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A Proxy Basin Approach for Hydrological Modelling in Ungauged Snow-fed Basin of Nepal

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Abstract
Runoff prediction in ungauged basins is a vital task in hydrologic sciences. This study implements a GR4J rainfall-runoff model to simulate runoff in two nested basins of western Nepal. The calibrated model parameters are then interchanged in a proxy-basin framework in order to assess spatially transferability of model parameters for runoff simulation in ungauged basin. The calibrated model showed good performance for both the downstream Chamelia basin and upstream Naugragad basin with a NSE of 0.86 and 0.83 during calibration and 0.84 and 0.64 during validation respectively. Spatial transfer of calibrated model parameters from upstream to downstream basin and vice-versa closely match the hydrograph obtained from calibrated model. The results show spatial transfer of model parameters as a feasible option for streamflow prediction in ungauged basins of Nepal.

Keywords
Ungauged, Chamelia, Proxy-basin, GR4J, Calibration

1. Introduction

Continuous discharge data is an important hydrologic variable for a wide range of applications such as hydraulic infrastructure design, flood and drought forecasting, watershed planning and management etc. However, discharge measuring stations are sparse and highly heterogeneous, especially in mountainous regions. Estimation of discharge from these headwater basins are vital since a large number of water-use activities such as hydropower generation, drinking water, irrigation, flood forecasting, impact assessments etc. are dependent upon the magnitude and timing of runoff from these basins [1, 2].

By definition, an ungauged basin is an area where discharge data is missing or is of poor quality [3]. This definition can also be further applied to basins which have undergone significant changes since historic streamflow records cannot portray the hydrologic behavior of the basin anymore [4]. Research focus on prediction in ungauged catchments was formally endorsed and set out by the PUB (Prediction in Ungauged Basins) Science and Implementation Plan [4] within the IAHS (International Association of Hydrological Sciences) Bureau in 2003. Regionalization techniques have been designed to enable estimates of streamflow signatures, e.g. flood frequency distribution, low flow frequency distribution, flow duration curves, etc., or rainfall-runoff model parameters to simulate continuous streamflow at ungauged catchment [5]. Regionalization provides a framework for the transfer of hydrologic information from gauged (donor) basins to ungauged (receptor) basins.

In Nepal, there are very few studies that have explored the potential of spatial transferring of model parameters. A study in Budhigandaki basin by spatial transferring calibrated parameters of SWAT model to the downstream station showed good prediction of daily streamflow [6]. Similarly, in another study in Tamor basin of Nepal, the calibrated model parameters of a J2000 model in Dudhkoshi basin is transferred to nearby Tamor basin with great success [7]. Methods to predict streamflow in ungauged basins currently applied in Nepal cannot predict the streamflow time series accurately mainly because they are empirical relationships derived with only a few gauges and without incorporating the hydrological

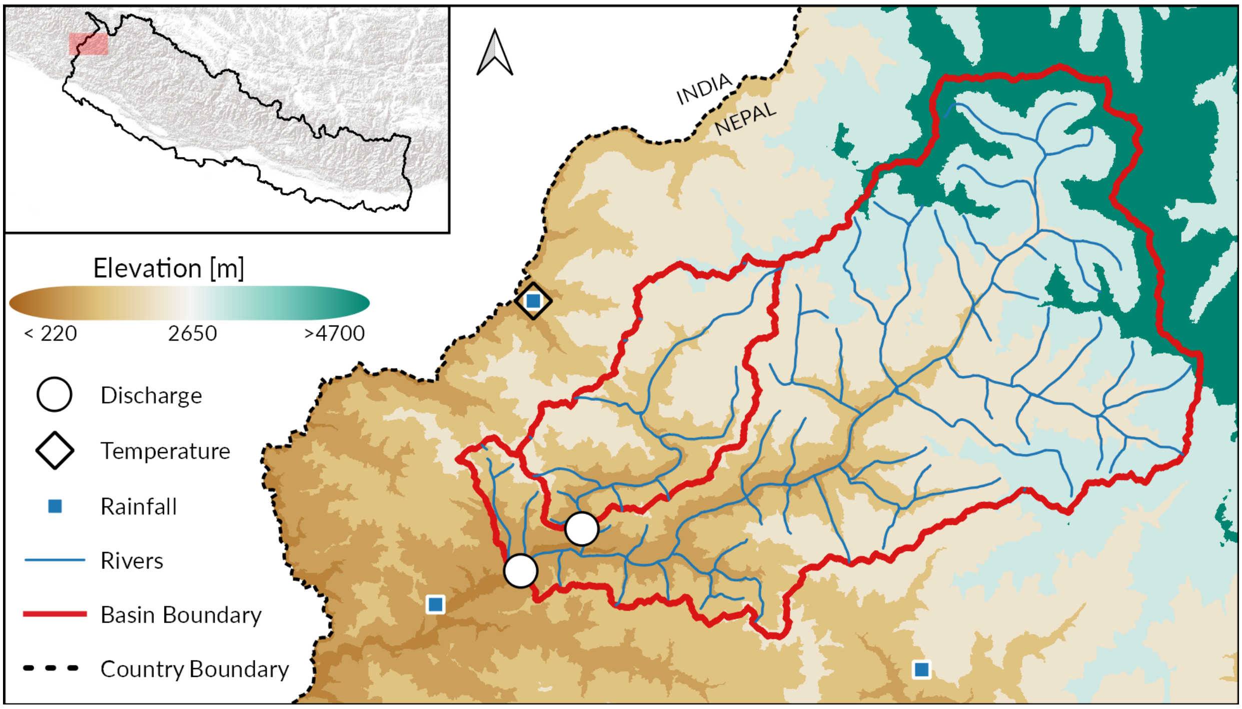

Figure 1: Map of study area showing elevation, river channels and hydro-meteorological stations.

components such as landcover and soil characteristics [8, 7, 6, 9]. This leads to underprediction or overprediction of engineering design that has adverse economic effects in the long term. Inaccuracy and uncertainty in predictions also hinder the proper formulation of water-related plans and policies. Hence, there is an immediate need of exploring how hydrologic processes can be modelled in the ungauged basins of Nepal.

The main objectives of this study are as follows:

1. To assess the performance of GR4J rainfall-runoff model for streamflow simulation in two basins of western Nepal, and
2. To explore transferrability of full model parameter set between upstream and downstream basins.

2. Study area and data

2.1 Study area

The selected area for this study is the Chamelia basin (st. index 120) and Naugragad basin (st. index 115). Figure 1 shows the location map of the study area with hydro-meteorological stations. The Chamelia basin is a snow-fed basin located in western Nepal with a total drainage area of 1183.60 km^2. The elevation ranges from 725 masl to 7006 masl with average elevation of 2980 masl. Similarly, mean basin-averaged precipitation is around 2290 mm with 81% of the precipitation contributed by summer monsoon. Naugragad is a small tributary of the chamelia basin. The drainage area of the basin is 205.76 km^2 which is around 17% of the total area of the Chamelia basin.

2.2 Data description

The hydrological and meteorological input data for model set-up was obtained from ground-based stations maintained by Department of Hydrology and Meteorology (DHM). The meteorological input data were quality checked before use in the model. It was ensured that no more than 25% of the data in the study period were missing. Errors in temperature data such as maximum temperature lesser than minimum temperature and outliers which was determined as values outside the range of $\pm$ 3 times of standard deviation were checked. All the erroneous data and outliers were treated as missing values. The missing data for precipitation was filled using APHRODITE [10] dataset whereas for temperature, missing data was filled using long-term average method. Basin-averaged precipitation was computed using Thiessen's/Voronoi polygon method. For daily potential evapo-transpiration data, Oudin's method [11] was used which is based on daily average

Table 1: Description of model parameters in the GR4J-CemaNeige model, search range for automatic optimization and calibrated parameters for Chamelia and Naugragad basins.

Parameters	Description	Search range	Chamelia	Naugragad
X_1	Maximum capacity of production storage	0.01 - 2500	1452.46	760.23
X_2	Groundwater exchange coefficient	-100 - 100	4.89	4.99
X_3	Capacity of routing storage	0.01 - 1000	495.03	744.20
X_4	Time base for unit hydrograph	0.5 - 10	0.64	0.87
θ_{G1}	Degree-day factor	0 - 10	9.98	9.83
θ_{G2}	Snow pack cold content	0 - 1	0.44	0.32

temperature, latitude and julian days and is computed as,

$$PET = \begin{cases} \frac{R_e}{\lambda\rho}\frac{T_a+5}{100}, & \text{if } T_a+5>0 \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

where, PET is the rate of potential evapotranspiration (mm/day), R_e is extraterrestrial radiation (MJm^{-2} day^{-1}), λ is the latent heat flux in (MJ/kg), ρ is the density of water (kg/m^3) and T_a is the daily air temperature (°C), derived from long term average.

3. Methodology

3.1 Hydrologic Modelling

The GR4J model [12] is a 4-parameter lumped conceptual rainfall runoff model. The model has two phases: a production phase and a routing phase. The unit hydrograph routing is employed to route the flow to the outlet. The GR4J model in its basic form doesn't incorporate snow processes. To account for the snow contribution in the basin, the model was coupled with a Cema-Neige snow module [13], a 2-parameter snow accumulation and melt model based on degree day approach. In the Cema-Neige model, the basin is divided into 5 elevation zones of equal area. The precipitation and evapotranspiration was assigned equal weightage for all the elevation zones. For each elevation band, the input temperature data are extrapolated using a constant lapse rate value and median elevation of the band given by,

$$T_z = T + \theta_z \times (Z_{stn} - Z_{med}) \tag{2}$$

where, T_z is the extrapolated temperature value, T is the temperature value of reference station, θ_z is the temperature lapse rate, Z_{stn} is the elevation of ground station and Z_{med} is the median elevation of the band.

An annual mean temperature lapse rate (θ_z) of 5.2 °Ckm^{-1} was adopted for this study [14].

The model was set-up for the Chamelia and Naugragad basins from years 2000-2015. The years 2001-2010 (10 years) was used as calibration period and 2011-2015 (5 years) was used as validation period. The first year was used for spin-up of model states. For automatic calibration of the model, shuffled complex evolution method developed by University of Arizona (SCE-UA) [15] was implemented. Table 1 shows the model parameters and their corresponding search ranges. The Nash-Sutcliffe efficiency (NSE) [16] metric was used as the objective function for calibration of the model and is given by,

$$NSE = 1 - \frac{\sum_{i=1}^{N}(Q_{mod,i} - Q_{obs,i})^2}{\sum_{i=1}^{N}(Q_{mod,i} - \overline{Q_{obs}})^2} \tag{3}$$

where, $Q_{mod,i}$ is the modelled streamflow in time step i, $Q_{obs,i}$ is the observed streamflow in time step i, N is the total time period and $\overline{Q_{obs}}$ is the long-term average observed streamflow.

Apart from the NSE metric, the verification of modelling results was also performed using visual inspection of simulated and observed hydrograph, Kling-Gupta efficiency (KGE, Eq. 4) [17] and Volumetric efficiency (VE, Eq. 5) metrics. Both the NSE and KGE ranges from -∞ to 1 while VE ranges from 0 to 1. A score of 1 denotes perfect match.

$$KGE = 1 - \sqrt{(\gamma-1)^2 + (\alpha-1)^2 + (\beta-1)^2} \tag{4}$$

$$VE = 1 - \frac{\sum |Q_{mod} - Q_{obs}|}{\sum Q_{obs}} \tag{5}$$

where, γ is Pearson correlation coefficient, β is the the bias ratio and α is the variability ratio.

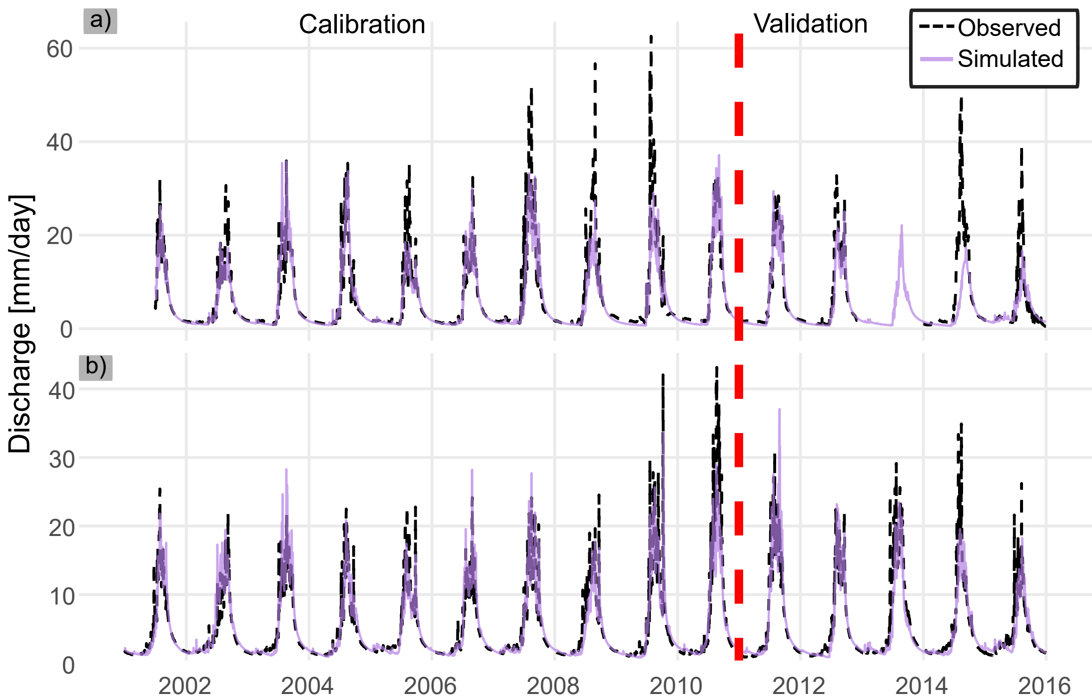

Figure 2: Observed and simulated hydrograph for Naugragad basin (a) and Chamelia basin (b) during calibration (2001-2010) and validation period (2011-2015).

3.2 Proxy-basin approach

The proxy-basin approach is one of the widely used regionalization methods for predicting continuous runoff in ungauged basins. The primary assumption of this approach is that the calibrated model parameters are transferrable to a similar basin. The transferrability of model parameters is tested based on spatial proximity wherein it is assumed that nearby basins are climatologically and hydrologically homogeneous. Under this assumption, the calibrated parameters in one basin was transposed to other basin and the resulting simulated runoff was validated and vice-versa.

4. Results and Discussion

4.1 Model performance

Results show good performance of the model for both the upstream (Fig. 2a.) and downstream basins (Fig. 2b.) during the calibration and validation periods. The model performance for simulation of daily hydrograph in terms of NSE, KGE and VE are also summarised in Table 2. For Chamelia basin, the model showed very good performance with a NSE of 0.86 and 0.84 for calibration and validation periods respectively. The NSE for Naugragad basin was found to be 0.83 during calibration period, however the performance declined during the validation period reaching a NSE value of 0.64. Overall, the simulated hydrograph closely replicates the annual pattern of streamflow, high flows as well as low flows with deficiency in reproducing the extremes.

4.2 Proxy-basin performance

After calibration and validation of the model, the calibrated parameters for upstream and downstream basins were swapped in order to assess the spatial transferrability for possible application in ungauged setting. Since the calibrated periods were same for both the basins, model performance of proxy-basin approach during calibration period denotes transferrability in spatial domain only whereas performance during validation period refers to transferrability in both spatial as well as temporal domain. The simulated hydrograph using proxy-basin approach and calibrated model are compared with the observed flows in Figure for year 2012 of validation period. The hydrograph from transferred parameters closely replicates the hydrograph from calibrated model for upstream (Figure 3.a) and downstream basin (Figure 3.b). Results of model run from proxy-basin parameters were comparable to that from calibrated parameters with a NSE of 0.80 and 0.62 for Naugragad and 0.84 and 0.83 for Chamelia during

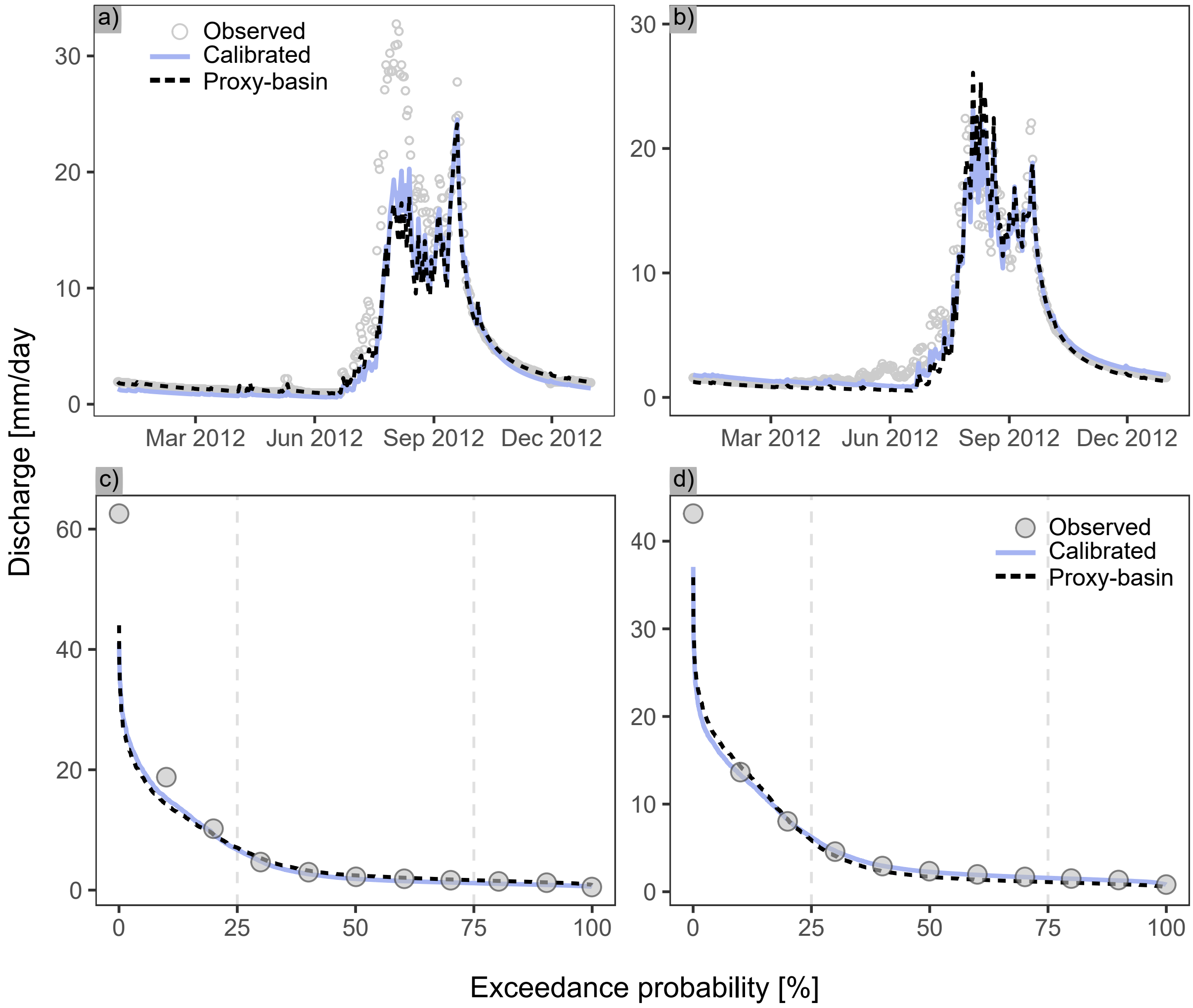

Figure 3: Daily hydrograph for year 2012 of validation period and flow duration curve obtained from observed flow, calibrated and proxy-basin parameters for upstream Naugragad basin (a,c) and downstream Chamelia basin (b,d).

calibration and validation periods respectively (Table 2). Similarly, the proxy-basin parameters were also able to reproduce the flow duration curve obtained from observed as well as simulated flow from calibrated model (Figure 3.c and 3.d).

		NSE	KGE	VE
Calibrated				
Naugragad	Calibration	0.83	0.80	0.76
	Validation	0.64	0.55	0.65
Chamelia	Calibration	0.86	0.89	0.78
	Validation	0.84	0.87	0.76
Proxy-basin				
Naugragad	Calibration	0.80	0.75	0.74
	Validation	0.62	0.52	0.64
Chamelia	Calibration	0.84	0.90	0.75
	Validation	0.83	0.87	0.75

Table 2: Performance metrics for simulation of daily hydrograph using calibrated model parameters and proxy-basin parameters during calibration and validation periods.

5. Conclusion and future outlook

This study explores the spatial transferrability of hydrologic model parameters for runoff prediction in ungauged basins using a proxy-basin approach. The GR4J-CemaNeige model was employed in two snow-fed basins of western Nepal - the Chamelia basin and Naugragad basin. The model showed good performance for simulation of daily hydrograph in both basins during calibration and validation period. By interchanging the model parameters, the model could still reproduce the hydrograph and flow duration curve obtained from calibrated model.

Since the regionalized model cannot outperform a calibrated model, the performance of regionalization depends upon the performance of hydrologic model. Despite the good results obtained from spatial proximity based regionalization in this study, other widely used regionalization methods such as physical similarity, regression-based methods should be assessed in a wide range of basins in order to justify the robustness of these methods. In conclusion, regionalization of hydrologic model parameters seems to be a viable option for hydrologic prediction in ungauged basins of Nepal.

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References

[1] Mandira Singh Shrestha, R Heggen, K Thapa, M Ghimire, and N Shakya. Flood risk and vulnerability mapping using GIS: a Nepal case study. In *Proceeding of the second Asia Pacific Association of Hydrology and Water Resources Conference, Singapore*, volume 1, pages 180–190, 2004.

[2] Suraj Lamichhane and Narendra Man Shakya. Integrated assessment of climate change and land use change impacts on hydrology in the Kathmandu Valley watershed, central nepal. *Water*, 11(10):2059, 2019.

[3] Y He, A Bárdossy, and E Zehe. A review of regionalisation for continuous streamflow simulation. *Hydrology and Earth System Sciences*, 15(11):3539–3553, 2011.

[4] Murugesu Sivapalan, K Takeuchi, SW Franks, VK Gupta, H Karambiri, V Lakshmi, X Liang, JJ McDonnell, EM Mendiondo, PE O'connell, et al. IAHS decade on predictions in ungauged basins (pub), 2003–2012: Shaping an exciting future for the hydrological sciences. *Hydrological sciences journal*, 48(6):857–880, 2003.

[5] Ludovic Oudin, Alison Kay, Vazken Andréassian, and Charles Perrin. Are seemingly physically similar catchments truly hydrologically similar? *Water Resources Research*, 46(11), 2010.

[6] Suresh Marahatta, Laxmi Devkota, and Deepak Aryal. Hydrological modeling: a better alternative to empirical methods for monthly flow estimation in ungauged basins. *Journal of Water Resource and Protection*, 13(3):254–270, 2021.

[7] Santosh Nepal, Wolfgang Flügel, Peter Krause, Manfred Fink, and Christian Fischer. Assessment of spatial transferability of process-based hydrological model parameters in two neighbouring catchments in the himalayan region. *Hydrological Processes*, 31(16):2812–2826, 2017b.

[8] Jeeban Panthi, Rocky Talchabhadel, Ganesh R Ghimire, Sanjib Sharma, Piyush Dahal, Rupesh Baniya, Thomas Boving, Soni M Pradhanang, and Binod Parajuli. Hydrologic regionalization under data scarcity: Implications for streamflow prediction. *Journal of Hydrologic Engineering*, 26(9):05021022, 2021.

[9] Marc F Müller and Sally E Thompson. Comparing statistical and process-based flow duration curve models in ungauged basins and changing rain regimes. *Hydrology and Earth System Sciences*, 20(2):669–683, 2016.

[10] Akiyo Yatagai, Kenji Kamiguchi, Osamu Arakawa, Atsushi Hamada, Natsuko Yasutomi, and Akio Kitoh. APHRODITE: Constructing a long-term daily gridded precipitation dataset for asia based on a dense network of rain gauges. *Bulletin of the American Meteorological Society*, 93(9):1401–1415, 2012.

[11] Ludovic Oudin, Frédéric Hervieu, Claude Michel, Charles Perrin, Vazken Andréassian, François Anctil, and Cécile Loumagne. Which potential evapotranspiration input for a lumped rainfall–runoff model?: Part 2—towards a simple and efficient potential evapotranspiration model for rainfall–runoff modelling. *Journal of hydrology*, 303(1-4):290–306, 2005.

[12] Charles Perrin, Claude Michel, and Vazken Andréassian. Improvement of a parsimonious model for streamflow simulation. *Journal of hydrology*, 279(1-4):275–289, 2003.

[13] Audrey Valéry, Vazken Andréassian, and Charles Perrin. 'as simple as possible but not simpler': What is useful in a temperature-based snow-accounting routine? part 2–sensitivity analysis of the cemaneige snow accounting routine on 380 catchments. *Journal of hydrology*, 517:1176–1187, 2014.

[14] Dambaru Ballab Kattel, T Yao, K Yang, L Tian, G Yang, and D Joswiak. Temperature lapse rate in complex mountain terrain on the southern slope of the central himalayas. *Theoretical and applied climatology*, 113(3):671–682, 2013.

[15] Qingyun Duan, Soroosh Sorooshian, and Vijai Gupta. Effective and efficient global optimization for conceptual rainfall-runoff models. *Water resources research*, 28(4):1015–1031, 1992.

[16] J Eamonn Nash and Jonh V Sutcliffe. River flow forecasting through conceptual models part I—A discussion of principles. *Journal of hydrology*, 10(3):282–290, 1970.

[17] Hoshin V Gupta, Harald Kling, Koray K Yilmaz, and Guillermo F Martinez. Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling. *Journal of hydrology*, 377(1-2):80–91, 2009.