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Effects of distribution level of hydrological models in mountainous catchments

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Abstract The main purpose of this study is to investigate the effects of distribution level of hydrological models in a seasonally snow covered and mountainous area. Five different versions of the Hydrologiska Byråns Vattenbalansavdelning (HBV) model, i.e. the lumped model ("LWhole"), semi-distributed model with 10 elevation bands ("SBand"), 1 km grid-based model without routing ("GRZero"), 1 km grid-based model with hillslope routing ("GROne") and 1 km grid-based model with both hillslope and river routing ("GRTwo"), were compared on two seasonally snow-covered mountainous catchments, the Losna (11 213 km^2) and the Norsfoss (18 932 km^2) catchments in central southern Norway. According to the Nash-Sutcliffe efficiency of daily models, the rank of the five models is "GRTwo", "GROne", "GRZero", "SBand" and "LWhole". The results show that the finer representation of input data and hydrologic process can lead to better model performance in these two catchments and the effects of distribution level of hydrological models also depend on the catchment characteristics. No significant improvement was achieved by the Muskingum-Cunge channel routing method showing that the channel routing is not necessarily required in daily flow simulation at these mountainous catchments.

Key words distributed modeling; HBV; mountainous and snow covered area; Norway

INTRODUCTION

The development of hydrological models has gone through several stages, input-output black-box models, lumped conceptual models, distributed conceptual models, and physically-based distributed models (Singh, 2002). Distributed models were expected to outperform lumped models due to their more explicit representation of hydrological processes and larger parameter space. However, the value of distributed modelling cannot be highly recognized if the sole objective is the best discharge fit at the catchment outlet (Beven, 2001, 2002). The Distributed Model Intercomparison Project (DMIP) showed that the lumped models overall outperformed distributed models, some distributed models showed comparable results to lumped models in many basins and few distributed models showed clear improvements in one or more basins. The results of the comparison highly depended on the shape, orientation and soil characteristics of the basins (Reed *et al.*, 2004). The conclusions from other researchers were not consistent due to the differences in the models they used in their own research, the data quality and the basin characteristics (Refsgaard & Knudsen, 1996; Bell & Moore, 1998; Zhu & Peng, 2010). Many studies have shown that distributed models were not better than the semi-distributed or lumped models based on the same model concepts, e.g. SCS methods (Michaud & Sorooshian, 1994), HBV model (Das *et al.*, 2008; Wrede *et al.*, 2013), and the possible explanation was the limited use of the spatial information. Although it is difficult to define the requirements of "fully-distributed" models, it is of scientific and practical interest to investigate the value of distributed modelling for hydrological simulation.

More precipitation falls as snow than rain at higher latitude and altitude area, and runoff depends on snow melting rather than the timing of precipitation. A significant duration of seasonal snowpack exists in all Europe, Asia and North America above 40°N, as well as in the Andean cordillera in South America and small high-mountain ranges in Australia and Africa. In addition, the hydrological importance of snow is not restricted to areas where it lies for months: many dry land rivers in areas with little or no snow are fed largely by melt water from high mountains 100–1000 km away (Ferguson, 1999). However, few snowmelt runoff models are reported for basin scale due to the complex physical snowmelt process and difficulty in observations (Singh, 2001). The Hydrologiska Byråns Vattenbalansavdelning (HBV) model is chosen in this research due to its wide uses both in the general and snow hydrology for scientific research and practical purposes in cold and mountainous Scandinavian countries.

The main objective of this study is to investigate the effects of distribution level of the HBV model in a seasonally snow covered and mountainous area. This study should not only contribute to the overall understanding of the effects of spatial discretization of hydrological processes in conceptual rainfall–runoff modelling, but also provide an improved modelling tool for flood forecasting and water resources assessment for seasonally snow-covered mountain basins.

STUDY AREA AND DATA

Study area

The Glomma catchment is located in central southern Norway and covers around 15% of the whole of Norway (Fig. 1). With two main branches, the Glomma River, with a basin area of 41 963 km^2, is the longest river, and has the largest drainage basin area in Norway. Climate varies considerably along the Glomma River from upper glacial regions in the northwest to the lowlands in the south. The northern part is characterized by lower temperature, more precipitation and more snow than the southern part (Tockner *et al.*, 2009) due to higher altitude as well as to the strong North Atlantic Oscillation effects (Skaugen *et al.*, 2012). Records (1961–1990) from the meteorological station in Lillehammer (226 m above sea level) within the Glomma catchment show that mean annual temperature is 2.9°C, ranging from –9.3°C to 14.7°C in January and July, respectively. The mean annual precipitation is 720 mm, of which more than 50% falls as snow. Floods in the lower Glomma are usually associated with snow melting, heavy precipitation or their combination (Tockner *et al.*, 2009). The Losna and Norsfoss catchments lie in the upstream of the western and eastern branches of the Glomma River, with an area of 11 213 km^2 and 18 932 km^2, respectively. The mean altitude of the Losna catchment is 1158 m above sea level whereas the mean altitude of the Norsfoss catchment is 732 m above sea level. The mean values of slope are 11.8° in the Losna catchment and 6.7° in the Norsfoss catchment.

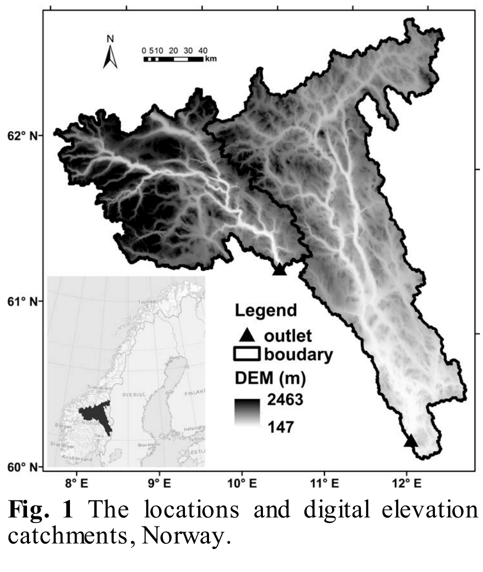

Fig. 1 The locations and digital elevation models (DEM) of the Losna (left) and Norsfoss (right) catchments, Norway.

Data description

Digital map data from the Norwegian Mapping Authority (NMA) were used to determine land cover and elevation for each model grid. The 1 km DEM and slope data were aggregated from original datasets of 25 m. The land cover data were classified based on vector data at a scale of 1:50 000 (lakes, glaciers, forests and bogs) and all other land cover classes were classified as open land or mountainous areas. The potential tree level, which can be thought of as a continuous surface cutting through the landscape along the tree line, from NMA was used to separate areas above and below tree level. These four land cover classes were subdivided to seven land cover types, i.e. lake, bog, forest, bedrock, heather, subalpine and open land according to the data from a Norwegian Vegetation Atlas (Beldring *et al.*, 2003).

The drainage networks delineation was constructed based on the D8 algorithm by ArcGIS10 and was finally checked by visual inspection according to the digital river networks defined by the Norwegian Water Resources and Energy Directorate (NVE), and manually modified if necessary.

Estimating the channel cross-sectional size is difficult, but essential in river flow routing modelling. In the Losna and Norsfoss catchments, 93 and 111 measurements, respectively, were achieved from maps (Chen *et al.*, 2011). The measured values near the Otta River in the Losna catchment and the Folla River in the Norsfoss catchment were similar to the main channel width measured in the flooding zone projections done by NVE. However, the measured river cross-sectional sizes were not able to be used in the models without preprocessing. In Norway, some lakes, e.g. Losna and Storsjøen, are very long and crossed by rivers, which would cause big errors near the lakes. Additionally, the digital river network sometimes cannot overlap with the natural river system, which would lead to a small number of measured river cross-sections. To reduce the uncertainty and make full use of the measured data, a method was developed to get the river width of the cell. First, the digital river network was ordered by Strahler number (Strahler, 1957) and river network was divided into different sections. Then, the width of one river section was assigned the mean value of all the river cross-sections measured in the respective local sub-catchment.

Daily maps of precipitation and temperature in 1 km horizontal resolution interpolated from the meteorological stations and corrected for elevation differences by the Norwegian Meteorological Institute (NMI) were used in this study (Mohr, 2008). These datasets are available from 1960 up to now and can be downloaded from www.senorge.no. The discharge data of the Losna and Norsfoss stations from the station network of the Hydrology Department, NVE, were used in the calibration and validation of the model. The daily discharge data were transformed from the original observed stage level with quality control of Bayesian Rating Curve Fitting method (Petersen-Øverleir *et al.*, 2009).

MODELS AND PARAMETERIZATION

The HBV model concept was developed by the Swedish Meteorological and Hydrological Institute (SMHI) in the early 1970s (Bergström, 1976), and has been developed into many versions focusing on different aspects (Sælthun, 1996; Beldring *et al.*, 2003; Ehret *et al.*, 2008; Wrede *et al.*, 2013). The main routines are snow accumulation and melting, soil moisture accounting and runoff generation. A simple degree-day method was used for snowmelt calculation, and the evapotranspiration was calculated based on field capacity and permanent wilting point. The runoff was simulated by two nonlinear parallel reservoirs representing the direct discharge and the groundwater response with the spatial distribution of soil saturation controlling the response described by a nonlinear distribution function. Additional detailed information of the model version used in this study can be found in the references (Sælthun, 1996; Lindström *et al.*, 1997; Beldring *et al.*, 2003).

To give a full picture of the effects of spatial representation of hydrological processes in discharge simulation, five different models were compared in the study, including a lumped model for the whole catchment, a semi-distributed model with 10 elevation bands, a grid-based model without routing, a grid-based model with hillslope routing and a grid-based model with hillslope routing and river routing. (1) The lumped model for the whole catchment is called “LWhole”. The mean value time series of the 1 km grid meteorological data within the catchment were used as the input. (2) The semi-distributed model with ten elevation bands for each catchment is called “SBand”. The meteorological data were extracted for every elevation band from 1 km grid meteorological data and the mean was used as the input of every elevation band. (3) The first grid-based model, called “GRZero”, divides each catchment into 1 km square grids, and runoff generation is performed in every grid. The outlet discharge is the runoff sum-up of all the catchment cells. (4) The second grid-based model, named “GROne”, also considers the distributed hillslope routing. The calculation procedure is as follows. First, the runoff generation subroutine runs in the most upslope cells, and the generated runoff is added to the soil moisture storage and subsequently to groundwater storage in downslope landscape cells. Second, runoff from the downslope cells is determined by the HBV water balance calculations with local input equal to runoff from the upslope cells and the local net precipitation. Third, runoff generation routine performs from the upslope cells to the downslope cells until the runoff discharges into the river cell. (5) The third grid-based HBV called “GRTwo”, considers both the distributed hillslope and river routing. The runoff is summed at the respective river element and routed by the Muskingum-Cunge method between the river elements. The river channel cross-section was assumed to be rectangular. When the Courant number is greater than one, the output discharge is equal to input discharge, which means no routing at the local gird on that day. Details of the Muskingum-Cunge method can be seen in Todini (2007).

The parameters were calibrated by a model-independent nonlinear parameter estimation and optimization package called PEST (Parameter ESTimation). It is frequently used for model calibration in different research fields (Doherty & Johnston, 2003). Insensitive parameters are fixed and others, e.g. snow accumulation threshold temperature, and upper zone and lower zone recession coefficients, with a physical range were calibrated twice. The initial values of the second round were the results of the first round calibration. The same parameter values were used for all the lakes in the study area, and land cover parameter values varied for each land cover. The objective function used in this research was the Nash-Sutcliffe efficiency, and PEST will approach the global optimized parameter set by maximizing this objective function.

RESULTS AND DISCUSSION

The five models defined in the previous chapter were calibrated during 1981–1990 and validated during 1991–2010, both in the Losna and Norsfoss catchments. The Nash-Sutcliffe efficiency and water balance bias are used as the criteria for model performance. The relative water volume biases of the models are less than 3% with two exceptions during the validation period in the Losna (7%) and Norsfoss (5%) catchments of the “LWhole” model. Only the results of Nash-Sutcliffe efficiency are shown in Fig. 2.

It is seen from Fig. 2 that: (1) all the five models in Norsfoss catchment outperformed the same models in the Losna catchment. That is mainly due to that the Losna catchment is located at higher elevations with steeper slopes and has more complex meteorological conditions. Additionally, the Losna catchment is more regulated by reservoirs than the Norsfoss catchment, and the HBV algorithm in our research is for natural conditions. (2) The finer spatial representation in the

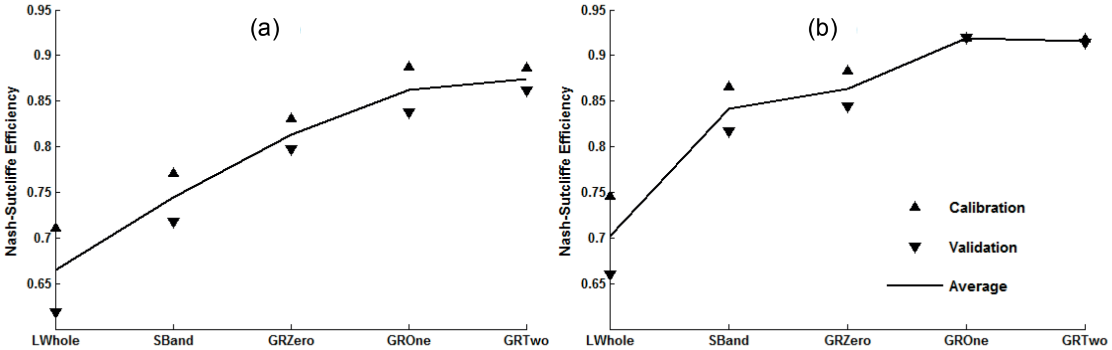

Fig. 2 Nash-Sutcliffe efficiency of “LWhole”, “SBand”, and three grid-based models in the (a) Losna and (b) Norsfoss catchments for the calibration and the validation. “Average” is the mean of the calibration and the validation.

input data and the hydrologic processes improve the models in both catchments, but with different magnitudes. The differences existing in the “LWhole”, “SBand” and “GRZero” show the effects of finer spatial representation of the input data, and the differences existing in the “GRZero”, “GROne” and “GRTwo” show the effects of finer spatial representation of the hydrologic process. (3) The remarkable improvements from “LWhole” to “SBand” show that the precipitation and temperature, the main factors controlling the hydrological processes, are very much dependent on the elevation in the high latitude and altitude mountainous areas of the catchments. (4) More significant improvement from “SBand” to “GROne” in the Losna catchment than in the Norsfoss catchment is due to the higher spatial variability of the meteorological conditions in the Losna catchment than in the Norsfoss catchment. These different improvements indicate that the catchment spatial variability determines if the finer spatial scale models are able to outperform the large scale and the lumped models. (5) The significant improvements from “GRZero” to “GROne” in both catchments show that the distributed hydrologic hillslope process simulation is essential in the mountainous areas. The small improvements from “GROne” to “GRTwo” in the two catchments imply that the channel routing is not necessarily required in the daily mean flow simulation in these mountainous catchments. This is quite reasonable for moderate-sized catchments in the high slope and shallow soil mountainous area of Norway.

For illustrative purpose, the daily discharge graphs for the validation period simulated by four models and the observations are shown in Fig. 3. “GRTwo” and “GROne” are very similar, especially in the Norsfoss catchment, so “GROne” is not plotted in Fig. 3. It clearly shows that “GRTwo” is the best in terms of fitness in the discharge simulation, and all the same models are better in the Norsfoss catchment than in the Losna catchment. These results are consistent with results shown in Fig. 2. “GRZero” and “SBand” overestimated the high flow, and “SBand” and “GRZero” underestimate the low flow in the Losna catchment and in the Norsfoss catchment. The river flow in Norway is highly fed by groundwater (Colleuille *et al.*, 2006), therefore the absence of slope routing in the models will reduce the delayed effects of groundwater and lead to fast response of runoff to the rainfall and snow melting, shown as opposite error in the high flow and low flow. The low flow simulation of the same models in the Losna catchment is worse than in the Norsfoss catchment, especially from August to December, which is due to the flow regulation in the Losna catchment.

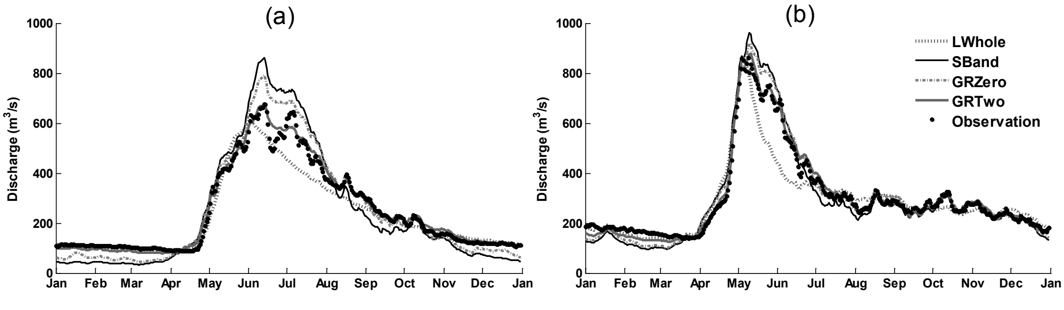

Fig. 3 Mean daily discharge for the validation period of the Losna (a) and Norsfoss (b) catchments simulated by four models and the observation. The “GROne” (not shown) is very similar to the “GRTwo”, especially in the Norsfoss catchment.

CONCLUSIONS

In this paper, five variants of the HBV model, i.e. the whole lumped (“LWhole”), semi-distributed with 10 elevation bands (“SBand”), 1 km grid-based without routing(“GRZero”), 1 km grid-based with hillslope routing (“GROne”), and 1 km grid-based with both hillslope and river routing (“GRTwo”) are compared in the cold and mountainous Losna and Norsfoss catchments. According to the Nash-Sutcliffe efficiency of daily models, the rank of five models is “GRTwo”, “GROne”, "GRZero", "SBand" and "LWhole". The results show that both the finer representation of input data and the hydrologic processes can lead to better model performance, and the magnitude of improvement is dependent on the catchment characteristics. No improvement was achieved by the Muskingum-Cunge channel routing method showing that the channel routing is not necessarily required in daily flow simulation at these mountainous catchments. It is mainly due to the fast river flow in the V-shape river channels with high slope and low roughness.

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