Global re-analysis datasets to improve hydrological assessment and snow water equivalent estimation in a Sub-Arctic watershed

David R. Casson[1,2], Micha Werner[1,2], Albrecht Weerts[2,3], Dimitri Solomatine[1,4]

[1] IHE Delft Institute of Water Education, PO Box 3015, 2601 DA, Delft, Netherlands
5 [2] Deltares, P.O. Box 177, 2600 MH Delft, Netherlands
[3] Wageningen University and Research, P.O. box 47, 6700 AA, Wageningen, Netherlands
[4] Delft University of Technology, P.O. Box 5048, 2600 GA, Delft, Netherlands

Correspondence to: David R. Casson (dave.casson@deltares.nl)

Abstract. Hydrological modelling in the Canadian Sub-Arctic is hindered by sparse meteorological and snowpack data. Snow Water Equivalent (SWE) of the winter snowpack is a key predictor and driver of spring flow, but use of SWE data in hydrological applications is limited due to high uncertainty. Global re-analysis datasets that provide gridded meteorological and SWE data may be well suited to improve hydrological assessment and snowpack simulation. To investigate

15 representation of hydrological processes and SWE for application in hydropower operations, global re-analysis datasets covering 1979-2014 from the European Union FP7 eartH2Observe project are applied to global and local conceptual hydrological models. The recently developed Multi-Source Weighted-Ensemble Precipitation (MSWEP) and the Watch Forcing Data applied to ERA-Interim data (WFDEI) are used to simulate snowpack accumulation, spring snowmelt volume and annual streamflow. The GlobSnow-2 SWE product funded by the European Space Agency with daily coverage from

20 1979-2014 is evaluated against in-situ SWE measurement over the local watershed. Results demonstrate the successful application of global datasets for streamflow prediction, snowpack accumulation and snowmelt timing in a snowmelt driven Sub-Arctic watershed. The GlobSnow-2 product is found to under-predict late season snowpack over the study area, and shows a premature decline of SWE prior to the true onset of the snowmelt. Of the datasets tested, the MSWEP precipitation results in annual SWE estimates that are better predictors of snowmelt volume and peak discharge than the WFDEI or

25 GlobSnow-2. This study demonstrates the operational and scientific utility of the global re-analysis datasets in the Sub-Arctic, although knowledge gaps remain in global satellite based datasets for snowpack representation.

Keywords: Hydrology, SWE, Sub-Arctic, snowmelt, cryosphere, GlobSnow, eartH2Observe, MSWEP, WFDEI, global dataset, WFLOW, HBV

30

Study Highlights:

- Global re-analysis datasets from the European Union FP7 eartH2Observe project are applied to a distributed, conceptual hydrological model of a snow-melt driven watershed in the Canadian Sub-Arctic.
- Global re-analysis datasets have clear benefit to improve the period of record and model performance in hydrological assessment. However, estimates of snowfall quantity and resulting modelled SWE have high uncertainty for prediction of snowmelt volume.
- Maximum annual SWE generated from MSWEP is more predictive of snowmelt volume and peak discharge than WFDEI forcing or GlobSnow-2 SWE.
- Methods applied in the study are readily applicable for hydrological modelling and assessment in data sparse snowmelt driven watersheds in the Sub-Arctic.

1 Introduction

Snowpack accumulation and melt are the main drivers of hydrology and peak flow events in high latitude (>60^{0}N) watersheds. Snow Water Equivalent (SWE) stored in the winter snowpack is the key contributor and predictor of spring and

5   summer streamflow (Liu et al., 2015). In-situ measurement of SWE can provide valuable information to operational water managers, but data collection is challenging in remote high latitude watersheds, and uncertainty in maximum annual SWE remains a key constraint in hydrological forecasting (Larue et al., 2017). In Northern Canada, uncertainty in SWE measurement and a lack of developed hydrological modelling tools result in high uncertainty in the prediction of snowmelt driven flood events, leading to infrastructure risk and hindering operational water management. Climate change is also

10   shifting the hydrology regime at high latitudes, with Global Circulation Models and observational trends indicating a reduction in spring snowpack duration, although the trend in SWE is less clear (Brown and Mote, 2009; Rees et al., 2014). This will increase risk to hydroelectric facilities, mining operations and local communities as rapid spring snowmelt, rain-on-snow events and variable precipitation patterns that cause flooding become more severe (AMAP, 2012; McCabe et al., 2007; National Research Council, 2007).

SWE measurements from ground and remote-sensing sources have high uncertainty for hydrological application. Although field measurement of SWE can be accurate at point locations, these provide only limited spatial and temporal coverage. Precipitation gauge measurements to quantify snowfall at high latitudes have high uncertainty due to the scarcity of meteorological stations, short duration of active stations and systematic measurement error (Devine and Mekis, 2008; Mekis

20   and Vincent, 2011; Sugiura et al., 2006). Remote sensing is used to monitor snow on a global scale and measurement of

snow depth with passive microwave has advantages of frequent re-visit times, long-term data records and large spatial extent of data collection (Nolin, 2011). GlobSnow-2 provides a long term (1979-2014) daily record of SWE over the Northern hemisphere (Luojus et al., 2014). However, passive microwave measurement of SWE is limited for the measurement of deep or wetted snow packs, relies on estimates of density, and tends to underestimate SWE in tundra environments (Rees et

5   al., 2007).

Global reanalysis data products, which integrate multiple data sources, are well suited to provide meteorological data at high latitudes due to complete spatial and extended temporal coverage. Research into the reliability of re-analysis products at high latitudes is, however, limited for precipitation and SWE due to a lack of reliable comparison data (Mudryk et al. 2015; Wong

10   et al., 2016). In this study a local distributed, conceptual hydrological model using a simplified snow accumulation and melt routine is forced with eartH2Observe meteorological data to simulate SWE and catchment discharge.

Meteorological datasets generated as part of the eartH2Observe project have been used to force global hydrological models (Schellekens et al., 2016). These global hydrological models can be used to improve understanding of water resources in

15   regions like the Sub-Arctic where information is lacking, but the models have large uncertainties in part due to simplifications of physical processes (Bierkens and Van Beek, 2009; van Dijk et al., 2014). This study examines the application of global re-analysis data products for hydrological modelling and representation of SWE in the Snare Watershed in the Canadian Sub-Arctic. The available datasets hold great potential to allow accurate discharge modelling for Sub-Arctic watersheds and development of more advanced modelling systems. This has real and practical relevance for operational

20   water management at high latitudes and provides a basis for hydrological forecasting and data assimilation to further improve model performance.

The three main goals of this paper are to:

1) Determine the skill of a local distributed, conceptual (in each cell) hydrological model for a snowmelt driven, high
25   latitude watershed forced with long-term meteorological re-analysis data developed in the eartH2Observe project.

2) Assess the representation of SWE in both the local and global scale models, and compare to the GlobSnow-2 daily SWE product as well as available long-term records of snowpack surveys.

3) Determine the predictive capacity of SWE measurement from in-situ snowpack surveys, GlobSnow-2 SWE as well as local and global hydrological models for snowmelt volume and peak discharge rates.

30   **2 Study Area and Context**

The Snare Watershed is located in the Northern extent of the Mackenzie River Basin in Canadian Sub-Arctic. The watershed covers an area of roughly 14,000 km² above a cascade of 4 hydropower stations as depicted in Figure 1 (NTPC,

2013). The Snare Watershed is typical of many watersheds across Northern Canada where temporal and spatial coverage of meteorological data is very sparse, but where historic discharge gauging records are available.

The Snare Watershed has low topographic relief and is characterized by low rolling hills of exposed bedrock with
5   depressions from glacier scouring forming wetlands, shallow lakes and streams (ECG, 2008). The Southern extent of the watershed is boreal forest, while the Northern extent is above the treeline and is covered mostly by shrub and sedge tundra (Government of Canada, 2013). Annual precipitation is generally low and in the range of 200 to 500 mm and temperatures are below 0°C for extended periods in the winter months (ECG, 2008).

10   Several meteorological stations have been installed in the Snare Watershed, however precipitation records are very short, with a maximum duration of 3 years. Gauge measurement of snowfall is known to have systematic underestimation and large bias correction factors (80-120%) are required for snowfall at high latitudes, though factors in the boreal/tundra region of the Snare Watershed may be closer to only 20% (Mekis and Vincent, 2011; Yang et al., 2005). Snowpack accumulated from winter snowfall is highly spatially variable in depth and SWE with lower accumulation over lake and plateau areas
15   (Rees et al., 2014). Snowfall measurements at high latitudes are particularly difficult to verify due to the sublimation effects on precipitation totals (Mekis and Hogg, 1998).

Sublimation, the direct conversion of snow particles to vapour and a major factor in removing snow from tundra areas (Marsh et al., 1995), and along with wind redistribution is a dominant factor in the spatial variability and quantity of SWE.
20   Sublimation estimates in the Sub-Arctic boreal forest and tundra regions vary considerably in a general range from 10-50% of total snowfall (Dery and Yau, 2002; Liston et al., 2002; Marsh et al., 1995; Pomeroy et al., 1999.; Pomeroy et al., 1997). Direct measurement of sublimation is very difficult, so values are more often determined through water balance assessment (Liston and Sturm, 2004).

25   Improved modelling of streamflow and SWE has a direct benefit for the operation of active hydropower facilities in the Snare Watershed. Current approaches for hydropower operations in the Snare Watershed use ground SWE measurements and analogue hydrographs to anticipate discharge. The system planner uses anticipated streamflow to determine whether to hold or spill water, and whether it is necessary to order diesel should hydroelectric generation fall short and needs to be offset using generators. This forecasting approach is limited as it cannot incorporate additional information such as changing
30   temperature regimes, antecedent water storage and meteorological forecasts. In this study the operational context of the Snare Hydro System is used to demonstrate that global datasets are not only useful for broad scale assessment, but can be applied for accurate discharge modelling and development of a hydrological forecasting system.

3 Methodology

3.1 Hydrological Models

3.1.1 WFLOW-HBV Model

WFLOW-HBV is a based on the conceptual HBV-96 algorithm and is developed as a distributed hydrological modelling
platform using the PCRaster python framework (Karssenberg et al., 2010; OpenStreams, 2016b). WFLOW-HBV includes a
simplified snow accumulation and melt routine based on the degree-day method and kinematic wave approximation for
routing (Bergström, 1992). The snow routine does consider snowpack melt and refreezing, but not moisture loss from the
snowpack (sublimation) and wind redistribution. Several attempts have been made to improve on the snowmelt modelling of
the HBV model, but it has been found that inclusion of more advanced routines and additional input data have had only
limited improvement of results (Lindstrom et al., 1997). The WFLOW-HBV model is highly parameterized and requires a
structured approach to calibration to achieve suitable streamflow and physical process representation.

A Python-based framework for optimization, pyOpt, was implemented for calibration of the WFLOW-HBV model (Perez et
al., 2012). Single objective, constrained parameter optimization of Nash-Sutcliffe Efficiency (NSE) was performed using the
Augmented Lagrangian Harmony Search Optimizer (Geem et al., 2001). Constraints on specific model parameters based on
land cover type and introduction of lakes and reservoirs were used to improve physical process representation. Observed
discharge data was separated into calibration, validation and testing periods. The difference between validation and testing
periods is that validation results are seen and evaluated by the modeller in an iterative calibration process, while testing data
are not used until the final model parameter values are set.

3.1.2 Global Hydrological Models

Global hydrological models considered in this study are conceptual rainfall-runoff models as presented in Table 1. Model
state variables such as SWE for selected models and forcing datasets can be obtained from the eartH2Observe project Water
Cycle Integrator (WCI) (EartH2Observe, 2017).

3.2 Data

3.2.1 Meteorological Data

Meteorological stations are sparse in the study area, as they are across Northern Canada (Mekis and Vincent, 2011). Local
meteorological stations data collected from Government of Canada Historical Climate Data records were reviewed to

determine consistency and completeness (ENR, 2016; Simpson, 2016). With the exception of the Yellowknife station, precipitation records for both rainfall and snowfall were, however, found to be incomplete or of short duration. Temperature records for several nearby stations shown in Figure 1 were found to be complete and suitable for comparison validation.

5   Global re-analysis datasets generated as part of the eartH2Observe project were used as forcing data for the WFLOW-HBV model. The primary precipitation forcing dataset used is the Multi-Source Weighted-Ensemble Precipitation (MSWEP) available at a daily timestep from 1979-2015 at a resolution of 0.25° x 0.25°. MSWEP was created through combination of gauge, satellite and reanalysis data and includes a long term bias correction procedure based on discharge observations (Beck et al., 2016). Precipitation and temperature data from the Watch Forcing Data applied to ERA-Interim reanalysis data
10 (WFDEI) were used at a daily timestep 1979-2012 at a resolution of 0.5° x 0.5° (Weedon et al., 2014). Potential Evapotranspiration (PET) for this study was selected as Penman Monteith calculated at a daily timestep at a 0.25°x 0.25° resolution based on eartH2Observe Water Resource Re-analysis 2 (WRR2) data.

Available ground weather station data sources and long-term climate normals were used to validate the re-analysis datasets
15 from eartH2Observe. Mean annual precipitation for the eartH2Observe datasets are comparable at the nearest gauge with long term records at Yellowknife. Undercatch corrected annual mean precipitation totals for Yellowknife were 377.7 mm, with MSWEP and WFDEI totalling 356.3 mm and 370.7 mm respectively (ENR, 2016). A comparison of monthly precipitation to undercatch corrected local datasets shows slightly better correlation and performance for MSWEP ($y = 0.93x$, $R^2 = 0.27$) than WFDEI ($y = 0.88x$, $R^2 = 0.25$). Daily mean temperature data for several local stations were well
20 correlated with WFDEI (Lower Carp Lake, $R^2 = 0.98$; Indin River, $R^2 = 0.97$) with low biases.

3.2.2 Discharge Data

Discharge in the Snare Watershed follows a distinct and highly seasonal pattern which is typical of the Sub-Arctic (Kokelj, 2003). Low winter flows are followed by a large peak discharge due to snowmelt. In some years, rainfall in the late fall will cause a notable secondary peak before flow recession in the end of the year. Discharge is available both as a historic
25 timeseries from as early as 1978 and in near real-time provided by the Water Survey of Canada (ENR, 2016, 2017) for the three hydrological stations presented in Figure 1. Although the period of record is different for each of the three stations, the annual water yields are well correlated between the three catchments helping to validate the rating curves and reported discharge rates.

3.2.3 In-situ SWE Data

Measurement of SWE can be performed in-situ with accurate snow depth and density at point locations. However the resulting datasets have limited spatial and temporal coverage (Derkson et al., 2008). The in-situ measurements, or snowpack surveys, are often collected near the end of the snow accumulation season to provide advance information for anticipated snowmelt volume. A long term record [1978-2016] of end of winter snowpack surveys is available at locations distributed across the Snare Watershed (GNWT, 2016). Snowpack surveys measurements contain inherent uncertainty related to site selection, sampling protocols and interpolation methods used to create spatial estimates. Despite these limitations, snowpack survey data is considered the most reliable SWE available in the study area.

3.2.3 GlobSnow-2 SWE Data

GlobSnow-2 SWE, hereafter referred to as GlobSnow, is a long term (1979-present) daily record of SWE covering the non-mountainous areas of the Northern Hemisphere (Luojus et al., 2014). GlobSnow uses a Bayesian non-linear iterative assimilation approach with passive microwave measurements and ground weather station measurements to create a 25 km by 25 km gridded SWE product (Takala et al., 2011). GlobSnow has limitations and uncertainty consistent with the measurement of SWE from passive microwave measurements leading to underestimation in tundra environments due to several contributing factors (Rees et al., 2007). Passive microwave algorithms provide limited measurement of melting snow as the presence of even small amounts of water in the snowpack results in an emissivity similar to land with no snow cover (Nolin, 2011). In GlobSnow, a microwave derived dry snow mask is first used to determine snow covered area and SWE retrievals are only retained for those areas determined to have snow cover. When snow is wet, the snow masking procedure underestimates the snow covered area.

GlobSnow algorithm performance has been tested in Canada by comparing retrievals to in-situ measurements for a variety of Canadian land covers. The overall RMSE for comparison with Canadian data is 40 mm, although algorithm retrieval is poor for boreal forest snow where the SWE is greater than 150 mm (Takala, 2011). Sparsity of weather station snow depth measurements in boreal regions results in stronger weighting of microwave based retrievals in the GlobSnow algorithm, contributing to underestimation of SWE due to the volume scatter from dry snowpacks exceeding 150 mm.

3.3 Snowmelt Volume

Snowmelt volume was approximated using the local minimum method from the hydrograph stream flow separation program (HYSEP) implemented in MATLAB (Burkley, 2012). This is a mathematical technique that mimics manual methods for stream flow separation as opposed to an explicit representation of the physical processes (Sloto and Crouse, 1996). A further manual correction was used for secondary hydrograph peaks driven by late summer and fall rainfall events. A simple

exponential regression was used to estimate the recession curve (Toebes et al., 1969). The method applied in this study results in an annual mean contribution of SWE to total stream flow of 63%, with a standard deviation of 10%. These values of snowmelt contribution to streamflow are consistent with literature estimates (30-80%) from more detailed catchment studies (DDC, 2014; McNamara et al., 1998; Schelker et al., 2013; Stieglitz et al., 1999), if a little on the high side.

3.3 Prediction of Snowmelt Volume and Peak Discharge from Maximum Annual SWE

Prediction of spring streamflow is largely dependent on the accuracy of SWE estimates prior to snowmelt (Sospedra-Alfonso et al., 2016). Rank correlation analysis is used to compare maximum annual SWE to the corresponding spring snowmelt volume and peak discharge. Use of maximum annual SWE allows comparison between local and global model datasets, GlobSnow and in-situ measurements. Spearman's rho is used as a non-parametric measure of the monotonicity (i.e. whether the trend is entirely increasing or decreasing) between datasets as calculated in Eq. (1) (Yue et al., 2002).

$$r_s = 1 - \frac{6 \sum d_i^2}{n(n^2 - 1)} \; where \; d_i = rg(X_i) - rg(Y_i) \qquad (1)$$

where r_s is Spearman's rho and $rg(X_i)$ is the rank of observation X_i in a sample of size n. Spearman's rho test includes a two-sided p-value for significance

4 Results

4.1 Discharge Simulations

Graphical results for the testing period of the WFLOW-HBV model presented in Figure 2 show good overall model representation of discharge. From the graphical assessment, it appears that model results could be improved with slightly greater attenuation of streamflow. Modelled discharge in 2014 is anomalous with over prediction of the discharge volume due to snowmelt contribution to streamflow. Analysis of the in-situ data show that low snowpack SWE was recorded in snowpack surveys collected in 2014, though this is not reflected in the MSWEP forcing data.

Results only from the testing period are shown graphically in Figure 2, while the performance statistics over the calibration, validation and testing periods are shown in Table 2. These statistics would generally be classified as good or very good calibration under the model evaluation guidelines defined by Moriasi et al. (2007).

4.2 Snow Water Equivalent

The accumulated SWE over the Snare Watershed has been measured by in-situ snowpack surveys and can be used to evaluate GlobSnow-2 and hydrological models. Figure 3 shows the quantity and timing of SWE accumulation and melt

patterns over the period of record. Each snowpack survey point is the spatial mean of a set of snowpack survey stations collected in the same field program. The line graphs represent the spatial mean of daily mean, maximum and minimum SWE estimates from GlobSnow-2, hydrological and land surface models.

5   The comparison of the GlobSnow data with the in-situ SWE measurements in Figure 4, where the blue crosses are the observations taken in early spring while the red asterisks are the observations from late spring, shows GlobSnow tends to overestimate SWE in the early season and underestimate in the late season. Error is also correlated to the magnitude of the GlobSnow measurement (right hand figure). The assumption of a constant density of 0.24 g/cm³ in the GlobSnow retrieval algorithm contributes to this trend. The mean density in the Snare Watershed snow surveys is 0.21 g/cm³ with a standard

10   deviation of 0.06 g/cm³ (GNWT, 2016). The assumption of constant density would lead to overestimation of SWE for freshly fallen snow and underestimation for mature snow packs.

The high overall RMSE (45.1%) and Percent Bias (18.3%), showing under prediction by GlobSnow are consistent with a recent validation study of GlobSnow over Canadian boreal forest and tundra environments (Larue et al., 2017; Takala,

15   2011). In this study, a key contributing factor to the high RMSE is that comparison is made with late season measurements where GlobSnow SWE retrievals have premature decline. The spatial distribution of RMSE and PBIAS in Figure 5 indicate better performance over the Northern tundra areas compared to Southern areas where boreal forest land cover dominates. The checkered pattern of the error statistics is due to the 25 km by 25 km resolution of the GlobSnow product.

20   **4.3 Prediction of Snowmelt Volume and Peak Discharge**
Maximum annual SWE is a key predictor of spring and summer streamflow rates. Rank correlation analysis provides evaluation the predictive power of measured and modelled SWE to snowmelt volume and peak discharge rates. Table 3 shows results for Spearman's rho (r_s) and two sided p-test (p), correlating the maximum SWE found in each of the dataset/model combinations considered, and the observed snowmelt volume and peak discharge. The last column provides

25   the correlation to the SWE obtained from ground measurements.

The selection of forcing data has a clear effect on correlation of model maximum annual SWE to snowmelt volume, peak discharge and in-situ data. MSWEP forcing precipitation has superior performance to WFDEI irrespective of the conceptual model used. The local WFLOW-HBV model forced with MSWEP is the best and only statistically significant (p < 0.05)

30   predictor of snowmelt volume and peak discharge. This can be attributed to the calibration of the local model, while global models are generally uncalibrated. GlobSnow has poor correlation to snowmelt volume, peak discharge and in-situ data which is consistent with expected limitations from SWE measurement with passive microwave measuring deep and late-season snow packs.

5 Discussion

5.1 Global re-analysis datasets for predicting streamflow, snowpack accumulation and melt

Global re-analysis datasets applied in this study allow considerable gains in hydrological assessment in a high latitude watershed compared to what can be achieved with in-situ data. Local meteorological datasets are simply too short, inconsistent and spatially disperse to be applied in long term modelling. The use of hydrological models allows the estimation of hydrological state variables such as snowpack accumulation and streamflow using both local and global conceptual hydrological models.

The local watershed model developed in this study, forced with MSWEP precipitation was calibrated to available streamflow records. The resulting calibrated model is able reliably and accurately model streamflow based on calibration, validation and testing statistical results. Local model maximum annual SWE was found to be a better predictor of snowmelt volume and peak discharge than snowpack survey data.

In global hydrological models, which are not calibrated to streamflow data, MSWEP has better performance over the Snare Watershed in predicting snowmelt volume and peak discharge compared to WFDEI. The selection of forcing data is this study has a greater effect than the choice of conceptual hydrological model owing to the control over precipitation volumes. Study of streamflow in calibrated versions of the global hydrological models have also found superior performance using MSWEP (Beck et al, 2016).

Limitations of conceptual models in high latitude watersheds include lack of important physical processes such as permafrost interactions, ice effects on rivers and lake outlets and complex processes in the snow-pack. Calibration of highly parameterized models such as WFLOW-HBV mask underlying physical processes and do not explicitly represent them. This limits applicability for certain types of assessment such as permafrost thaw with climate change, which will alter runoff processes (Duan et al., 2017). Incorporating additional remote sensing data, including land and lake cover can improve the spatial representation of physical processes and allow assessment based on land use changes.

5.2 SWE measurement for operation and planning purposes

SWE is used by operational water managers to predict the inflow volumes from snowmelt and anticipate peak discharge rates. Study results demonstrate that SWE measurement for application in hydrological forecasting is still problematic in the Snare Watershed.

In-situ measurement of SWE from snowpack survey provides an end-of-season snapshot measurement, and due to the long data record in the Snare Watershed allows comparison with previous years. Field data collection could be improved with strategies that consider topographical and vegetative characteristics of the watershed to improve and standardize site selection (Rees et al., 2014). The recognition that while inter-annual variability of snowpack is high, distribution patterns are

5   relatively consistent would improve SWE measurement due to typifying station measurements based on topographic relief.

Snowpack SWE in the conceptual hydrological models forced by MSWEP and WFDEI global have comparable magnitudes to snowpack survey measurements. Given that conceptual models do not include sublimation, which is known to remove a large quantity of snowpack SWE, the MSWEP and WDFEI global re-analysis datasets tend to underestimate actual snowfall.

10 This is difficult to verify as precipitation gauge measurements at high latitudes are known to have large under catch. Sublimation of snowpack SWE is also very difficult to measure and verify, particularly from remote sensing data (Petropoulos, 2013).

GlobSnow is well suited to provide accessible, timely SWE data as supplementary information for water managers and for

15 assimilation into operational modelling systems. Snow data assimilation for hydrological forecasting is an emerging field with application in operational water management systems (Huang et al., 2017; Montero et al., 2016). However, SWE products based on passive microwave such as GlobSnow under predict SWE of tundra and boreal environments present across Northern Canada (Larue et al., 2017; Takala, 2011). Improvement of retrieval algorithms and the assimilation of in-situ estimates can reduce error, though overcoming inherent limitations measuring deep (>150 mm) or wetted snowpack will

20 require novel approaches. Study results indicate the assumption of a constant density used in GlobSnow is a source of error in the early and late periods of accumulation, and advancing over this assumption could help improve the SWE estimates from products such as GlobSnow.

5.3 Global Re-analysis Datasets for Local Application

To be of use in operational managers and planners, the global re-analysis datasets and hydrological models presented in this

25 study must provide reliable data to inform decision making and decrease uncertainty. In the context of the Snare Watershed and snowmelt driven hydropower operations, the snowpack SWE is the predominant source of uncertainty. Current operation of the Snare Hydro System relies on local expert knowledge, historical records and surrogate hydrographs. These methods will be challenged by changes to local hydrology, snow duration and snowmelt quantity with climate change.

30 The use of global re-analysis datasets helps in short term planning by allowing the development of more reliable and accurate hydrological models which form the basis of forecasting systems. Hydrological models developed with local data alone will have greater calibration parameter uncertainty and less rigorous validation. The calibrated WFLOW-HBV model

was integrated into the Delft-FEWS operational forecasting platform (Werner, 2013). The use of this established framework and forecasting tool can improve operator confidence around water release and operation within water license limits. Data products available in Near-Real Time such as MSWEP-NRT, which is under development at the time of writing, would allow the calibrated model to be initialized for forecasting.

Study results demonstrate that SWE estimation for prediction of snowmelt volume and peak discharge is a persistent challenge. Choice of forcing data has a large effect compared to selection of conceptual model, and while global hydrological models can replicate the magnitude of end of season SWE, the difficultly is in accurately predicting inter-annual variability. SWE estimation from passive microwave was found to be a poor predictor, which is consistent with a

10 recent validation study of GlobSnow over Eastern Canada which concludes the product accuracy to currently be insufficient for hydrologic simulations (Larue et al., 2017). SWE measurement for passive microwave has poor agreement with spring discharge volume, possibly due to algorithm errors at high SWE values (Rawlins et al., 2006). A local calibrated hydrological model generated snowpack SWE that the more predictive of snowmelt volume and peak discharge than uncalibrated global models.

The manual collection of end of-winter snowpack survey data is justified, as the study shows that ground data is a comparatively reliable predictor of snowmelt contribution to streamflow and peak discharge. Field measurement methods would increase the reliability of in-situ measurement, but would reduce the ability to compare to the existing historical record.

The methods described in this study improve representation of the hydrological processes and forecasting application could allow a better operational strategy to be implemented. Global datasets, in particular meteorological reanalysis data are useful not only for broad scale assessment, but can be applied for accurate discharge modelling and development of a hydrological forecasting system. This has real and practical relevance for operational water management in the Sub-Arctic.

25 **6 Conclusions**

This study demonstrates that considerable gains in hydrological assessment and model performance for high latitude watersheds can be achieved with global re-analysis datasets and conceptual hydrological models. The findings of this study are relevant to operational water management in high latitude catchments with sparse meteorological data and to current scientific research in the estimation of SWE with global remote sensing and re-analysis data. The methods described in this

30 study can be readily applied in the Canadian Sub-Arctic where watersheds do not have comprehensive meteorological data or operational hydrological models.

Application of global re-analysis datasets to a local, distributed conceptual model (WFLOW-HBV) results show that the spring snowmelt discharge can be predicted well in terms of timing and magnitude over a 30 year period. Model performance for discharge and select physical processes is improved through constrained parameter optimization, but it is also clear from the results that the calibrated HBV model parameters may compensate for cryosphere processes such as
5 sublimation that are lacking in the model.

This study highlighted the limitations of SWE derived from global re-analysis datasets and conceptual hydrological models to predict the volume of snowmelt and peak discharge rates. Comparison of global re-analysis datasets in the eartH2Observe project shows improved performance in MSWEP precipitation forcing compared to WFDEI for snowpack representation.
10 MSWEP forcing data produced more realistic inter-annual snowpack SWE better able to predict snowmelt volume and peak spring discharge. This finding was consistent for five global conceptual hydrological models assessed over the local study area, demonstrating the importance of precipitation forcing data relative to conceptual model structure.

SWE estimation for prediction of snowmelt volume and peak discharge is a persistent challenge. SWE products based on
15 passive microwave such as GlobSnow under predict SWE in boreal and tundra environments, particularly in the late winter season prior to snowmelt. Improvement of retrieval algorithms and the assimilation of in-situ estimates can reduce error, though overcoming inherent limitations measuring deep (>150 mm) or wetted snowpack will require novel approaches. Study results indicate the assumption of a constant density used in GlobSnow is a source of error in the early and late periods of accumulation, and advancing over this assumption could help improve the SWE estimates from products such as
20 GlobSnow.

The conclusions in this study related to global re-analysis products including MSWEP, WFDEI and GlobSnow-2 are specific to the Snare watershed area and should not be broadly generalized to other catchments. For further study a gridded SWE product could be used for assimilation to improve spatial representation of the snowpack. Assimilation of remote sensing
25 snow data is an active research field, but is beyond the scope of this study. Snow cover and extent would also provide a great deal of additional data, particularly regarding the timing of snowmelt.

This study has demonstrated the utility of global re-analysis datasets for hydrological assessment in the data sparse Canadian Sub-Arctic. In the operational context of the Snare Hydro System, the length and breadth of hydrological assessment as
30 presented here is much greater than could be achieved with local meteorological data. The continued development of these datasets and modelling frameworks is promising to help improve understanding of water resources in data sparse Northern regions in the face of climate change.

7 Acknowledgements

This research received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement no. 603608, "Global Earth Observation for integrated water resource assessment": eartH2Observe. This study would not have been possible without access to open-source datasets generated from the eartH2Observe project and the

5   development of open-source software packages including WFLOW and Delft-FEWS. Chris Derksen and Emanuel Dutra are acknowledged for their advice throughout study and helpful comments to the manuscript.

8 Data Availability

All input data and modelling software used in this study are available online free of charge for research purposes. Meteorological forcing datasets are accessible from the eartH2Observe database (PML, 2015; Schellekens, 2016).

10 GlobSnow-2 SWE is available via FTP access (Luojus et al., 2014). WFLOW-HBV is open-source modelling framework and the latest versions are available for download (Openstreams, 2016a). Local data for discharge stations, meteorological stations and snowpack surveys are available online (GNWT, 2016; WSC, 2016).

9 References

15 AMAP. (2012). Arctic Climate Issues 2011: Changes in Arctic Snow, Water, Ice and Permafrost. In A. M. a. A. Programme (Ed.), *Overview Report*. Gaustadalléen 21, N-0349 Oslo, Norway SWIPA 2011.

Beck, H., Albert, I., van Dijk, V., Schellekens, J., Miralles, G., Martens, B., and Roo, A. (2016). MSWEP: 3-hourly 0.25° global gridded precipitation (1979–2015) by merging gauge, satellite, and reanalysis data. *Hydrol. Earth Syst. Sci.* doi: 10.5194/hess-2016-236

20 Bergström, S. (1992). The HBV Model - its structure and applications. In SMHI (Ed.), *SMHI Reports Hydrology*. NORRKÖPING, Sweden.

Bierkens, M. F. P., and Van Beek, L. (2009). The Global Hydrological Model PCR-GLOBWB. In F. o. E. S. Department of Physical Geography, Utrecht University (Ed.). P.O. Box 80115, 3508 TC, Utrecht, the Netherlands.

Brown, R. D., and Mote, P. W. (2009). The Response of Northern Hemisphere Snow Cover to a Changing Climate. *Journal*
25   *of Climate, 22*, 2124.

Burkley,   J.   (2012).   Hydrograph   Separation   using   HYDSEP.   Retrieved   from http://nl.mathworks.com/matlabcentral/fileexchange/36387-hydrograph-separation-using-hydsep/content/f_hysep.m

Clark, D. B., Mercado, L. M., Sitch, S., Jones, C. D., Gedney, N., Best, M. J., . . . Cox, P. M. (2011). The Joint UK Land Environment Simulator (JULES), model description - Part 2: Carbon fluxes and vegetation dynamics. *Geoscientific*
30   *Model Development, 4*(3), 701-722. doi: 10.5194/gmd-4-701-2011

DDC. (2014). Hydrology Baseline Report , ANNEX X: APPENDIX A: ANNOTATED BIBLIOGRAPHY. In D. D. Corporation (Ed.), *Developer's Assessment Report/Environmental Impact Statement*. Yellowknife, NWT, Canada: Golder Associates Ltd.

Derkson, C., Sturm, M., Liston, G. E., Holmgren, J., Huntington, H., Silis, A., and Solie, D. (2008). Northwest Territories
35   and Nunavut Snow Characteristics from a Subarctic Traverse: Implications for Passive Microwave Remote Sensing. *Journal of Hydrometeorology, 10*, 448 - 462.

Dery, S., and Yau, M. (2002). Large-scale mass balance effects of blowing snow and surface sublimation. *Journal Of Geophysical Research-Atmospheres, 107*(D23). doi: 10.1029/2001jd001251

Devine, K., and Mekis, E. (2008). Field accuracy of Canadian rain measurements. *Atmosphere-Ocean, 46*(2), 213-227. doi: 10.3137/ao.460202

Duan, L., Man, X., Kurylyk, B., and Cai, T. (2017). Increasing Winter Baseflow in Response to Permafrost Thaw and Precipitation Regime Shifts in Northeastern China. *Water, 9*(25). doi: 10.3390/w9010025

Dutra, E., Balsamo, G., Viterbo, P., Mirand, P., Beljaars, A., Schar, C., and Elder, K. (2009). New snow scheme in HTESSEL: description and offline validation. In ECMWF (Ed.), *Technical Memorandm 607*.

EartH2Observe. (2017). eartH2Observe Water Cycle Integrator (WCI). Retrieved 03 March, 2017, from https://wci.earth2observe.eu/

ECG. (2008). Ecological regions of the Northwest Territories. In E. C. G. E. D. o. E. a. N. Resoruces (Ed.). Yellowknife, NT, Canada: Government of Northwest Territories.

ENR. (2016, 2015-11-18). Historical Climate Data - Online Database. *Weather, Climate and Hazard.* Retrieved Oct 28, 2016, from http://climate.weather.gc.ca/index_e.html

ENR. (2017). Real-Time Hydrometric Data. from https://wateroffice.ec.gc.ca/mainmenu/real_time_data_index_e.html#wb-cont

Flörke, M., Kynast, E., Bärlund, I., Eisner, S., Wimmer, F., and Alcamo, J. (2013). Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: A global simulation study, Global Environmental Change,. *23*, 144–156.

Geem, Z., Kim, J., and Loganathan, G. (2001). A New Heuristic Optimization Algorithm: Harmony Search. *Simulation, 76*(2), 60-68.

GNWT. (2016). *Snow Survey - Spreadsheet Summary*. Retrieved from: http://www.enr.gov.nt.ca/programs/snow-surveys/spreadsheet-summary

Government of Canada. (2013). National Ecological Framework. *National Ecological Framework.* Retrieved 29 Jan, 2017, from http://sis.agr.gc.ca/cansis/nsdb/ecostrat/index.html

Huang, C., Newman, A. J., Clark, M. P., Wood, A. W., and Zheng, X. (2017). Evaluation of snow data assimilation using the ensemble Kalman filter for seasonal streamflow prediction in the western United States. *Hydrol. Earth Syst. Sci., 21*(1), 635-650. doi: 10.5194/hess-21-635-2017

Karssenberg, D., Schmitz, O., Salamon, P., de Jong, K., and Bierkens, M. (2010). A software framework for construction of process-based stochastic spatio-temporal models and data assimilation. *Environmental Modelling and Software, 25*(4), 489-502. doi: http://dx.doi.org/10.1016/j.envsoft.2009.10.004

Kokelj, S. (2003). Hydrologic Overview of the North and South Slave Regions In I. a. N. A. Canada (Ed.). Yellowknife, Northwest Territories, Canada: Water Resources Division

Larue, F., Royer, A., De Sève, D., Langlois, A., Roy, A., and Brucker, L. (2017). Validation of GlobSnow-2 snow water equivalent over Eastern Canada. *Remote Sensing of Environment, 194*, 264-277. doi: https://doi.org/10.1016/j.rse.2017.03.027

Lindstrom, G., Johansson, B., Persson, M., Gardelin, M., and Bergstrom, S. (1997). Development and test of the distributed HBV-96 hydrological model *Journal of Hydrology, 201*, 272-288.

Liston, G., McFadden, J., Sturm, M., and Pielke, R. (2002). Modelled changes in arctic tundra snow, energy and moisture fluxes due to increased shrubs. *Global Change Biology, 8*, 13-32.

Liston, G., and Sturm, M. (2004). The role of winter sublimation in the Arctic moisture budget. *Nordic Hydrology, 35*(4-5), 325-334.

Liu, Peters-Lidard, C. D., Kumar, S. V., Arsenault, K. R., and Mocko, D. M. (2015). Blending satellite-based snow depth products with in situ observations for streamflow predictions in the Upper Colorado River Basin. *Water Resour. Res., 51*, 1182–1202. doi: 10.1002/2014WR016606.

Luojus, K., Pullianen, J., Takala, M., J. Lemmetyinen, Kangwa, M., M. Eskelinen (FMI), . . . (MeteoSwiss), N. F. (2014). GlobSnow-2 Final Report. In E. S. A. S. C. REPORT (Ed.).

Marsh, P., Quinton, B., and Pomeroy, J. (1995). HYDROLOGICAL PROCESSES AND RUNOFF AT THE ARCTIC TREELINE IN NORTHWESTERN CANADA Saskatoon, Sask.: National Hydrology Research Institute

McCabe, G. J., Clark, M., and Hay, L. E. (2007). Rain on Snow Events in the Western United States. *American Meterological Society*.

McNamara, J., Kane, D., and Hinzman, L. (1998). An analysis of streamflow hydrology in the Kuparuk River Basin, Arctic Alaska: a nested watershed approach *Journal of Hydrology, 206*, 39-57.

Mekis, E., and Hogg, W. (1998). Rehabilitation and analysis of Canadian daily precipitation time series. *Atmosphere-Ocean, 37*(1), 53-85. doi: 10.1080/07055900.1999.9649621

Mekis, E., and Vincent, L. (2011). An Overview of the Second Generation Adjusted Daily Precipitation Dataset for Trend Analysis in Canada. *Atmosphere-Ocean, 49*(2), 163-177.

Montero, R. A., Schwanenberg, D., Krahe, P., Lisniak, D., Sensoy, A., Sorman, A. A., and Akkol, B. (2016). Moving horizon estimation for assimilating H-SAF remote sensing data into the HBV hydrological model. *Advances in Water Resources, 92*, 248-257. doi: http://dx.doi.org/10.1016/j.advwatres.2016.04.011

Mudryk, L., C. Derksen, P. Kushner, and R. Brown. 2015. Characterization of Northern Hemisphere snow water equivalent datasets, 1981–2010. Journal of Climate. 28: 8037-8051.

National Research Council. (2007). Colorado River Basin Water Management: Evaluating and Adjusting to Hydroclimatic Variability (2007).

Nolin, A. W. (2011). Recent advances in remote sensing of seasonal snow. *Journal of Glaciology, 56*(200), 1141-1150.

Openstreams. (2016a, 2015). wflow 1.0 Master Documentation. Retrieved 12-Sept, 2016, from http://wflow.readthedocs.io/en/latest/

OpenStreams. (2016b). wflow - PCRaster-Python based distributed hydrological models. from https://publicwiki.deltares.nl/display/OpenS/wflow+-+PCRaster-Python+based+distributed+hydrological+models

Perez, R., Jansen, P., and R., J. (2012). pyOpt: A Python-Based Object-Oriented Framework for Nonlinear Constrained Optimization. *Structural and Multidisciplinary Optimization, 45*(1), 101-118

Petropoulos, G. (2013). Remote Sensing of Energy Fluxes and Soil Moisture Content: Challenges and Future Outlook: CRC Press.

PML. (2015). PML RGS THREDDS Data Server. *earth2observe catalogue.* Retrieved 25 Nov, 2016, from https://wci.earth2observe.eu/thredds/catalog-earth2observe.html

Pomeroy, J., Hedstrom, N., and Parviainen, J. (1999.). Wolf Creek Research Basin: Hydrology, Ecology, Environment,. In E. Canada (Ed.), *National Water Research Institute* (pp. pp 15-30.). Saskatoon, SK,

Canada.

Pomeroy, J., Marsh, P., and Gray, D. (1997). Application of a Distributed Blowing Snow Model to the Arctic. *Hydrological Processes, 11*, 1451-1464.

Rawlins, M., Fahnestock, M., Frolking, S., and Vorosmarty, C. (2006). *On the Evaluation of Snow Water Equivalent Estimates over the Terrestrial Arctic Drainage Basin*. Paper presented at the 63nd EASTERN SNOW CONFERENCE, Newark, Delaware USA.

Rees, A., English, M., Derksen, C., and Silis, A. (2007). *The Distribution and Properties and Role of Snow Cover in the Open Tundra* Paper presented at the 64th EASTERN SNOW CONFERENCE St. John's, Newfoundland, Canada.

Rees, A., English, M., Derkson, C., Toose, P., and Sillis, A. (2014). Observations of late winter Canadian Tundra snow sover properties. *Hydrological Processes, 28*, 3962-3977. doi: 10.1002/hyp.9931

Schelker, J., Kuglerová, L., Eklöf, K., Bishop, K., and Laudon, H. (2013). Hydrological effects of clear-cutting in a boreal forest − Snowpack dynamics, snowmelt and streamflow responses. *Journal of Hydrology, 484*, 105-114. doi: http://dx.doi.org/10.1016/j.jhydrol.2013.01.015

Schellekens, J. (2016). Earth2observe downscaling tools. Retrieved November 25, 2016, from https://github.com/earth2observe/downscaling-tools/releases

Schellekens, J., Dutra, E., Martínez-de la Torre, A., Balsamo, G., Van Dijk, A., Weiland, F., . . . Weedon, G. (2016). A global water resources ensemble of hydrological models: the eartH2Observe Tier-1 dataset. *Earth Syst. Sci. Data Discuss*. doi: 10.5194/essd-2016-55

Sospedra-Alfonso, R., Merryfield, W. J., and Kharin, V. V. (2016). Representation of Snow in the Canadian Seasonal to Interannual Prediction System. Part II: Potential Predictability and Hindcast Skill. *Journal of Hydrometeorology, 17*(9), 2511-2535. doi: 10.1175/jhm-d-16-0027.1

Stieglitz, M., Hobbie, J., Giblin, A., and Kling, G. (1999). Hydrologic modelling of an Arctic Tundra Basin: Toward pan-Arctic predictions. *J Geophys Res, 104*(22), 507-527.

Sugiura, K., Ohata, T., and Yang, D. (2006). Catch Characteristics of Precipitation Gauges in High-Latitude Regions with High Winds. *Journal of Hydrometeorology, 7*, 7.

Takala, M. L., K; Pulliainen; J; Derksen, C; Lemmetyinen, J; Karna, J; Koskinen, J; Bokjov, B;. (2011). Estimating northern hemisphere snow water equivalent for climate research through assimilation of space-borne radiometer data and ground-based measurements. *Remote Sensing of Environment*. doi: 10.1016/j.rse.2011.08.014

Toebes, C., Morrissey, W. B., Shorter, R., and Hendy, M. (1969). Base Flow Recession Curves *Handbook of Hydrological Procedures*. Wellington, New Zealand.

van Dijk, A. I. J. M., Renzullo, L. J., Wada, Y., and Tregoning, P. (2014). A global water cycle reanalysis (2003–2012) merging satellite gravimetry and altimetry observations with a hydrological multi-model ensemble. *Hydrol. Earth Syst. Sci., 18*, 2955–2973. doi: doi:10.5194/hess-18-5-2955-2014

Weedon, G. P., Balsamo, G., Bellouin, N., Gomes, S., Best, M. J., and Viterbo, P. (2014). The WFDEI meteorological forcing data set: WATCH Forcing Data methodology applied to ERA-Interim reanalysis data. *Water Resources Research, 50*(9), 7505-7514. doi: 10.1002/2014WR015638

Wong, J., Razavi, S., Bonsal, B., Wheater, H., and Asong, Z. (2016). Evaluation of various daily precipitation products for large-scale hydro-climatic applications over Canada. *Hydrol. Earth Syst. Sci., 511*. doi: 10.5194/hess-2016-511

WSC. (2016, 2014-06-05). Historical Hydrometric Data Search. Retrieved 02-Nov, 2016, from https://wateroffice.ec.gc.ca/search/search_e.html?sType=h2oArc

Yang, D., Kane, D., Zhang, Z., Legates, D., and Goodison, B. (2005). Bias corrections of long-term (1973–2004) daily precipitation data over the northern regions. *Geophysical Research Letters, 32*. doi: 10.1029/2005GL024057

Yue, S., Pilon, P., and Cavadia, G. (2002). Power of the Mann-Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series. *Journal of Hydrology, 259*, 254-271.
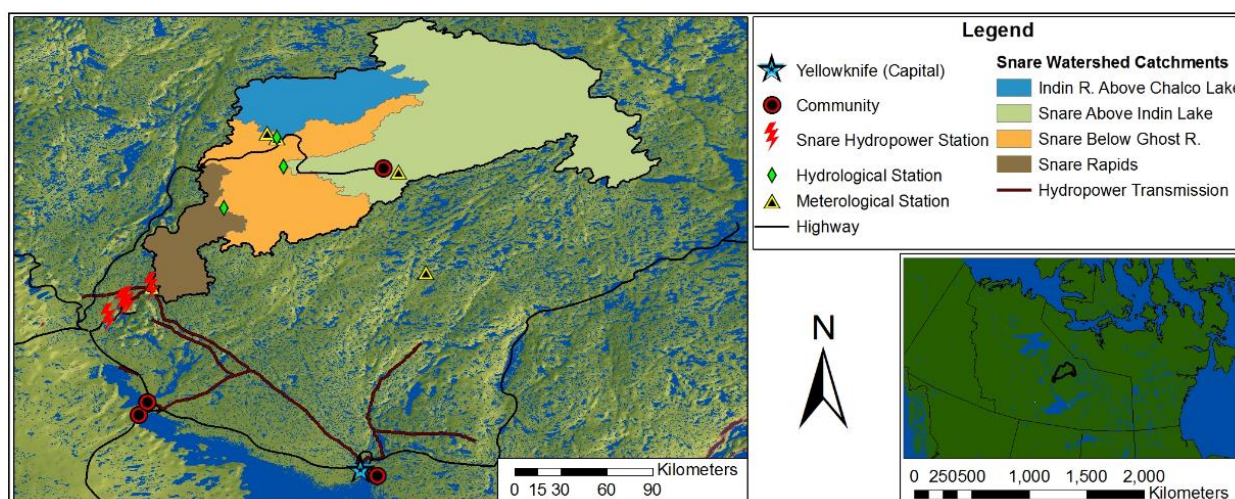
Figure 1: Snare Watershed Location in Northwest Territories, Canada
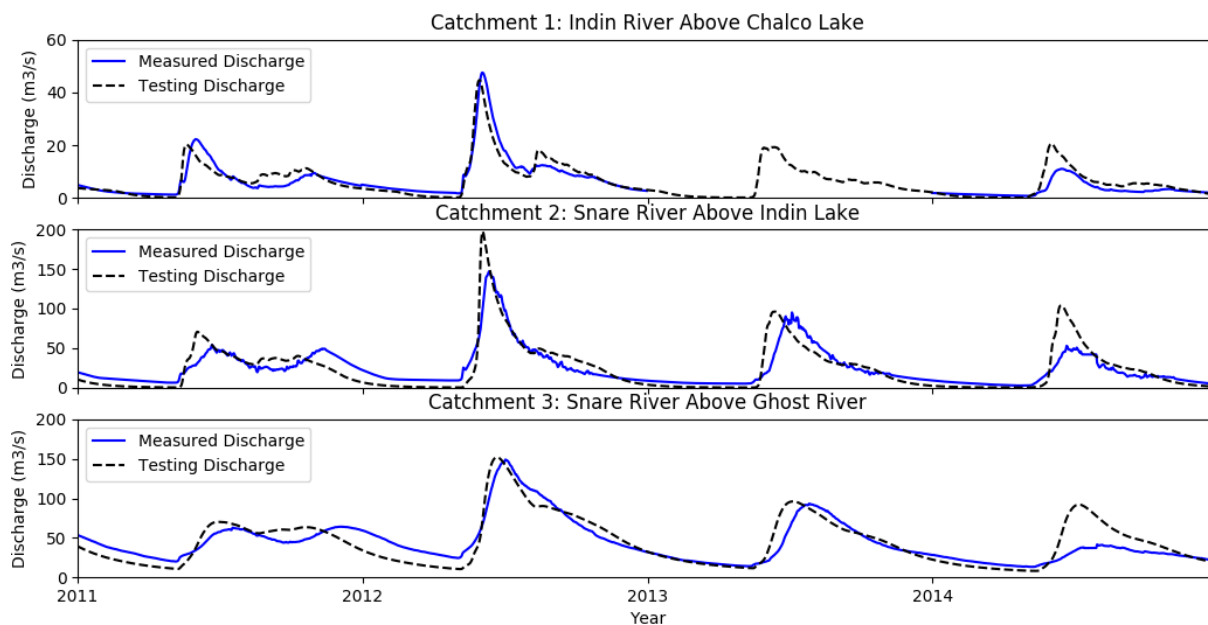
Figure 2: WFLOW-HBV discharge results for the testing period
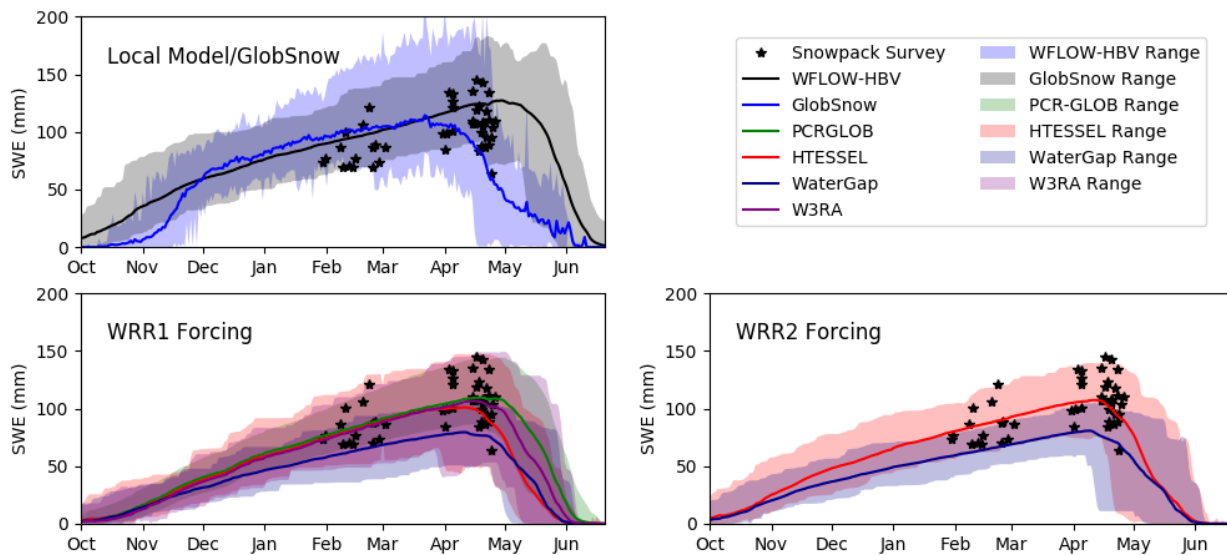
Figure 3: Daily Mean, Maximum and Minimum Daily SWE compared to Ground Measurements [1980-2012]
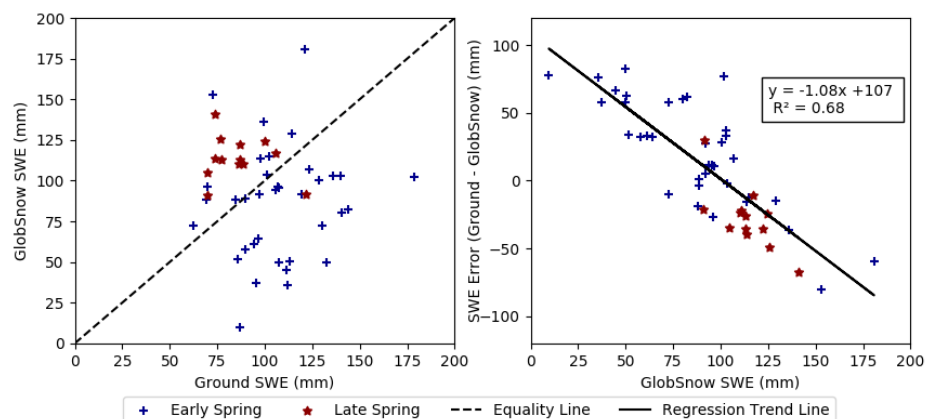
Figure 4: GlobSnow and Ground SWE Measurement Comparison
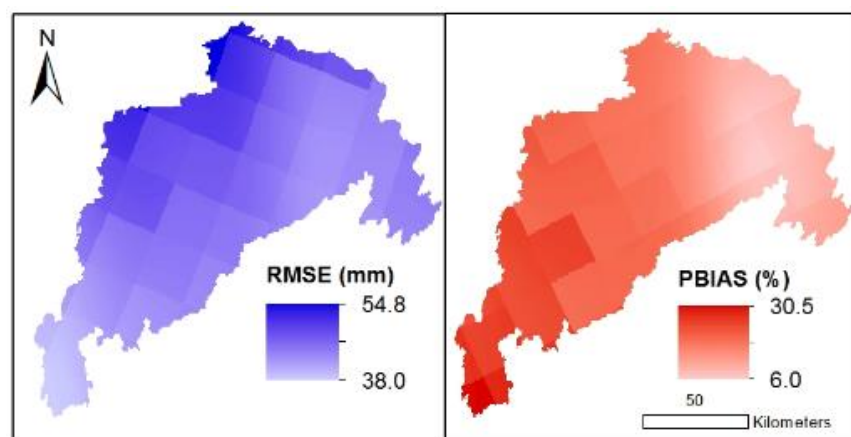
Figure 5: Error from comparison of GlobSnow SWE and interpolated in-situ SWE [1980-2012]

Table 1: Global Model and Process Summary

Model	Evaporation	Snow	Lake-Reservoirs	Routing	Reference
HTESSEL	Penman-Monteith	Energy Balance	No	CaMa-Flood	(Dutra et al., 2009)
JULES	Penman-Monteith	Energy Balance	No	No	(Clark et al., 2011)
PCR-GLOBWB	Hamon (Tier 1) or imposed as forcing	Temperature Based Melt Factor	Yes	Travel-time Approach	(Bierkens and Van Beek, 2009)
W3RA	Penman-Monteith	Degree-Day	No	Cascading Linear Reservoirs	(van Dijk et al., 2014)
WaterGAP3	Priestley-Taylor	Degree-day	Yes	Manning-Strickler	(Flörke et al., 2013)

Table 2: WFLOW-HBV Discharge Statistical Results

Variable	Catchment 1			Catchment 2			Catchment 3		
	Calibration	Validation	Testing	Calibration	Validation	Testing	Calibration	Validation	Testing
Duration (yr)	22	9	4	9	3	4	20	6	4
Error Statistics									
NSE	0.84	0.68	0.80	0.88	0.68	0.59	0.83	0.70	0.67
KGE	0.88	0.65	0.88	0.91	0.83	0.70	0.90	0.74	0.81
PBIAS (%)	-2.6	-15.1	6.0	-5.0	-6.5	0.5	-3.3	-15.2	3.4
RSR	0.44	0.77	0.46	0.32	0.56	0.51	0.39	0.64	0.51

Table 3: SWE, Snowmelt and Peak Discharge Rank Correlation Analysis

Model	Forcing Dataset	Snowmelt Volume		Peak Discharge		Ground SWE Measurement	
		r_s	p	r_s	p	r_s	p
WFLOW-HBV	MSWEP	0.52	0.004	0.54	0.003	0.53	0.004
HTESSEL	MSWEP	0.47	0.011	0.48	0.010	0.55	0.002
JULES	MSWEP	0.47	0.012	0.48	0.010	0.62	0.000
WaterGap	MSWEP	0.34	0.076	0.36	0.063	0.67	0.000
HTESSEL	WFDEI	0.25	0.193	0.25	0.201	0.04	0.834
JULES	WFDEI	0.23	0.243	0.23	0.250	0.01	0.976
WaterGap	WFDEI	0.17	0.382	0.13	0.509	0.15	0.440
W3RA	WFDEI	0.15	0.451	0.10	0.601	0.16	0.409
PCR-GLOB	WFDEI	0.14	0.465	0.12	0.532	0.15	0.438
GlobSnow	Passive Microwave / Snow Gauge Data	0.14	0.484	0.18	0.360	0.18	0.371