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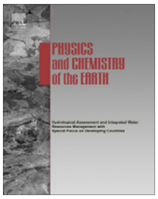

Regionalisation of land surface hydrological model parameters in subarctic and arctic environments

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ABSTRACT

The need for improved processes understanding to develop enhanced knowledge and modelling strategies is a central issue within the Prediction in Ungauged Basins (PUB) initiative. Prediction of snow-cover depletion and spring-melt runoff in arctic basins is particularly challenging due to the spatial heterogeneity of the snow-cover as a result of topographic and vegetation effects on snow accumulation, wind redistribution, and ablation processes. Additionally the remote location and winter inaccessibility of Arctic basins contribute to the lack of proper data to model the hydrology of these sites. This study was conducted in two topographically distinct cold regions research basins in the north-west of Canada characterised as tundra environments, one an alpine mountain tundra at 60°N and the other a rolling planar tundra at approximately 70°N.

This paper examines the transference of parameters of a distributed physically based land surface hydrological model from one site to another across 1350 km using a step-wise calibration procedure. The transference methodology uses a physiographic similarity criterion to identify similar landscapes units and makes use of landcover-based parameters rather than the usual relationships between parameters and basin characteristics.

Results showed that simulations using regionalised vegetation parameters performed better than those using default parameters and accurately described both snow-cover ablation and snowmelt runoff in both basins.

1. Introduction

One of the main challenges for the hydrological modelling community is to produce accurate and reliable predictions in ungauged or poorly-gauged basins. This issue had led to the IAHS initiative on Prediction in Ungauged Basins (PUB) (Sivapalan et al., 2003) which mainly focuses in the need of improved processes understanding as a framework to developed enhanced knowledge and modelling strategies.

Current debate is also centred on the difficulty of incorporating landscape heterogeneity and finding distributed information that can fulfill the requirements of distributed physically based models. These issues have forced hydrologists to conceptualise the physics of distributed models and seek effective parameter values typically at the catchment scale. As a result, hydrological models are usually calibrated against observed streamflow data (Klemeš, 1986). The importance of parameter calibration in regionalisation methods was stressed by Blöschl (2005) by showing that calibrated parameters were able to represent regional differences in the hydrological conditions and suggesting that is possible to derive regional relationships between calibrated parameters and basin attributes.

Alternative methods for parameter estimation such as regionalisation techniques or the transference of information from other basins or sources are needed where the lack of streamflow data does not allow for calibration of hydrological models. Regionalisation methods usually imply the transference of model parameters from a basin that is expected to behave similarly to the basin of interest. The similarity measure can be based on spatial proximity, basin attributes, or similarity indices Blöschl (2005). Typically, regionalisation techniques involve the definition of relationships based on regression methods between calibrated model parameters and basin attributes (Abdulla and Lettenmaier, 1997). The difficulty is that the relationships are likely to be weak due to parameter equifinality since many parameter sets might produce similar simulations. For example, Kuczera and Mroczkowiski (1998) suggested that the problem of parameter identifiability in

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conceptual catchment models due to the existence of multiple optima and high correlation amongst model parameters, makes the regionalisation of model parameters in ungauged basins virtually impossible.

Hydrological regionalisation studies have so far shown limited success and in general depend on the degree of similarity between the basins and on the type of the data used in the regional analysis (Littlewood, 2003). Fernandez et al. (2000) addressed this issue by performing a regional calibration approach where parameters were identified by both minimising model biases and maximising goodness of fit of relationships between parameters and basin characteristics. Regional calibration techniques were also performed by Hundecha and Bárdossy (2004) using a semi distributed conceptual model in 95 sub-basins of the Rhine basin where the coefficients of the relationships between basin attributes and parameters were calibrated rather than the model parameters, however, a limitation of these methods could be the large number of coefficients to be calibrated. Alternatively, Parajka et al. (2007) proposed an iterative regional calibration method as a solution to the dimensionality of the calibration problem where local information such as streamflow data was combined with regional information such as an a priori distribution of the model parameters from gauged basins in the area in one objective function. Götzinger and Bárdossy (2007) showed that regionalisation methods using conditions imposed on the parameters by basin characteristics in distributed conceptual models were the ones that performed best due to the reduction of parameter space. Merz and Blöschl (2004) after comparing several regionalisation methods in 308 Austrian basins found that methods based on spatial proximity performed better than regression methods based on basin attributes. Similarly Parajka et al. (2005) showed that both a kriging approach (i.e. based on spatial proximity) and a similarity approach had similar performance. Goswami et al. (2007) demonstrated that the regionalisation of rainfall-runoff model parameters which were calibrated against regional pooling of streamflow data of twelve basins in France was the one that performed best amongst three methods involving calibration, concluding that the assessment of regional homogeneity and analysis of data are very important for regionalisation approaches using calibration methods.

Arctic environments due to their remote location, inaccessibility, and importance of the winter processes (e.g. snow accumulation and redistribution) in the hydrological cycle, are generally poorly-gauged or ungauged (Pomeroy et al., 2005). Thus, improved regionalisation approaches in these environments are even more important for accurate predictions of snow-cover ablation and snowmelt runoff.

The objective of this paper is to evaluate the transference of landcover-based parameters of a distributed and physically based Land Surface Hydrological (LSH) model between two basins in northern cold regions. This approach is intended for use in distributed models where typical basin-wide regionalisation relationships are conceptually unsuitable due to scale issues. The study focuses on the application of detailed physically based process descriptions developed in cold region environments within modelling units which are delimited based on a basin-wide understanding of the responses of the main hydrological processes. This study extends from the Dornes et al. (in press-b) paper, where landscape-based snowmelt parameters were calibrated and validated in a subarctic basin to analyse the regional representativeness of these parameters.

2. Study area

The study area embraces two basins located in the north-west of Canada (Fig. 1). Granger Basin (GB) is a small sub-basin ($8\ \mathrm{km}^2$) of the Wolf Creek Research Basin located 8 km south of Whitehorse at 60°31′N, 135°07′W. It is in a subarctic mountainous environment in the southern part of Yukon. The landscape varies from sparsely-vegetated open tundra composed of grasses, mosses, and isolated short shrubs with exposed mineral soils in the high elevation areas, to shrub tundra vegetation characterized by tall shrubs (1–2.8 m) and soils capped with an organic layer in wet and lower elevation areas. Intermediate areas with better drainage such as the plateau area (PLT) have short shrubs (<1 m) whereas north facing (NF) and south facing (SF) slopes are covered by shrubs of intermediate height (0.5–1.5 m). Elevation ranges from 1310 to 2035 m.a.s.l. and the basin is underlain by discontinuous permafrost which is mainly located at higher elevations and on the NF slope.

The second basin is Trail Valley Creek (TVC) Research Basin. TVC is an arctic basin with an area of $63\ \mathrm{km}^2$ and lies approximately 55 km north-east of Inuvik in the Northwest Territories at 68°45′N, 133°30′W. The area has a low relief characterized by gently rolling hills with some deeply incised river valleys. The landscape is dominated by open tundra in the upland areas, whereas shrub tundra is along streams, lake edges, and river valleys, as well as some upland areas. Elevation ranges from 40 to 187 m.a.s.l. and the basin is underlain by continuous permafrost.

Despite topographic differences, both basins experience extensive wind redistribution of snow (Pomeroy et al., 1997, 2004; Essery et al., 1999; Essery and Pomeroy, 2004a; Pohl et al., 2005b; McCartney et al., 2006). There are common features in both basins, including open tundra areas that act as source of blowing snow, whereas shrubs behave as sinks or snow traps that result in the formation of characteristic snow drifts in the direction of the prevailing winds that play a significant role in the timing (i.e. lengthering) of the snowmelt runoff. Both basins also show a similar snowmelt pattern, with higher snowmelt rates on the SF slopes than in the NF slopes due to the increased incident solar radiation whereas observations of the streamflow show that peak flows are due to snowmelt, and the timing of the peak is associated with the timing of the snowmelt in the shrub tundra vegetation zone, while the duration of the peak is associated with the duration of the snowmelt on the NF slopes and high elevation zones.

3. Methodology

3.1. Model descriptions

Two models were used in this study. The Canadian Land Surface Scheme (CLASS) version 3.3 introduced by Verseghy (1991) and Verseghy et al. (1993) was applied in GB to simulate snow-cover depletion, whereas the MESH model was used to simulate both snow-cover depletion and snowmelt runoff in TVC basin. As part of the MEC (Modélisation Environmentale Communautaire) system developed by Environment Canada (Pietroniro et al., 2007), MESH (MEC – Surface and Hydrology) is a stand-alone LSH model configuration that couples CLASS (version 3.3) with hydrological routing schemes (Kouwen et al., 1993; Soulis et al., 2000, 2005). Pre-processing corrections for slope and aspect effects on the incoming short wave radiation were performed using the Cold Regions Hydrological Model (CRHM) (Pomeroy et al., 2007; Dornes et al., in press-a).

The spatial discretisation is based on the Group Response Unit (GRU) approach (Kouwen et al., 1993) where a parameter set is identified for each landscape class. The definition of the GRU can vary and it is left to the hydrologist to define "*a priori*". The concept relies on our hydrological understanding of the region and requires that similar areas in the model domain share the same parameterisation. In this mosaic approach, the land surface scheme (LSS) is

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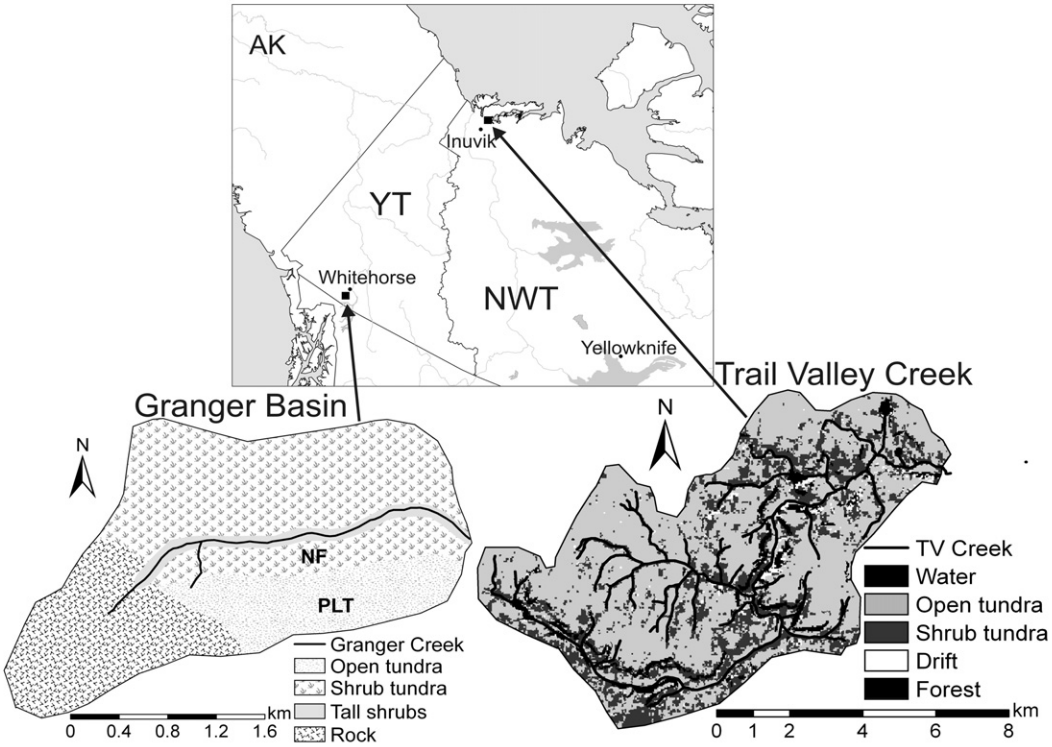

Fig. 1. Location of the study basins in Canada. Granger Basin: schematic landcover representation. PLT: plateau area. NF: North facing slope. Trail Valley Creek: landcover-based on Thematic Mapper satellite image (adapted from Pomeroy et al., 1997).

run on each land-cover type tile, then the fluxes and state variables from all the tiles are averaged over a grid cell, and finally water is routed between the cells and the river network.

3.2. Landscape heterogeneity and observations

The spatial model representation was based on an understanding of main processes and factors that control snowmelt in cold regions (Marsh and Pomeroy, 1996; Pomeroy et al., 2003). Several years of field observations in both basins allowed for the identification of the importance of both the specific characteristics (e.g. vegetation type, exposure) and the location of the landscape units as key factors to describe snow accumulation processes and energy and mass balance calculations. The importance of snow accumulation and posterior snow redistribution by wind was stressed by Pomeroy et al. (1997), and Essery and Pomeroy (2004a). Effects of slope and aspect during the snowmelt energy balance were analysed by Pomeroy et al. (2003) and Pohl et al. (2005a) and Pohl et al. (2006) to show that topography strongly affects the energetics and rates of snow ablation, whereas their consequences in modelling snowmelt was shown by Pohl et al. (2005b), Davison et al. (2006), Pohl and Marsh (2006) and Dornes et al. (in press-b). McCartney et al. (2006) studied vegetation effects on hydrology and reported that tall shrubs play a key role in both snow accumulation and in the streamflow regime. Pomeroy et al. (2006) showed the importance of shrub exposure in governing snow melt energy by enhancing melt energy due to greater long-wave and sensible heat fluxes to snow whereas Bewley et al. (2007) studied the effects of the shrub canopy in the extinction of the solar radiation and their effects on snowmelt. Therefore, five main landscape units were identified in GB according to vegetation and exposure criteria: Upper Basin, PLT, NF, SF, and Valley Bottom. Estimation of SWE values in each of those landscape units were obtained from snow survey transects where measurements of snow depth and snow density were performed every 5 and 10 m, respectively. Length of the transects varied as a function of the landscape heterogeneity, resulting in approximately 50 and 25 measurement points in the UB, and the PLT area, whereas 20, and 6 points were measured in the NF and SF slopes, and the VB, respectively. For each of those, independent CLASS runs were performed in a point mode (Dornes et al., in press-b). In this study, simulations of snowcover ablation in the PLT and NF were selected. In TVC basin following Pohl et al. (2005b), four landscapes types were identified as the spatial model representation in MESH using a 1 km by 1 km model grid size. The dominant types are open tundra and shrub tundra covering 75% and 22% of the basin area, respectively. Black spruce forest and water cover 2% and 1% of the basin area, respectively.

Forcing data were obtained from meteorological observations in both basins. Thus, half hourly observations of incoming short and long wave radiation, precipitation, temperature, specific humidity, barometric pressure, and wind speed were used to force the models. Simulations were performed during the snowmelt periods of 2002–2004 (20 April–15 June) in GB, whereas in TVC basin model runs were performed in the snowmelt seasons of 1996 and 1999 (1 May–30 June), respectively. Given the lack of observations of incoming long wave radiation in TVC, the same forcing data used by Pohl et al. (2005b) and Pohl and Marsh (2006) were applied. Therefore, outputs from the numerical weather model (GEM, Global Environmental Multiescale) model of Environment Canada were used in 1996, whereas calculated empirical values with the Satterlund (1974) equation that were found to match fairly closely the GEM outputs, were used in the 1999 snowmelt season.

Simulations of snow-cover depletion were contrasted to the observed basin average snow covered area (SCA) in TVC. Observed values were determined from SPOT satellite images by aggregating the 20 m resolution images to 1 km grid squares corresponding to the model grid. Six images were obtained during the snowmelt

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period of 1996 (23 May, 25 May, 28 May, 1 June, 5 June, and 8 June) (Neumann and Marsh, 1998), whereas three SPOT images (23 May, 28 May, and 10 June) were used in the 1999 snowmelt seasons (Pohl and Marsh, 2006). Hourly streamflow records obtained from Water Survey Canada at the basin outlet were used to evaluate the MESH predictions of the spring runoff in TVC.

3.3. Modelling strategy

The modelling framework used to transfer the physically based model parameters from GB to TVC basin consisted of three steps (Fig. 2); the first two were applied in Dornes et al. (in press-b): (1) run CRHM in GB in order to correct the observed incoming short wave radiation (K_{obs}) due to slope and aspect effects. This was accomplished in the GLOBAL and the SLOPE modules using theoretical formulations based on those proposed by Garnier and Ohmura (1970) and a cloudiness index calculated from the relation between the K_{obs} and the estimated theoretical radiation on the horizontal surface (K_{theo}); (2) run CLASS in a point model in each landscape unit of GB to simulate snow-cover ablation using the corrected incoming short wave radiation (K_{cor}) calculated with CRHM along with the rest of the meteorological observations; and (3) run MESH in TVC basin using the vegetation parameters determined in point 2 to simulate both depletion of the snow covered area and snowmelt runoff.

3.4. Regionalisation strategy

The regionalisation strategy used to transfer the parameters from CLASS to the LSH model (MESH) was based on the understanding of the main factors that control snow-cover ablation and runoff. The transference of the parameters was derived from a landcover (i.e. vegetation cover) similarity criterion, therefore parameters from the PLT and NF slope landscape units of GB were transferred to the MESH model in TVC basin in order to represent the most similar and dominant landscape units (i.e. open tundra and shrub tundra). The parameterisation of the forest area in TVC was not included in the regionalisation due to both its low coverage (2%) and the lack of a forested area in GB. Forest parameter values were set according to Davison et al. (2006). Thus, this approach included the transference of the CLASS parameters that govern snowmelt which were obtained through calibration and taking into account the redistribution of the winter snow-pack prior to melt (i.e. using distributed observations of SWE) and topographic effects on the incoming solar radiation (see Fig. 2).

The selection of this regionalisation strategy was based on the data availability and the understanding of the underlying hydrological processes in the basin. Snowmelt parameters were calibrated in GB where distributed observations of snow-cover ablation were available and tested in TVC basin using remotely sensed data of snow-cover depletion. The regionalisation involved the transference of all the CLASS (landcover-based) parameters, except the snow-cover depletion curve (SDC) parameter. The decision to exclude the SDC parameter from regionalisation was based on the differences between the theoretical considerations of the evolution of the SCA during melt (Pomeroy et al., 1998, 2004; Essery and Pomeroy, 2004b) and the topographic differences (i.e. exposure) between GB and TVC that influence the snow redistribution. The snow-pack ablation in the model is conceptualised by assuming a continuous snow-cover until a given snow depth (D_{100}) is reached. A straight line is then used to simulate the changing in SCA with time (Donald et al., 1995) and thus relate snow depth to SCA. Although the D_{100} is a landcover-based parameter it involves both vegetation cover and surface roughness characteristics, therefore it is strongly affected by snow redistribution by wind and topography influences such as slope, aspect, and micro-relief that affect both snow accumulation and energetics. Daily observations of snow-cover depletion (i.e. snow depth and density) measured over a snow transect every 5 m in GB indicate instability in the D_{100} value. For example, a complete snow-cover was observed until a snow depth of 44 cm was reached at the PLT in 2003, whereas the NF showed D_{100} values of 69, 55, 69 cm for the 2002–2004 snowmelt seasons. In the shrub tundra area of TVC, on the other hand a lower value (29 cm) was measured in 1996 presumably due to a larger survey scale (10 m). Sensitivity analysis of the D_{100} parameter showed an effect only in the early stages of melt, resulting in a delay or acceleration of the beginning of melt for lower and higher D_{100} values, respectively. Similarly, the variability of D_{100} affected the estimation of the early streamflow peak. These results agreed with the findings of Pohl et al. (2005b). As a result of

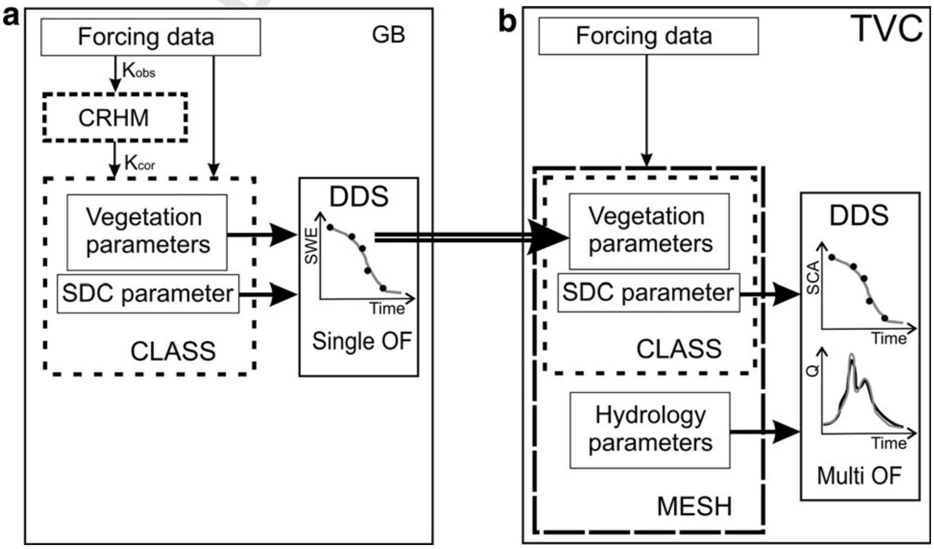

Fig. 2. Outline of the coupled modelling and regionalisation (double line arrow) frameworks. (a) Granger Basin (GB), (b) Trail Valley Creek Basin (TVC). CRHM: Cold Regions Hydrological Model, CLASS: Canadian Land Surface Scheme, MESH: Modélisation Environmentale – Surface and Hydrology, DDS: Dynamically Dimensioned Search optimization algorithm, K_{obs} and K_{cor}: observed and corrected incoming short wave radiation (W m^{-2}), SWE: snow water equivalent, SCA: snow covered area, Q: streamflow discharges SDD: snow depletion curve, and OF: objective function.

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these uncertainties and mainly due to the difficulty to derive a value from observations, the SDC parameter was not transferred and calibrated in TVC instead.

3.5. Model calibration

Calibration was performed using the Dynamically Dimensioned Search (DDS) global optimization algorithm (Tolson and Shoemaker, 2007). A two step-wise calibration procedure was applied: (1) the CLASS (i.e. vegetation and D_{100}) parameters that control snow-cover ablation (Table 1) in GB were estimated using a single objective function, the root mean square error (RMSE) with respect to the observations of snow water equivalent (SWE) (see Dornes et al., in press-b), and (2) MESH was calibrated in TVC on the D_{100} and hydrological parameters (Table 2) that conceptualise tile flow (i.e. overland and interflow) and streamflow, whereas the vegetation parameters that govern snowmelt were set according to the values obtained in GB in step 1 (see Fig. 2).

Simulations of snow-cover ablation in GB were calibrated in 2003 and validated in 2002 and 2004 in those landscapes where observations were available, whereas in TVC simulations of both SCA and basin streamflow were calibrated and validated in 1996 and 1999, respectively.

Effective parameter sets for GB were obtained after performing 500 independent model simulations using the DDS algorithm on the PLT and NF slope landscape units. After 100 model simulations DDS was generally able to find good solutions. Since the computational time was not a limitation (~20 s), the number of simulations was increased to 500 to ensure that the best DDS derived parameter set better approximated the global minimum with respect to the objective function value.

Calibration of the MESH model in TVC was formulated using a multi-objective function (E_{agr}), which aggregates the Nash Sutcliffe efficiency coefficient, (E; Nash and Sutcliffe, 1970) of the simulations SCA and basin streamflow:

$$E_{agr} = w_1 \cdot \left[1 - \frac{\sum_{i=1}^{n}(S_{sca} - O_{sca})^2}{\sum_{i=1}^{n}(O_{sca} - \bar{O}_{sca})^2}\right] + w_2 \cdot \left[1 - \frac{\sum_{i=1}^{n}(S_{Q} - O_{Q})^2}{\sum_{i=1}^{n}(O_{Q} - \bar{O}_{Q})^2}\right] \qquad (1)$$

where S_{SCA} and O_{SCA} are the simulated and observed basin average snow covered area, S_Q and O_Q are the simulated and observed basin streamflow, n is the number of samples evaluated, and w_1 and w_2 are the weights used to reflect the relative priorities of each variable given to certain objectives. In this case they were set to 0.20 and 0.80, respectively.

Effective parameter sets (i.e. hydrology and D_{100}) in TVC, were identified after performing 500 simulations using DDS (Table 2).

Table 1
Optimised snowmelt parameter values for the open tundra (PLT, plateau area) and shrub tundra (NF, north facing slope) landscape units in Granger Basin

Parameter	PLT	NF
	Open tundra	Shrub tundra
Maximum LAI (LAMX)	0.53 (0.5, 2)	2.81 (2, 3)
Minimum LAI (LAMN)	0.28 (0.5, 3)	0.99 (0.4, 1)
LN roughness length (LNZ0) [m]	−4.09 (−4.8, −3.5)	−2.42 (−3.7, −1.8)
Visible albedo (ALVC)	0.183 (0.02, 0.2)	0.087 (0.03, 0.2)
Near-infrared albedo (ALIC)	0.424 (0.2, 0.4)	0.464 (0.3, 0.5)
Biomass Den. (CMAS) [kg m^{-2}]	0.11 (0.05, 0.35)	6.13 (6, 10)
Min. stomatal resist. (RSMN)	251.5 (50, 300)	51.9 (50, 300)
Coef. stomata resp. to light (QA50) [W m^{-2}]	46.1 (20, 60)	21.1 (20, 60)
Coef. stomatal resist. to VP deficit (VPDA)	1.31 (0.2, 1.5)	1.08 (0.2, 1.5)
Coef. stomatal resist. to VP deficit (VPDB)	0.61 (0.2, 1.5)	0.93 (0.2, 1.5)
Coef. stomatal resist. to soil WS (PSGA)	146.7 (50, 150)	93.5 (50, 150)
Coef. stomatal resist. to soil WS (PSGB)	4.92 (1-10)	1.09 (1-10)
Lower snow depth limit for 100% SCA (D_{100}) [m]	0.42 (0.05-0.5)	0.81 (0.05-1)

Adapted from Dornes et al. (in press-b). Values between parentheses indicate the lower and upper parameter bound, respectively.

Table 2
Optimised parameter values using a multi-objective approach in trail valley creek

Parameter	GRU		River network
	Open tundra	Shrub tundra	
Lower snow depth limit for 100% SCA (D_{100}) [m]	0.121 (0.05, 0.4)	0.111 (0.05, 0.4)	
Drainage density (DD) [m m^2]	4.725 (1, 5)	3.177 (1, 5)	
Effective slope (XSLP)	0.094 (0.01, 0.1)	0.061 (0.01, 0.1)	
Coef. of k_{sat} change in the first meter of soil (GRKF)	0.879 (0.01, 1)	0.946 (0.01, 1)	
Manning roughness (n)	0.073 (0.025, 0.1)	0.063 (0.025, 0.1)	
Surface sat. hydraulic conductivity (WFCI) [m s^{-1}]	8.9E^{-6} (1.0E^{-9}, 1.0E^{-5})	4.3E^{-6} (1.0E^{-9}, 1.0E^{-5})	
River roughness (wf_r2)			0.168 (0.1, 0.95)
Lower limit ponding water (ZPLIMS) [m]			0.052 (0.02, 0.15)
Upper limit ponding water (ZPLIMG) [m]			0.081 (0.02, 0.15)

GRU: group response unit (model tile). Parentheses indicate parameter bounds.

4. Results and discussions

Independent simulations of CLASS in a point mode in each landscape unit of GB showed reasonable descriptions of the snow-cover ablation with E values that ranged from 0.70 to 0.98 for both the calibration and validation periods (Dornes et al., in press-b). Fig. 3 displays the comparisons between calibrated and validated SWE simulations of CLASS using the calibrated and the default parameter sets in the landscape units of GB (i.e. NF and PLT) used to regionalise the parameter sets. The default parameters are the standard values, set according to the literature for the open tundra and shrub tundra, used in the numerical weather predictions of the GEM model. Fig. 3a and b shows the simulations corresponding to calibration period (2003) whereas the validation were conducted in 2002 and 2003 where additional snow survey data were available (Fig. 3c–e).Overall, a good agreement between simulated values using calibrated and default parameters was observed in the NF, however, in the PLT when the default parameters were used; underestimation of the observed melt drastically degraded the model performance (Table 3). This discrepancy was not unexpected, since the parameterisation of the operational GEM model assumes uniform land-cover for each GRU (i.e. landscape unit) and the same SDC is used in both cases. In this parameterisation dissimilar melt rates such as in the PLT were poorly described. On the other hand, more homogenous melt on the NF due to the coincidence of high SWE and lower incoming solar radiation were adequately described.

In contrast, SWE simulations using calibrated parameters with parameters ranges defined according to local observations such

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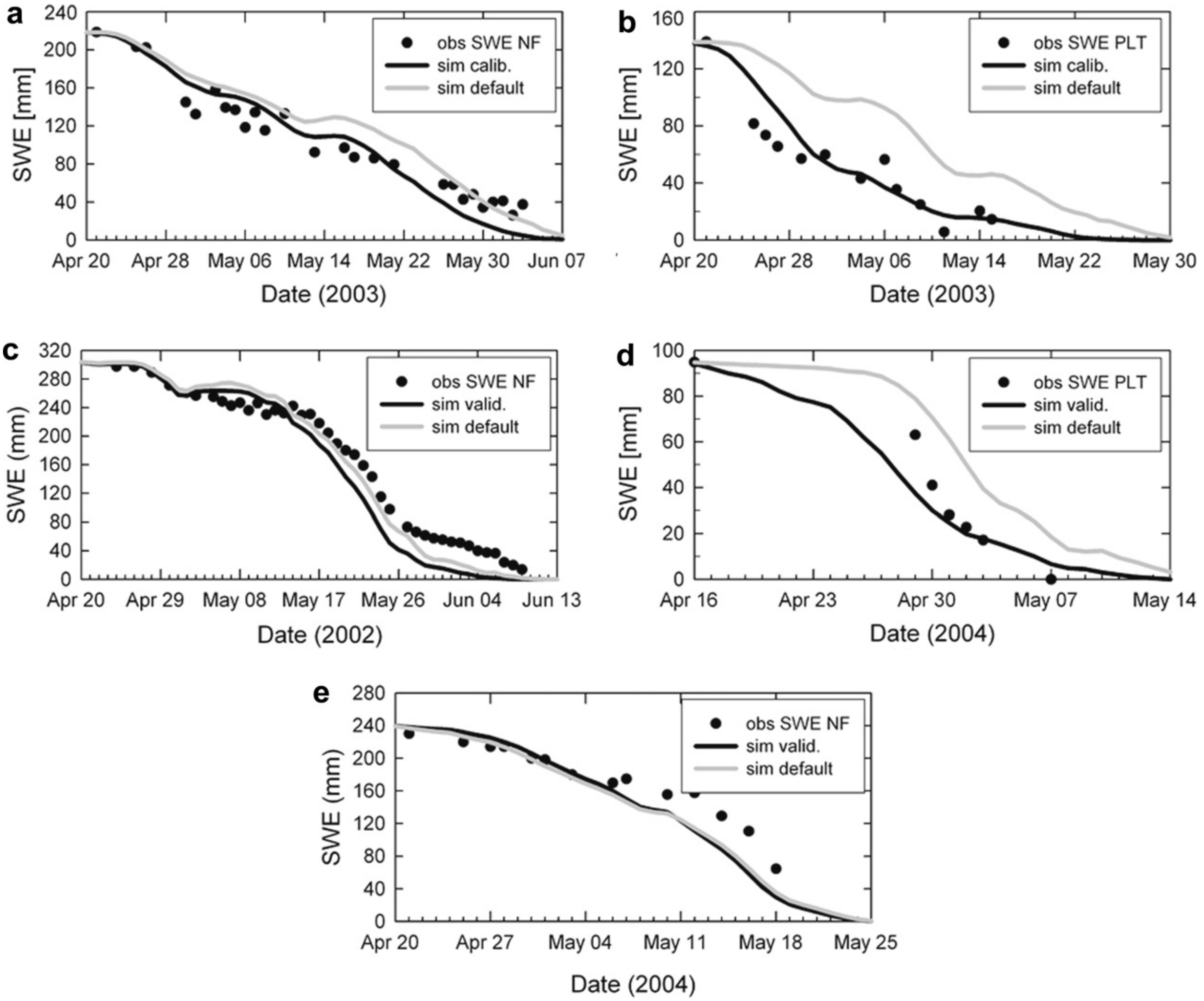

Fig. 3. Observed and simulated areal snow water equivalent (SWE) values using calibrated and default parameters in the North facing slope (NF) and Plateau area (PLT) of Granger Basin. (a) 2003 NF calibration, (b) 2003 PLT calibration, (c) 2002 NF validation, (d) 2004 PLT validation, and (e) 2004 NF validation.

Table 3
Comparison of model performances (E; Nash Sutcliffe coefficient) in the PLT and NF landscape units of granger basin (GB), and in trail valley creek (TVC)

Simulated variable	GB				TVC		
	NF		PLT		Calib.	Regional.	Default
	Calib.	Default	Calib.	Default			
SWE cal. 2003	0.87	0.85	0.80	−0.76			
SWE val. 2002	0.92	0.95					
SWE val. 2004	0.72	0.72	0.86	0.37			
SCA cal. 1996					0.98	0.96	0.65
SCA val. 1999					0.28	0.63	0.32
Q cal. 1996					0.94	0.83	0.52
Q val. 1999					0.81	0.67	0.47

Calib.: simulations obtained calibrating all the parameters, Regional.: simulations using regionalised vegetation parameters, Default: simulations using default vegetation parameters. SWE: snow water equivalent, SCA: basin average snow covered area, and Q: streamflow. Cal. and val. correspond to calibration and validation periods, respectively.

as density and height of the vegetation were able to properly describe the observed values with E values of 0.87 and 0.76 for the NF and PLT landscape units, respectively, whereas reasonable model performances for the validation period with E values between 0.92 and 0.72 (Table 3) corroborated the representativeness of the effective parameter sets used to simulate snow-cover ablation in the NF and PLT of GB.

Regional transference of the snowmelt (i.e. vegetation) parameters from GB to TVC basin was evaluated in Figs. 4 and 5 and Table 3 where remotely sensed SCA and observed streamflow were compared to MESH simulations using both the regionalised and the default vegetation parameters. In both cases, a multi-objective calibration was performed on the SDC and hydrological parameters. In order to evaluate the incidence of the vegetation parameters on the results, simulations using the regionalised parameters were compared with those obtained through the calibration of all the model parameters (i.e. vegetation, SDC, and hydrology parameters). Results showed the model ability to capture the variability

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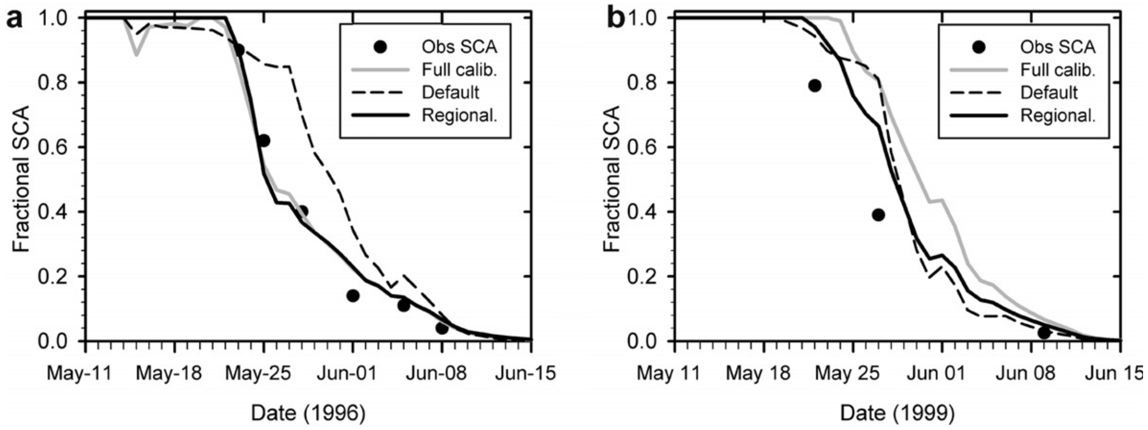

Fig. 4. Observed and simulated basin average snow covered area (SCA) in TVC using regionalised parameters from GB and default parameters. (a) 1996 calibration period, and (b) 1999 validation period.

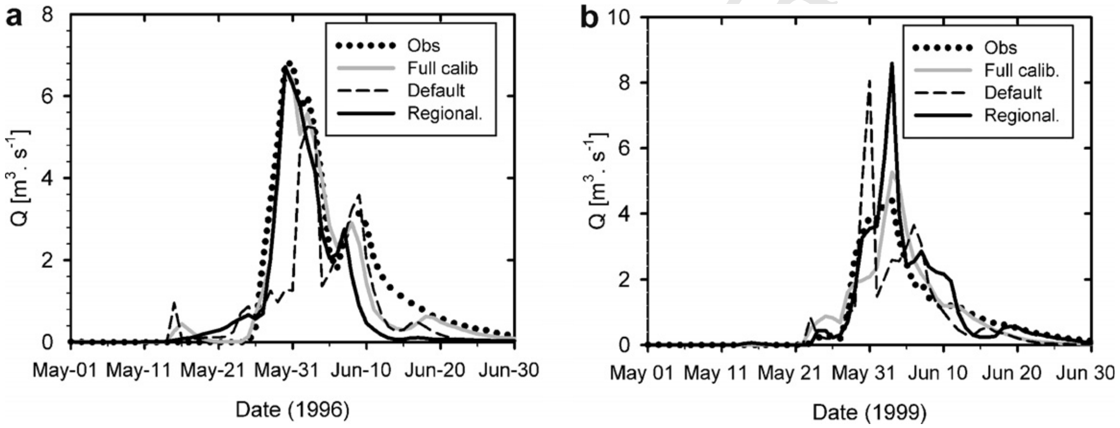

Fig. 5. Observed and simulated streamflow in TVC using regionalised parameters from GB and default parameters. (a) 1996 calibration period, and (b) 1999 validation period.

of both the snow-cover depletion and basin runoff using a multi-objective calibration approach. Simulations of snow-cover ablation for the calibration period in 1996 (Fig. 4a) with the regionalised parameters gave a very accurate description of the SCA with a *E* value of 0.96 whereas the simulated ablation with the default vegetation parameters underestimated the snow free area during most of the melt season, degrading the model performance to 0.65. Similarly, for the validation period in 1999 (Fig. 4b) the snow ablation using the regionalised parameters was reasonably well described. However, due to the model overestimation of the SCA early in melt season, the model efficiency decreased to a *E* value of 0.63. Validated results with the default parameters showed similar snow-cover decay with larger differences early in the melt season that reduced the model performance. These early melt discrepancies indicate that the assumption of a uniform end-of-winter snow-cover without considering redistribution of the snow by wind can lead to considerable errors in the predicted SCA, resulting in inaccurate surface energy fluxes for open arctic environments. This agrees with the findings of Déry et al. (2004), Pohl and Marsh (2006) where it was suggested that both snow-cover and snowmelt energy heterogeneity be incorporated to properly simulate snow-cover depletion and energy fluxes. The fully calibrated simulation showed a slightly better description of the snow-cover ablation in 1996 than the simulation using the regionalised parameters, whereas a less accurate simulation was seen for the validation period in 1999.

Fig. 5a displays the observed and simulated basin streamflow in TVC for the calibration period in 1996. Overall, simulations using the regionalised parameters showed an accurate description of the observed hydrograph with a *E* value of 0.83. Despite some small differences early in melt season, the timing of the rising and falling limbs, time-to-peak, and the magnitude of the peak were accurately described. However, a faster recession limb than in the observed hydrograph was seen in the simulated streamflow. In contrast, when default vegetation parameters were used the simulations did not capture the dynamics of the observed streamflow which dropped the model efficiency to a *E* value of 0.52. Validated results in 1999 (Fig. 5b) using the regionally transferred parameter set showed a reasonable overall description of the observed hydrograph in terms of the timing, reflecting a satisfactory snowmelt parameterisation, however, a significant overestimation of the peak dropped the model performance to a *E* value of 0.67. Results using the default parameters showed an even poorer description with a *E* value of 0.47. The fully calibrated simulations on the other hand, showed a better performance than those using the regionalised parameters for the calibration period in 1996. This resulted in a more accurate description of the dynamics of the streamflow ($E = 0.94$) for the entire period, particularly in the model ability to replicate the second peak and recession curve of the observed hydrograph. Validation of this parameterisation in 1999 (Fig. 5b) exhibited a good description of the timing, however, a less accurate description of the peak was observed.

Comparatively the improvement of the results using the fully calibrated parameter set was less noticeable in the simulations of SCA than on the simulations of snowmelt runoff. The improvement

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of the simulations when all the parameters were included in the calibration scheme showed the importance of the vegetation parameters in modelling performance. It also indicates that the satisfactory results obtained using the regionalised parameters are not just due to calibration of the remaining parameters (i.e. SDC and hydrology parameters). Further the lack of a difference in the estimation of the snow-cover ablation in early stages of melt and the enhancement of the streamflow results over the entire simulation period showed that the influence of the SDC parameter is not dominant, and hence not necessarily more important than the vegetation parameters, given that its sensitivity is constrained to the early stages of melt (Pohl et al., 2005b).

As expected, the use of a default parameterisation for the vegetation and its atmospheric transport fluxes had a poorer performance than the regional parameterisation defined using observations such as the initial snow-pack and vegetation (e.g. height, density) measurements. This parameterisation is necessary in order to simulate important effects of the albedo and the timing of the shrubs exposure (Pomeroy et al., 2006). The default parameterisation constrained the remaining parameter space (i.e. SDC and hydrology parameters) and thus did not permit the DDS algorithm to find a parameter set that closely matched the observed streamflow, leading to poorer descriptions of both SCA and streamflow. The solutions were greatly enhanced by use of the regional values despite the 1350 km distance and topographic differences between the basins.

5. Conclusions

A regionalisation approach for transferring parameters of a physically based LSH model in subarctic and arctic environments has been presented. This approach was based on a landscape similarity criterion and focused on two aspects. First, model parameters are landcover-based rather than basin-based, and second a step-wise calibration procedure was used to estimate the effective parameters. The landcover-based parameters offer an interesting alternative for PUB due to the difficulties in finding basin-based criteria for transferring parameters. Further, the separate calibration of parameters that govern snowmelt from those controlling streamflow provides a useful framework that reduces computational time (i.e. run CLASS in a point mode) and focuses in the main hydrological processes one at a time.

Results also show that when effective landscape-based parameters are defined considering the effects of the initial conditions (e.g. redistribution of the snow-cover by wind) and forcing data (e.g. topographic effects on the incoming solar radiation) such those in GB, better simulations of both snow-cover depletion and snowmelt runoff than the descriptions obtained using a default parameterisation are seen.

In summary, the identification of landscape units according to a basin-wide process understanding led to the definition of reliable effective landscape-based parameters for predicting both snow-cover depletion and snowmelt runoff. In contrast, calibration is used only to deal with uncertainties in the data, related to the lack of distributed information, or when parameters such as the SDC could not be derived from observations. Therefore for distributed and physically based models, landscape-based parameters appear to be a more feasible framework for transferring information between catchments than regionalisation schemes using regression methods based on basin characteristics. This is likely due to the large number of parameters involved.

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