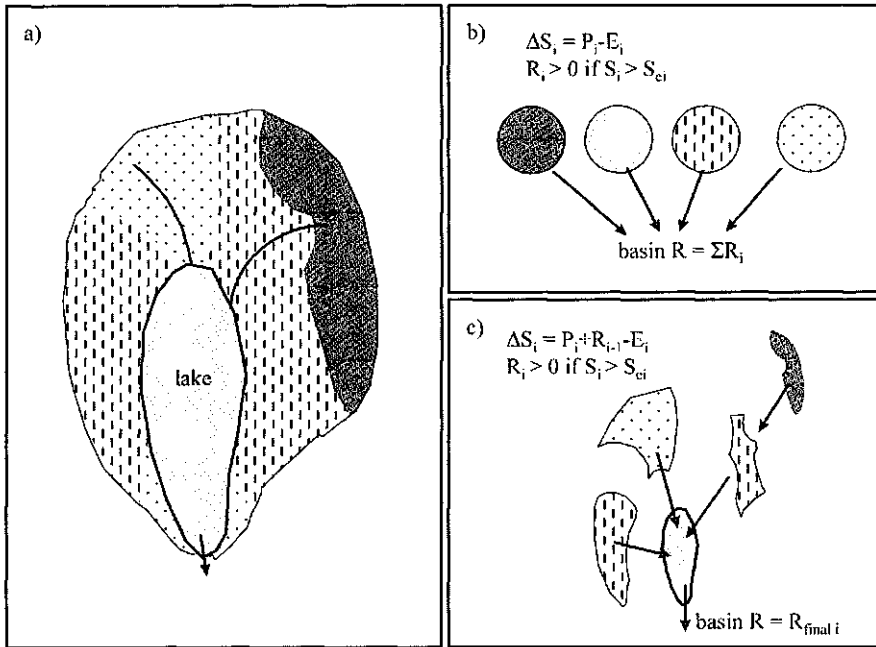


Fig. 2 Runoff in a Canadian Shield headwater basin as represented in SLURP and determined by field studies.

CONCLUSION

The differences illustrated in Fig. 2(b) and (c) show why response unit models may produce inaccurate results in the heterogeneous landscape of the subarctic Canadian Shield. Modelling exercises and field studies indicate that model errors are due to to-stream routing schemes that do not account for storage capacities that must be met in each landscape unit before runoff can be routed out of the basin. A method that includes topological relationships between land cover types is proposed as an alternative in modelling the hydrology of heterogeneous landscapes at the sub-grid scale.

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