Journal of Hydrology 536 (2016) 147–160

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Effects of uncertainties in hydrological modelling. A case study of a mountainous catchment in Southern Norway

Kolbjørn Engeland [a,*], Ingelin Steinsland [b,c], Stian Solvang Johansen [d], Asgeir Petersen-Øverleir [d], Sjur Kolberg [c]

[a] Norwegian Water Resources and Energy Directorate (NVE), P.O. Box 5091 Majorstuen, 0301 Oslo, Norway
[b] Department of Mathematical Sciences, Norwegian University of Science and Technology, 7491 Trondheim, Norway
[c] SINTEF Energy Research, 7465 Trondheim, Norway
[d] Statkraft, 0284 Oslo, Norway

ARTICLE INFO

Article history:
Received 8 October 2015
Received in revised form 9 February 2016
Accepted 17 February 2016
Available online 26 February 2016
This manuscript was handled by Andras Bardossy, Editor-in-Chief, with the assistance of Vazken Andreassian, Associate Editor

Keywords:
Hydrological modelling
Streamflow uncertainty
Precipitation uncertainty
Temperature uncertainty

SUMMARY

In this study, we explore the effect of uncertainty and poor observation quality on hydrological model calibration and predictions. The Osali catchment in Western Norway was selected as case study and an elevation distributed HBV-model was used. We systematically evaluated the effect of accounting for uncertainty in parameters, precipitation input, temperature input and streamflow observations. For precipitation and temperature we accounted for the interpolation uncertainty, and for streamflow we accounted for rating curve uncertainty. Further, the effects of poorer quality of precipitation input and streamflow observations were explored. Less information about precipitation was obtained by excluding the nearest precipitation station from the analysis, while reduced information about the streamflow was obtained by omitting the highest and lowest streamflow observations when estimating the rating curve. The results showed that including uncertainty in the precipitation and temperature inputs has a negligible effect on the posterior distribution of parameters and for the Nash–Sutcliffe (NS) efficiency for the predicted flows, while the reliability and the continuous rank probability score (CRPS) improves. Less information in precipitation input resulted in a shift in the water balance parameter P_{corr}, a model producing smoother streamflow predictions, giving poorer NS and CRPS, but higher reliability. The effect of calibrating the hydrological model using streamflow observations based on different rating curves is mainly seen as variability in the water balance parameter P_{corr}. When evaluating predictions, the best evaluation scores were not achieved for the rating curve used for calibration, but for rating curves giving smoother streamflow observations. Less information in streamflow influenced the water balance parameter P_{corr}, and increased the spread in evaluation scores by giving both better and worse scores.

1. Introduction

The operational motivation for this study is streamflow forecasting for hydropower scheduling. Probabilistic forecast are useful to make better decisions (i.e. increase the gain), in particular during critical situations when the reservoirs are full or close to filled. For more than three decades quantification of uncertainties on model simulations and predictions has been an active area of research (e.g. Beven and Binley, 1992; Cloke and Pappenberger, 2009; Kavetski et al., 2006a; Knoche et al., 2014; Kuczera, 1983; Thiemann et al., 2001; Xie et al., 2009; Yapo et al., 1998; Zhao et al., 2015), Streamflow simulations are characterized by four important sources of uncertainties (Refsgaard and Storm, 1996):

1. Uncertainties in inputs (e.g. temperature and precipitation).
2. Uncertainties in streamflow used for calibration.
3. Uncertainties in model parameters.
4. Uncertainties and errors in model structure.

During calibration and evaluation of hydrological models, the total uncertainty is a complex interaction of a forward uncertainty propagation of precipitation and temperature, inverse uncertainty propagation of streamflow data used for optimization of model parameters, and the ability of the model structure and its parameters to transform the inputs to outputs. To disentangle each uncertainty component and assess how each of them contributes to the

* Corresponding author.
E-mail address: koe@nve.no (K. Engeland).

http://dx.doi.org/10.1016/j.jhydrol.2016.02.036
0022-1694/© 2016 Elsevier B.V. All rights reserved.

total uncertainty is a challenging task. A path to gain understanding is to explicitly describe the uncertainty of each component in the modelling chain and perform sensitivity studies. In this paper we addressed the uncertainty components (1), (2) and (3) in an explicit way. Uncertainties and errors in model structure were not analyzed.

Uncertainty can be divided into random errors and systematic errors. Random errors are (almost) independent from time step to time step, and can contribute much to the uncertainty for short-term predictions, i.e. for daily or hourly lead times. Systematic errors persist for the whole period under investigation. The systematic errors are important for correct calculations of seasonal water balance and snowmelt floods.

Important random errors in precipitation and temperature inputs originate from the measurements themselves and from interpolation between gauges. Important systematic errors originate from the under-catch in precipitation gauges and from unknown spatial trends that are approximated in the interpolation. The effect of uncertainty in inputs on streamflow predictions is often addressed using a Monte Carlo approach where an ensemble of inputs is shuffled through a hydrological model to get an ensemble of outputs (e.g. Spank et al., 2013; Yoo et al., 2012). Alternatively, an inverse approach might be used by applying a multiplier to each rainfall event (Kavetski et al., 2006a,b; Reichert and Mieleitner, 2009; Sun and Bertrand-Krajewski, 2013; Vrugt et al., 2008). In Renard et al. (2011) this method is refined by applying a conditional precipitation simulator to extract a prior distribution of rainfall multipliers for each day. Also in operational hydrology there is a long tradition of calibrating the inputs manifested as precipitation correction factors and elevation gradients (e.g. Sælthun, 1996), but these are constant in time and no uncertainty is estimated.

The uncertainties in streamflow observations originate from errors in water level observations that introduce a random error and the translation from water level to streamflow via the rating curve that contributes mainly with a systematic error. The uncertainty in streamflow contributes in a two-fold way to our model calibration and evaluation strategy: (i) backwards uncertainty propagation during model calibration and (ii) possibly biased evaluation and consequently wrong conclusions since we use uncertain observations as references. Only a few publications study the effects of streamflow uncertainties in model calibration. Both McMillan et al. (2010) and Peña-Arancibia et al. (2015) assume independent rating curve errors between days, but they conclude differently. McMillan et al. (2010) find that the main effect of uncertain streamflow observations on model calibration is an increased parameter uncertainty, whereas Peña-Arancibia et al. (2015) find that their approach gives less uncertainty in the parameters. In a simulation study, Montanari and Di Baldassarre (2013) find that errors in streamflow observations have a small effect on model structure errors. Croke (2009) suggests an alternative objective function that accounts for the serial correlation uncertainties in the observed streamflow data caused by the rating curve uncertainty. The effect of rating curve uncertainty is also studied in the context of hydrological indices and signatures (Clarke, 1999; Clarke et al., 2000; Westerberg and McMillan, 2015) and flood frequency analysis (Kuczera, 1996; Neppel et al., 2010; Petersen-Øverleir et al., 2009). These papers demonstrate that the rating curve error has an important influence on the design flood estimates, and that the systematic errors caused by the rating curve model have a larger influence than random errors in water level observations. We find that there is a need for more understanding about the effect of streamflow uncertainties, especially systematic errors, on precipitation-runoff model calibration, predictions and evaluation.

Uncertainty in model parameters has been extensively investigated in hydrological literature. Different approaches to study uncertainty for calibrated parameters include Bayesian methods (e.g. Engeland et al., 2005; Kuczera, 1983; Thiemann et al., 2001), the GLUE method (e.g. Beven and Binley, 1992), multi-objective methods (e.g. Engeland et al., 2006; Yapo et al., 1998), and sensitivity-based methods (e.g. Spear et al., 1994). In this study, we chose a Bayesian approach.

From the cited papers above, we see that several approaches for integrating several uncertainty sources in model calibration are presented in literature. However, until now, as far as the authors know, there are no papers that systematically investigate the combined effect of uncertainties in inputs and observed streamflow in hydrological modelling.

The objective in this study was to systematically investigate the combined effect of uncertainties in inputs and observed streamflow in hydrological modelling, i.e. model calibration, predictions and evaluation. As our study system, we chose the Osali catchment. This catchment has a meteorological station measuring precipitation and temperature, and a rating curve of relatively high quality. The meteorological station is located in the lowest part of the catchment. For hydropower catchments in Norway with a meteorological station, this is a common situation. However, for most hydropower catchments, there are no meteorological stations inside the catchment, and available stations are at a lower altitude. Therefore, by removing the precipitation station inside Osali, we get a realistic situation with less information about precipitation. Further, by removing the most extreme streamflow observations when calculating the rating curve, we get a realistic quality of the rating curve for most gauged catchment in Norway. Hence, this case study allows us to study, in a realistic way, the consequences of having less information about the true precipitation and streamflow for model calibration, predictions and evaluation.

In particular, we wanted to answer the following research questions:

- What is the effect of including a random error in the precipitation and temperature inputs?
- What is the effect of decreased information about precipitation by excluding the nearest precipitation station?
- What is the effect of the uncertainty in streamflow observations?
- What is the effect of reduced information about the true streamflow by using a rating curve where the measurement of the highest and lowest streamflow is excluded when estimating the rating curve?

To answer these questions, we designed a set of calibration experiments and evaluation strategies. Note that all four questions concern model calibration, whereas the last two questions also concern model evaluation. We used the elevation distributed HBV model operating on daily time steps combined with a Bayesian formulation and the MCMC routine Dream (Vrugt et al., 2009) for parameter inference.

We will now continue to describe the data used and the hydrological model. It is followed by a description of uncertainty models for the inputs and the streamflow observations. We then describe our calibration strategies before the results are presented, discussed and some conclusions are drawn.

2. Study catchment, data, and hydrological model

The studied Osali catchment is located in southwestern Norway (Fig. 1). Its area is 22.6 km^2, the elevation range from 643 to 1345 m.a.s.l. with 890 m.a.s.l. as the average. Around 82% of the catchment is located above the tree line, 6% is covered by forests, 12% by lakes. There are no settlements within the catchment.