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Research papers

A simple model structure enhances parameter identification and improves runoff prediction in ungauged high-latitude catchments

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ABSTRACT

Using data from 22 catchments in Northern Finland, this study demonstrates how runoff prediction in ungauged high-latitude catchments can be improved using simplified conceptual models tailored to readily available data in the region. The newly developed current precipitation index (CPI_{snow}) model provides a parsimonious tool to predict streamflow in data-limited high-latitude regions. Use of current precipitation index (CPI) and runoff coefficient formulation in the soil moisture and response routine conceptualization makes soil moisture and response routine parameters in the model identifiable with catchment properties influencing storage, evapotranspiration, and infiltration losses. Most of the model parameters showed a significant relationship with observable physical catchment properties, climate properties, or both. This made it easier to estimate the values of the model parameters in an ungauged catchment with minimal uncertainty. The parameter functional relationships derived with catchment attributes produced equally good model results when applied to independent test catchments. Inclusion of snow-water equivalent records and use of multiple objective functions for both snow-water equivalent and runoff simulations in the model optimization process helped reduce the effect of parameter equifinality, thereby making it easier to determine the optimal parameter values. Ranges of parameter values are proposed for the CPI_{snow} model in relation to key observable catchment characteristics in the boreal zone, enabling application of the model in ungauged catchments in the region.

1. Introduction

In high-latitude regions where hydrological data are limited or nonexistent (Van der Linden and Woo, 2003; Gusev et al., 2007; Lique et al., 2016; Laudon et al., 2017), conceptual models are often used for runoff modelling due to their limited data demand (Bergström, 1991; Blöschl et al., 2013). Runoff prediction in ungauged catchments in these regions relies on model parameter regionalization through functional relationships to catchment attributes. However, because of the complex structure of most conceptual models, previous attempts to relate conceptual model parameters to catchment attributes have yielded mixed results, due to the effects of parameter non-uniqueness and equifinality caused by model over-parameterization (Magette et al., 1976; Hughes, 1989; Servat and Dezetter, 1993; Ibrahim and Cordery, 1995; Post and Jakeman, 1996; Sefton and Howarth, 1998; Seibert, 1999). Over-parameterization is often the result of a model structure requiring more input information than can be derived from available input data (Bergström, 1991; Van der Linden and Woo, 2003; Gupta et al., 2012; Ghasemizade et al., 2015; Shin et al., 2015; Chang et al., 2017). Beven (1989, 2012) and Bergström (1991) suggest that a simple model with a small number of parameters, good numerical implementation, and less data demand would eliminate the problem of over-parameterization. Moreover, Beven (2012) suggested that 3–5 parameters should be sufficient to reproduce most of the information in hydrological records.

The predominant linearity in the response of watersheds (Jakeman and Hornberger, 1993) indicates that rainfall-runoff models with only a small number of conceptual storage units will satisfactorily reproduce observed runoff records over a wide range of catchment scales. Kokkonen and Jakeman (2001) achieved more accurate reproduction of measured runoff with a simple conceptualized model than a highly conceptualized model. They concluded that substantial conceptualization of complex hydrological processes is not justified if only rainfall-runoff data are available. This is because more complexity requires several types of data, such as soil profile, groundwater position, etc., and higher information content for the model to achieve good performance. In addition, studies by e.g., Perrin et al. (2001), Valéry et al. (2014a,b), Orth et al. (2015), and Chang et al. (2017) have shown benefits from model simplification.

In previous work (Akanegbu et al., 2017), we developed a robust and simple hydrological model (CPI_{snow}) for streamflow prediction in

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seasonally snow-covered high-latitude regions based on the principle of current precipitation index (Smakhtin and Masse, 2000). In the present study, we investigated the effect of simplified linear conceptualization of the soil moisture and response routine in CPI_{snow} on its parameter uniqueness and identification with observable catchment descriptors. Our main focus was to test the efficiency of the model in predicting streamflow from ungauged high-latitude catchments using functional relationships between its parameters and observable catchment attributes. The hypotheses tested were that: i) Since the response routine in the CPI_{snow} model is conceptualized based on the principles of current precipitation index and runoff coefficients, its response routine parameters can be determined by observable catchment descriptors that influence evapotranspiration and infiltration losses in the catchment; and ii) since the CPI_{snow} model uses only one soil moisture routine parameter to account for low-flow conditions in the catchment, the parameter will be identifiable with catchment properties that regulate baseflow in the catchment, such as lake percentage and slope. An additional aim was to produce a range of parameter values for the CPI_{snow} model in high-latitude regions in relation to easily obtainable catchment physical and climate attributes.

2. Materials and methods

2.1. Study sites

The study was conducted using 22 forested boreal catchments located in Finland (Fig. 1). A set of 14 catchments with snow water equivalent records was used for model parameter optimization and parameter uniqueness evaluation, while the remaining eight catchments were used as independent catchments to test the performance of the established functional relationships between model parameters and observable catchment characteristics in mock ungauged high-latitude catchments. Three catchments in southern Finland were included, in order to ensure that differences in climate between the upper north and lower north were captured. The area of the catchments ranges from 13.62 to 3814 km^2 (Table 1). The dominant land use in the catchments is forest, covering > 50% of the area. The catchments have relatively flat topography, with the mean elevation difference being 195 m a.s.l., and a shallow water table (around 3–5 m below the surface) (Finnish Environmental Institute, 2017). The surface lithology of the catchments, with the exception of Myllymäki, Ylijoki, and Laanioja, is mainly basal till, which occupies over 40% of the land area. The surface lithology in Myllymäki is mainly fine (marine) sediment, while that in Ylijoki and Laanioja is mainly hummock moraine and migmatitic metapelite, respectively (Geological Survey of Finland database). Superficial deposits are on average 10 m thick and storage units in the catchments are mainly lakes and peatlands. Climate conditions in the region are humid, with an aridity index of 0.7–0.9. Mean annual air temperature is 1–5 °C in the south and 0 to −2 °C in the north, while mean annual precipitation is 600–700 mm in the south and 400–550 mm in the north (Finnish Meteorological Institute, 2017a). Mean snow depth at the end of March is 5–40 cm in the south and 60–80 cm in the north (Finnish Meteorological Institute, 2017b).

The catchments used in the study were selected based on availability of long-term runoff records, snow line records, and meteorological data. Precipitation and temperature data used in the study were national 10 km × 10 km interpolated gridded temperature and precipitation data from the Finnish Meteorological Institute. The snow course data and runoff data used were obtained from the Finnish Environmental Institute's open database (OIVA). The snow line measurement points used in the study were either located inside the study catchments or < 10 km from the catchment divide. Daily runoff from the catchments was measured using water stage recorders and weirs for smaller sites, as described in Seuna and Linjama (2004) and discharge rating curves for defined channel cross-sections for larger sites, and were checked for errors by the Finnish Environmental Institute.

2.2. CPI_{snow} model

The CPI_{snow} model was developed by Akanegbu et al. (2017) for use in high-latitude regions where snowmelt is the dominant hydrological process controlling runoff and hydrological data are limited. It is very similar to the HBV model (Bergström, 1976, 1992; Seibert, 1999) in the snow and routing routines. However, instead of using a soil box and storage boxes in the soil moisture and response routines as in HBV, CPI_{snow} uses a modified form of the current precipitation index equation by Smakhtin and Masse (2000) to transform precipitation into runoff hydrograph form (Akanegbu et al., 2017; see Appendix, Fig. A1). The transformed precipitation is converted to runoff using two runoff conversion parameters C_T and L_f for the winter-spring and summer-autumn period, respectively (Akanegbu et al., 2017; Fig. A1). The converted runoff is routed out using the same routing routine parameter *Maxbas* as in the HBV model. The snow routine in the CPI_{snow} model is controlled using five parameters (T_{crit}, *DDf*, *cfr*, *Tsf*, *f*, and S_{corr}). The soil moisture routine is controlled using only one parameter (Th_Q), while the response routine is controlled using three parameters (K_r, C_T, and L_f). An input modifier (P_{corr}) is used to correct for errors in precipitation input data. For a detailed description of the CPI_{snow} model algorithm and parameters, see Akanegbu et al. (2017) and the Appendix (Fig. A1).

2.3. Evaluation of parameter-catchment attribute relationships

2.3.1. Identification of runoff control factors

The first step towards evaluation of the model's parameter relationships with catchment attributes was to identify catchment physical and climate characteristics, which could have a profound effect on the CPI_{snow} model parameters. In order to fulfil the objectives of the study, only physical catchment data and catchment climate information measurable in ungauged basins without extensive site investigation were considered. Based on the structure of the CPI_{snow} model, the physical catchment characteristics considered were: catchment surface area (S_A, km^2), land use (forest (FST, %), agriculture (AGR, %), peatland (PTL, %)), mean slope (mSlp, %), mean slope of the highest-order stream channel (StSlp, Θ), lake percentage (LK, %), and outlet lake percentage (O-LK, %) (Table 1). The catchment climate characteristics considered were average total annual precipitation (Tot-P, mm/a), average summer-autumn total annual precipitation (TotSA-P, mm/a), average winter-spring total annual precipitation (TotWS-P, mm/a), snow-day ratio (SD_R, -), and warm-dry day index (WD, d). The snow-day ratio is defined as the number of days that experience precipitation when the average daily air temperature is below 2 °C, divided by the total number of days per year with precipitation (Sawicz et al., 2011). The warm-dry day index is defined as number of days with air temperature > 5th percentile of daily mean air temperature and precipitation < 25th percentile of daily amounts (Arsenović et al., 2013). The 75th percentile air temperature and 25th percentile daily precipitation were calculated from 22 years (1990–2011) average daily air temperature and precipitation in Finland. The highest-order stream was taken to be the main stream channel leading to the outlet, into which other lower-order channels drain (Fig. 2). The outlet lake was regarded as any lake that cuts across the highest-order stream channel, as shown in Fig. 2 and the lake coverage in each catchment was determined from CORINE land use data from Finnish Environmental Institute database using ArcGIS. The average slope (mSlp, %) of the catchments was calculated using a digital elevation map (DEM)-derived index characterizing typical hillslopes, while the average slope of the highest-order stream channel was calculated as mean gradient from elevation differences in the main stream channel. The summer-autumn period was defined to run from June 20 to October 20, while the winter-spring period was defined to run from October 21 to June 19. These seasonal periods were defined based on their average duration in Finland (Finnish Meteorological Institute, 2017c).