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Comparative performance of GR4JSG and J2000 hydrological models in the Dudh Koshi catchment of the Himalayan region

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Abstract: Hydrological models are widely applied to make informed decisions in water resources planning and management. However, the representation of hydrological processes in a model is subject to uncertainty due to the conceptualization of those processes. The choice of models is a trade-off among availability of data and understanding of processes in the catchment. In this study, we compared the performance of two hydrological models, the conceptual GR4JSG and the process based J2000 hydrological model in a glaciated alpine catchment in the Himalayan region. Both models were adapted to simulate the glacier melt runoff in which seasonal snowmelt and glacier icemelt occurs. Regarding the spatial heterogeneity, the catchments are represented by numbers of hydrological response units (or functional units in GR4JSG).

Both models were calibrated for the period 1986-1991 and validated for the period 1992-1997. The models were able to represent the overall hydrograph with a Nash Sutcliffe Efficiency (NSE) in the J2000 model of 0.84 and 0.87 for calibration and validation, respectively, and for the GR4JSG model, the NSE was 0.87 and 0.89 for the calibration and validate periods. Although the models simulated baseflow and medium range flows (recession and rising limbs) reasonably well, the peak flows were underestimated in some instances. On average, the percentage bias is below 3% in both models. The hydrograph suggested that the GR4JSG tends to underestimate observed hydrograph during pre-monsoon season. Similarly, GR4JSG tends to overestimate July-September compared to J2000. The glacier melt contribution to stream flow is about 13% and 17% for GR4JSG and J2000 respectively. The variation can be expected due to conceptualization of hydrological processes in both models.

Keywords: *GR4JSG model, J2000 model, Himalayan region, snow and glacier, melt runoff*

1. INTRODUCTION AND MOTIVATION

Hydrological models are widely applied to make informed decisions in water resources planning and management. The application of hydrological models ranges from understanding water balance and availability (Nepal et al., 2014), impact due to climate and land use change and sustainable land and water resources management (Lutz et al., 2014; Neupane et al., 2015). However, the representation of hydrological processes in a model is subject to uncertainty due to the conceptualization of those processes (Butts et al., 2004; Refsgaard et al., 2006). Therefore, model performance and thereby interpretation of results can differ depending upon how the important processes are taken into account and the approach of model calibration and validation. The physically based models aim to represent the processes in detail whereas conceptual models tends to replicate at a conceptual level (Singh et al., 2002). Therefore, the choice of models is a trade-off among availability and quality of input data and understanding of processes in the catchment (Butts et al., 2004).

In the context of global climate change, the warming climate might have serious implications in the water resources in the Himalayan region (Eriksson, et al. 2009). Many studies have attempted to understand the impact on hydrological regime using different hydrological models like SRM (Immerzeel et al. 2010; Khadka et al., 2014), SPHY (Lutz et al. 2014) and J2000 (Nepal et al. 2014). In the context of the Himalayan region, the snow and glacier melt processes can be conceptualized by simple or complex approaches depending upon the data availability (Hock, 2003). Some of the variability in model results can be attributed to differences in conceptualization of hydrological models. Therefore, it is important to compare the results from different models to possibly understand some of the sources of model uncertainty.

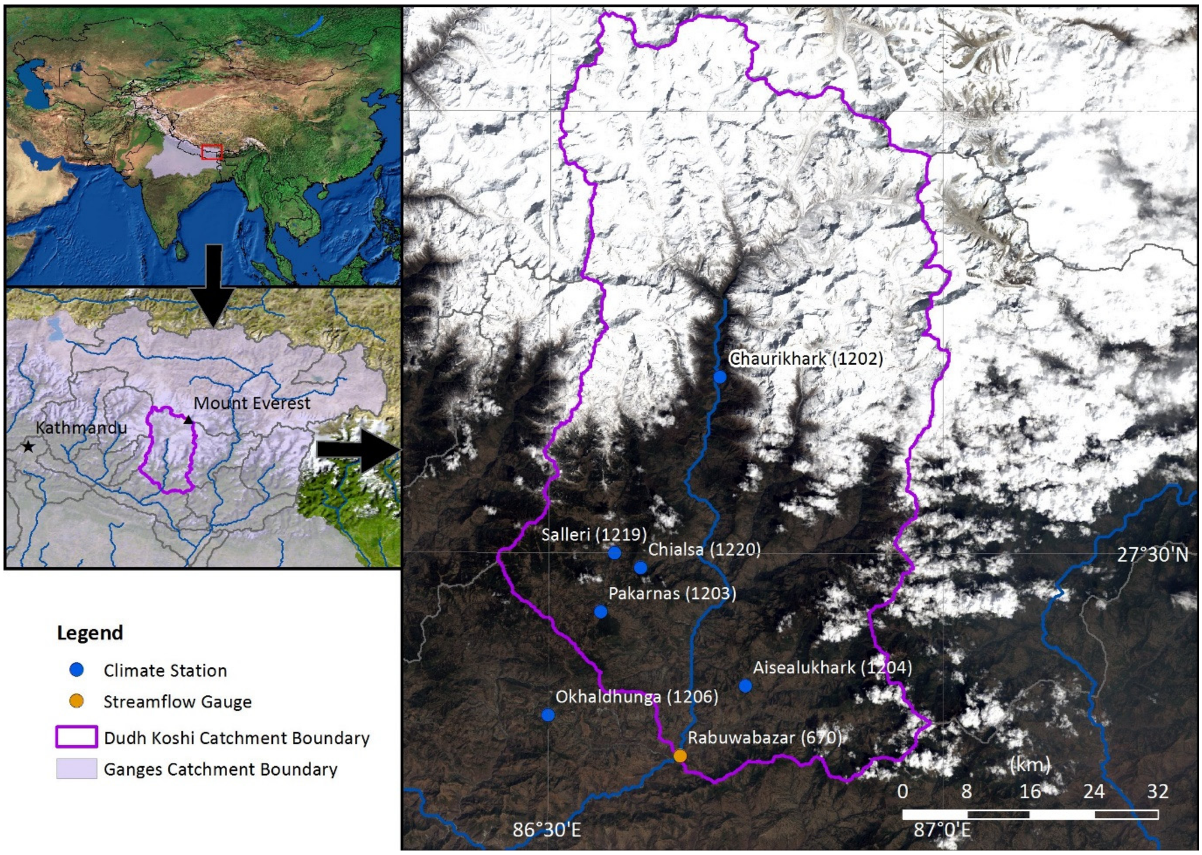

Figure 1. Location of the Dudh Koshi catchment in Eastern Nepal and hydro-meteorological stations.

This study aims to apply two different hydrological models – the lumped conceptual GR4JSG and process oriented J2000 – in the alpine catchment of the Himalayan region to evaluate the performance of a conceptual model and process based model and their estimation of hydrograph components. The performance of these models will be evaluated with the historic observed discharge data. Both models used the same input data to reduce the uncertainty due to model input. The results on different hydrological components are compared to discuss the different results for runoff components originating from the conceptualization of the two models.

2. STUDY AREA

The model was applied in the Dudh Koshi basin in eastern Nepal (3712 km^2). The basin has steep topography. It contains the world's highest mountain, Mt. Everest, at 8848 m. The lower part of the basin has temperate climate whereas the higher elevation areas have sub-alpine to alpine climate. The deciduous forest dominates the lower elevations while coniferous forest dominates the higher mountains. The high elevation areas of the basin are dominated by glaciers which occupies 13% of the catchment. The basin has six precipitation and one climate stations (as shown in Figure 1) which were used to force the hydrological models. The average annual precipitation of the six stations is 1934 mm, while the mean annual discharge is 1602 mm. Nearly 82% of the precipitation falls during the monsoon season (June-September) and about 77% of the discharge occurs during the same period. The average maximum and minimum temperature at the Okhaldhunga station located at 1720m (Figure 1) are 21°C and 12.6°C, respectively.

3. MATERIALS AND METHODS:

The study used two different hydrological models. GR4JSG is a conceptual model which uses functional units to define different catchment areas, and in this study, elevation and glaciers are used to define the different units. J2000 is a processed based distributed hydrological model which applies Hydrological Response Units (HRUs) as a modelling entity. A short description of these models and related catchment distribution are provided below:

3.1. GR4JSG model

The GR4JSG model developed by Perrin et al. (2003) is a daily lumped rainfall-runoff model with four parameters. As shown in Figure 2, the parameter x1 controls the size of the production store, x2 controls the flux to groundwater, x3 controls the size of the routing store and x4 controls the recession of the unit hydrograph. In addition to original GR4J, the GR4JSG (Figure 2) model attempts to include the snowmelt and glacier icemelt which are important hydrological processes in high mountain catchments like Dudh Koshi. The model distributes precipitation between rain and snow, depending upon the average temperature of the hydrological response units. The proportion of snow in total precipitation is estimated using same formulation as J2000 (Krause, 2002; Nepal, 2012).

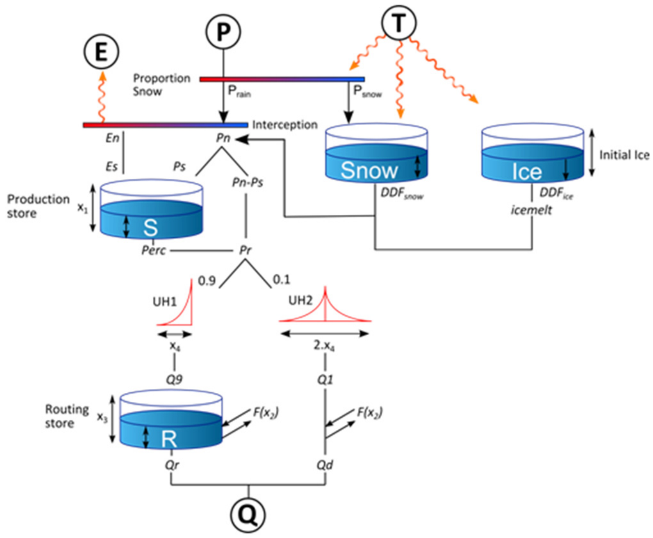

Figure 2. Conceptual layout of GR4JSG model.

The snow is stored in the form of snowpack. The snowmelt and glacier melt are estimated by applying degree-day factor (DDF) approach (Hock, 2003). Therefore, there are two additional parameters in the GR4JSG model, i.e., the DDF of snowmelt (DDFsnow) and icemelt (DDFice). The snowmelt or icemelt are regarded as additional precipitation and passed to the rainfall runoff model similar to the approach adopted by Valéry et al. (2014). It is assumed that when the glacier area is covered with seasonal snow, glacier icemelt begins after the snow storage is zero. Since there is little information available for glaciers in the catchment, in GR4JSG, glacier areas are considered time invariant and the dynamic process of glacier shrinking and expanding are not including in the GR4JSG model (same with J2000 also). Therefore, glaciers are initialized as having very large ice stores and it is considered that the gradual change in glacier area might not affect the model results for a short period. The eWater Source (Welsh et al, 2013) implementation of GR4JSG was used in this paper, where the catchments are divided into 46 functional units according to elevations and glacier cover.

3.2. J2000 model

The J2000 model is a distributed and process oriented distributed hydrological model for hydrological simulations of meso-and macro-scale catchments. It is implemented in the Jena Adaptable Modelling system (JAMS), which is a software framework for component-based development and application of environmental models (Kralisch and Krause 2006). The J2000 model represents the important hydrological processes of an alpine mountain hydrology, including snow and glacier melt processes. The layout of the J2000 hydrological model is provided in Figure 3. The model uses Hydrological Response Units (HRUs) as a modelling entity. Each HRU consists of a specific set of information related to land use, soil, geology and topographic properties (slope, aspect and elevation). The climatic information from stations are distributed to each HRU by applying Inverse Distance Weight (for precipitation) and lapse rate (for temperature).

The precipitation is distributed into rain and snow depending upon the air temperature. The interception storage holds a few mm of rainfall and snow on the leaf surface. Other than vegetation area, the rain and snow directly falls on the surface. The excess water is transferred to unsaturated zone of the soil surface where the model considers different infiltration processes (such as saturation excess and infiltration excess). The infiltrated water then percolates into underground geological formations as shown in the upper and lower zone of Figure 3. The detailed description of these processes can be found in (Krause 2002; Nepal 2012 and Nepal et al. 2014). A short description of snow and glacier melt processes are described herein:

The snowmelt module mainly describes the accumulation, melting and subsidence phases of a snow pack. The melt energy is provided in the form of temperature, rain and ground flux which estimates the potential melt from snowpack. The snow pack can store liquid water in its pores up to a certain critical density. The storage capacity is lost nearly completely when a certain amount of liquid water in relation to the total snow water equivalent is reached.

In the glacier area, the melt is driven by an enhanced degree day factor. First the snow on the glacier surface is melted in the snowmelt process described above. By using constant glacier layers, the ice melt is carried out using enhanced degree day factor (Nepal et al. 2014), which takes into account radiation, slope, aspect and debris covered factor. The outflow from an HRU is transferred to next downstream HRU until it is connected to reach. Each HRU produces four runoff components: Overland flow (RD1), Interflow 1 (RD2), Interflow 2 (RG1) and baseflow (RG2).

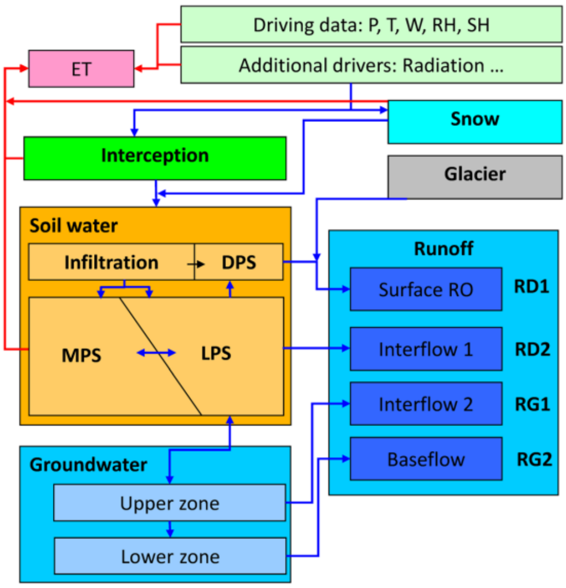

Figure 3. Conceptual layout of the J2000 model.

Both models have distributed the precipitation into rain and snow using same approach described above. The hydrological processes in the J2000 model has capsulated the hydrological processes which are controlled by 36 parameters (calibrated when values are not known). Whereas, the conceptual GR4JSG has 6 calibrated parameters.

3.3. Calibration and Validation

Both models were calibrated and validated independently. Of the 36 J2000 calibration parameters (Nepal et al., 2014), 16 sensitive parameters were optimized by applying Monte Carlo simulations. The regional sensitivity analysis (RSA) (Hornberger and Spear, 1981) has been used to analyze the sensitivity of the model parameters (Nepal et al., 2014). In the case of GR4JSG, the six parameters were calibrated using SCE-UA approach (Duan, et al., 1992). The models were calibrated using daily data from 1986-1991 and validated from 1992-1997 by applying split-sample test. The model performance was tested against Nash-Sutcliff Efficiency (NSE), coefficient of determination (r^2) and percentage bias (%).

4. RESULTS AND DISCUSSIONS

Figure 4 shows results of the calibration and validation periods for both models. The figure shows that both models are able to capture the hydrograph reasonably well. The model has captured the recession limbs especially after the monsoon season. The baseflow are also well captured in both periods, although slight underestimation can be observed during the initial years of the calibration period. The peak flows are underestimated in 1991 and 1993 by both models. During the validation period, the pre-monsoon flow is underestimated by GR4JSG compared to J2000 model. In this period, the melt process begins in the high-altitude areas. In general, the modelled discharge from both models have represented the observed hydrograph for calibration and validation periods, but with relative higher bias for high flow (>500 m^3/sec).

Table 1. Model efficiency results of the GR4JSG and J2000 models.

Period	Calibration (1986-1991)			Validation (1992-1997)		
Indices	r^2	NSE	Bias (%)	r^2	NSE	Bias (%)
GR4JSG	0.87	0.87	-4.3	0.90	0.89	1.99
J2000	0.85	0.84	+0.7	0.88	0.87	3.5

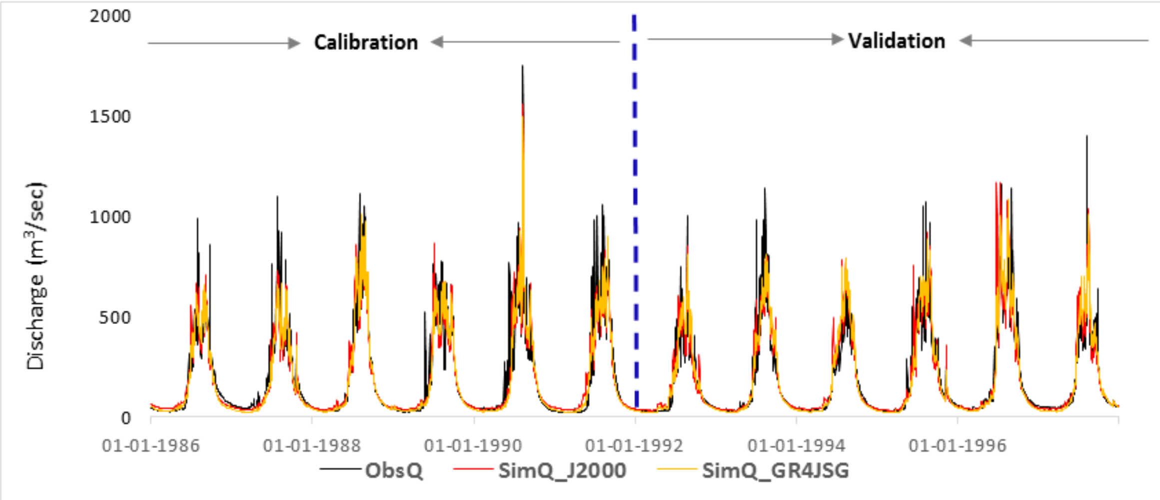

Figure 4. Observed and modelled hydrograph from the GR4JSG and J2000 models for calibration (left) and validation (right) periods. The dotted blue line divides the calibration and validation periods.

The good performance of both models is further illustrated in Table 1, with both models showing a coefficient of determination and Nash-Sutcliffe Efficiency scores in excess of 0.85 for both calibration and validation periods. The main disagreement between the models is on the bias, as GR4JSG underestimates the total volume in calibration period but overestimates it in validation periods, while the J2000 model overestimates the runoff in both periods, although with a very small bias in calibration. The average monthly hydrograph of observed and simulated discharge indicates that both models are able to capture the monthly dynamics (Figure 5). During April to June, GR4JSG tends to underestimate the hydrograph, whereas J2000 slightly overestimate. In GR4JSG, the percentage bias is +2% for the monsoon season and -1% for the whole period. Whereas for the J2000, the bias is +2% for the monsoon season and 1% for the whole period. During the pre-monsoon season when the melt runoff is the dominant component of the hydrograph, both GR4JSG and J2000 are in good

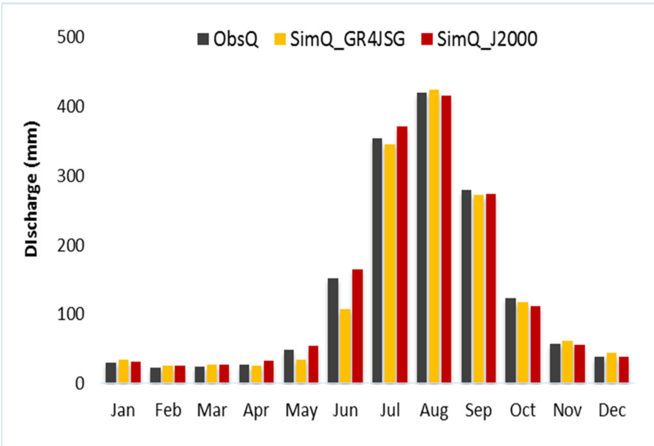

Figure 5. Average monthly hydrograph of the model run period of the two models.

agreement in March and April, whereas in May, GR4JSG underestimates the monthly flow and J2000 slightly overestimates.

Figure 6 shows the runoff from snowmelt and glacier melt for both models. The runoff contribution from melt for the J2000 model (555mm) is higher than in GR4JSG (484 mm). The melt runoff, including snowmelt and icemelt from the entire catchment, accounts 24% and 35% for the total simulated runoff in GR4JSG and J2000 models, respectively. From the glacier area, the contribution of melt runoff from GR4JSG is 13% including 7% from glacier ice melt. In the case of J2000, the contribution is 17% including 5% from glacier ice and 2% from rain runoff (i.e. rain-on-snow surface). However, outside of glacier area, both models produce similar results: 18% from GR4JSG and 17% from J2000. As both models have similar mean annual runoff, GR4JSG estimates a much larger contribution from rainfall to the catchment runoff. The differences in the melt estimations are due to the representation of the snow processes in both GR4JSG and J2000. In GR4JSG, the snowmelt runoff originates from a conceptual snow storage using a degree day factor. In J2000, the representation of snow processes is far more complex, with the model representing snowpack dynamics and including effects of rain on the surface of snow (rain-on-snow). This rain-on-snow is regarding as snowmelt in the J2000 model. The contribution of rain-on-snow is very high in low elevation areas and gradually decreases in high-altitude areas (Nepal et al. 2014). In the absence of detailed field measurements, it is difficult to determine which of the models (if any) has the best estimation of the runoff components. The two models are likely to provide different responses to investigations of climate change scenarios due to the differences in runoff components and conceptualization.

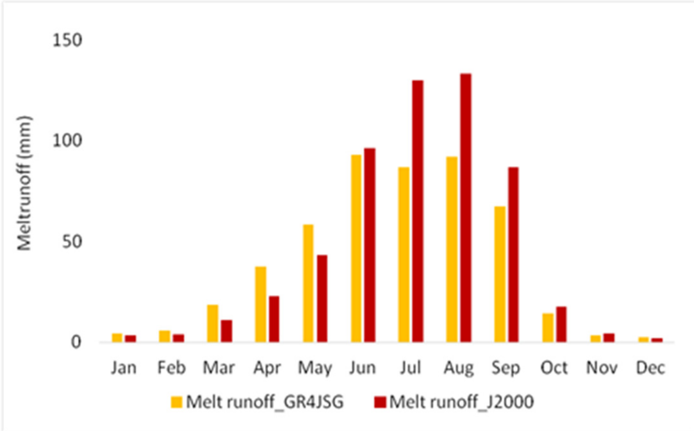

Figure 6. Melt runoff from glacier and non-glacier areas from the catchment provided by the GR4JSG and J2000 models.

5. CONCLUSIONS

In this study, we compared the performance of two hydrological models, the conceptual GR4JSG and the process based J2000 hydrological model in a glaciated alpine catchment in the Himalayan region. The results suggest that both GR4JSG and J2000 models are able to capture the hydrological dynamics of the monsoon dominated alpine catchment. The model efficiency results shows that both GR4JSG and J2000 have similar performance in terms of NSE, bias and r^2. This results also suggested that GR4JSG model in spite of being conceptual and having few parameters produces reasonably good results. The main variation lies with snowmelt which is coming from the different conceptualization of snowmelt processes in both models. Future research will focus on understanding these differences and validating the runoff components from other studies.

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REFERENCES

Butts, M.B., Payne, J.T., Kristensen, M., Madsen, H., 2004. An evaluation of the impact of model structure on hydrological modelling uncertainty for streamflow simulation. *J. Hydrol.* 298, 242–266.

Duan,Q., Sorooshian, S., Gupta, V.K., 1992. Effective and efficient global optimization for conceptual rainfall-runoff models. *Water Resour. Res.*, 28 (4),1015–1031

Eriksson, M., Jianchu, X., Shrestha, A. B., Vaidya, R. A., Nepal, S., & Sandström, K. (2009). The changing Himalayas: impact of climate change on water resources and livelihoods in the greater Himalayas. ICIMOD. Kathmandu

Hock, R. (2003). Temperature index melt modelling in mountain areas. *Journal of Hydrology*, 282(1), 104-115.

Hornberger, G.M., Spear, R.C., 1981. An approach to the preliminary analysis of environmental systems. *J. Environ. Manage.* 12 (1), 7–18.

Immerzeel, W.W., van Beek, L.P.H., Bierkens, M.F.P., 2010. Climate change will affect the Asian water towers. *Science* 328, 1382–5.

Khadka, D., Babel, M.S., Shrestha, S., Tripathi, N.K., 2014. Climate change impact on glacier and snow melt and runoff in Tamakoshi basin in the Hindu Kush Himalayan (HKH) region. *J. Hydrol.* 511, 49–60.

Kralisch S, Krause P. 2006. JAMS – a framework for natural resource model development and application. In Proceedings of the International Environmental Software Society (IEMSS), Vermont, USA.

Krause P. 2002. Quantifying the impact of land use changes on the water balance of large catchments using the J2000 model. Physics and Chemistry of the Earth 27: 663–673.

Lutz, A.F., Immerzeel, W.W., Shrestha, A.B., Bierkens, M.F.P., 2014. Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation. *Nat. Clim. Chang.* 4(7), 587-592.

Nepal S. 2012. Evaluating upstream–downstream linkages of hydrological dynamics in the Himalayan region. PhD Thesis, Friedrich Schiller University of Jena.

Nepal, S., Krause, P., Flügel, W.-A., Fink, M., Fischer, C., 2014. Understanding the hydrological system dynamics of a glaciated alpine catchment in the Himalayan region using the J2000 hydrological model. *Hydrol. Process.* 28, 1329–1344.

Neupane, R.P., White, J.D., Alexander, S.E., 2015. Projected hydrologic changes in monsoon-dominated Himalaya Mountain basins with changing climate and deforestation. *J. Hydrol.* 525, 216–230.

Perrin, C., C. Michael, and V. Andreassian (2003). Improvement of a parsimonious model for streamflow simulations. *Journal of Hydrology*, 279, 275–289.

Refsgaard, J.C., van der Sluijs, J.P., Brown, J., van der Keur, P., 2006. A framework for dealing with uncertainty due to model structure error. *Adv. Water Resour.* 29, 1586–1597.

Singh, V.P., Frevert, D.K., (eds.), 2002. Mathematical models of small watershed hydrology and applications. *Water Resources Publications*, Highlands Ranch, Colorado.

Valéry, A., Andréassian, V., Perrin, C., 2014. 'As simple as possible but not simpler': What is useful in a temperature-based snow-accounting routine? Part 1 – Comparison of six snow accounting routines on 380 catchments. *Journal of Hydrology*, 517, 1166-1175.

Welsh, W. D., Vaze, J., Dutta, D., Rassam, D., Rahman, J. M., Jolly, I. D., ... & Lerat, J. (2013). An integrated modelling framework for regulated river systems. Environmental Modelling & Software, 39, 81-102.