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Selecting hydrologic modelling approaches for water resource assessment in the Yongdam watershed

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Abstract

Robust hydrologic models are needed to help manage water resources under a changing climate. In this paper, we assessed daily streamflow predictions by applying two simple conceptual models (IHACRES and GR4J) and one physically-based, semi-distributed model (SWAT) for the Yongdam Dam watershed. We compared these models' capabilities in reproducing observed streamflow in the time and quantile domains. The calibration and validation of the three models were performed using 13-year daily datasets and the k-fold cross validation method. The Particle Swarm Optimization algorithm was used to optimize flow parameters for the more complex model, whereas the Shuffled Complex Evolution algorithm was used to calibrate the two simpler models. Global sensitivity analysis was performed for the complex model to reduce the number of flow parameters; the effective hydraulic conductivity in main channel alluvium was the most sensitive parameter, followed by the baseflow alpha factor for bank storage. The results showed that GR4J was slightly better than SWAT and IHACRES, and IHACRES had equivalent model performance to SWAT, with respect to the day-to-day flow comparison focused on reproducing the exact observed discharge hydrograph. However, SWAT performed best for reproducing the frequency distribution curve. Furthermore, SWAT performance was improved for each flow range of the flow duration curve by manually changing the most sensitive model parameters. In general, the results revealed that a multi-model ensemble approach with SWAT and either GR4J or IHACRES should be utilized for regional water resources assessment in the Yongdam watershed.

Keywords

IHACRES, GR4J, SWAT, water resource assessment, time-domain, quantile-domain

Introduction

There are numerous criteria that can be used for choosing the best hydrologic model. These criteria are usually project-dependent (Cunderlik, 2003) because every project has its own specific requirements and criteria are user-dependent, for example, the graphical user interface and computer operation system. The three models for this study were selected based on the following questions: (1) Does the model simulate the variables required by this research? (2) Is the model capable of simulating a continuous process? (3) Can all inputs required by the model be provided within time and cost constraints of the study? (4) Is the model freely available? (5) What was the model performance in previous studies?

Three rainfall-runoff models, SWAT (Arnold *et al.*, 1998; Arnold and Fohrer, 2005), IHACRES (Jakeman and Hornberger, 1993), and GR4J (Perrin *et al.*, 2003) were applied to Yongdam Dam watershed. Their capabilities in reproducing observed discharge frequency distributions and hydrographs were compared. These three structurally different hydrological models are seldomly used for assessing the hydrological impact of climate change in the Korean peninsula. Theoretically, a physically-based distributed model represents the underlying hydrological and land surface processes in greater detail than conceptual or statistical models (Beven, 2001), but the simple conceptual model that focuses on reproduction of the water balance within a basin is often a better choice in the case of water resources planning, such as in climate change assessments (Tegegne, 2017).

The selected three rainfall-runoff models have been successfully used in different studies, such as SWAT in Asia (e.g., Zhuang *et al.* 2015; Wang *et al.* 2015; Azari *et al.* 2016), IHACRES (e.g., Post and Jakeman, 1999; Dye and Croke, 2003; Croke *et al.*, 2004) and GR4J (e.g., Payan *et al.*, 2008; Oudin *et al.*, 2008; Andréassian *et al.*, 2009). Moreover, these three rainfall-runoff models were compared in Tegegne *et al.* (2017) in a data scarce region, Ethiopia; the author reported that the selected simple conceptual models, GR4J and IHACRES, performed comparably to the more complex model, SWAT, at a daily time step.

In climate change assessment studies, day-to-day model comparisons between observed and simulated flows are insufficient for identifying the best hydrological model. Therefore, we compared the three hydrological models based on flow duration curve as well as hydrographs. Flow duration curves focus on reproducing the observed discharge frequency distribution rather than the exact hydrograph. Under this comparison technique, we divided the whole flow time series into five flow intervals, i.e., high flow, moist flow, mid-range flow, dry conditions, and low flow conditions, after arranging the flow time series in descending order. Low flow selections are essential for water resource management, water supply planning, and ecological restoration, while peak flow analysis is useful for flood protection and water resources management. Hydrograph-based comparison focuses on reproducing the exact hydrograph rather than the observed discharge frequency distribution. For the hydrograph assessment we used the entire flow range.

Study basin and data

The Yongdam reservoir watershed is a sub-basin of the Geum River Basin, located in the south-west region of the Republic of Korea (Fig. 1). The watershed consists of 70% mountain and 21% agricultural areas. The mean annual temperature is 11.6°C and mean annual rainfall is 1362 mm, with heaviest rainfall events occurring in the summer. Daily streamflow data were collected from the Yongdam reservoir stream gauging station, which has a drainage area of 930.43 km^2. The elevation of the study area ranges from 220 to 1580 m above mean sea level.

Observed daily weather data, with a record length of 13 years from 2001 to 2013, were collected from five weather stations: Jeonju, Geumsan, Geochang, Imsil, and Jangsu. Data collected from these stations included precipitation, temperature, wind speed, relative humidity, and solar radiation. Areal rainfall was calculated using the

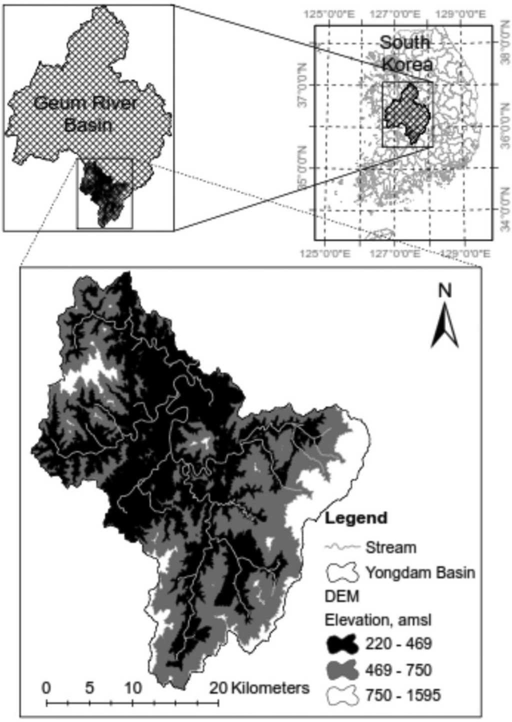

Figure 1 – Location of the Yongdam Dam watershed.

Thiessen polygon method and potential evapotranspiration data was generated with the Penman–Monteith method in the SWAT model, and these were used as input data for the IHACRES and GR4J models.

Methodology

Rainfall-runoff models

Soil and Water Assessment Tool (SWAT) model

The Soil and Water Assessment Tool (SWAT) (Arnold *et al.*, 1998) is a continuous-time and physically-based, semi-distributed hydrological model. SWAT was developed to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large complex watersheds with different soil, land use, and management conditions over long time periods (Eckhardt *et al.*, 2005). A more detailed description of SWAT can be found in Neitsch *et al.* (2005).

Potential evapotranspiration can be modelled with three options in SWAT, the Penman– Monteith, Priestley–Taylor, and Hargreaves methods (Neitsch *et al.*, 2005), depending on data availability; the Penman-Monteith method was used for this study. The modified SCS curve number method was chosen for computing surface runoff volume and the variable storage coefficient method was selected for flow routing through the channel. Daily rainfall, minimum and maximum temperature, wind speed, relative humidity, and solar radiation data were used for model simulation, with simulations conducted at a daily time step.

IHACRES model

IHACRES ('Identification of unit hydrographs and component flows from rainfall, evaporation, and streamflow data') is a lumped conceptual model that simulates the rainfall-runoff response of catchments, with parameters calibrated prior to simulation by comparison with observed streamflow data (Jakeman and Hornberger, 1993). It is comprised of two modules in series, a non-linear and a linear module. The non-linear loss module links rainfall and air temperature to effective rainfall with the following parameters: C – volume as a conceptual catchment wetness constant (days), T(w) – decaying time constant (days), and F – temperature modulation factor. It uses temperature and rainfall data to estimate the relative catchment moisture index, which determines the proportion of rainfall that becomes effective rainfall. The linear unit hydrograph module links effective rainfall to streamflow with the following parameters: T(q) – quick flow response decay time constant (days), T(s) – show flow response decay time constant (days), and V(s) – proportional volumetric contribution of slow flow streamflow. In IHACRES, it has been shown that the parameters in the non-linear module, C, T(w), and F, have significant direct effects on the volume and peak of the flow hydrograph, while parameters in the linear module, T(s), T(q), and V(s), have an effect on the peak flow but not volume (Taesombat and Sriwongsitanon, 2010). For calibration, the model requires rainfall, stream flow, and temperature time series data.

GR4J model (mode'le du Ge´nie Rural a' 4 parame'tres Journalier)

GR4J is a rainfall-runoff model based on four free parameters from daily rainfall data: X1 – maximum capacity of production store (mm), X2 – groundwater exchange coefficient (mm), X3 – maximum capacity of routing store (mm), and X4 – time peak ordinate of unit hydrograph UH1 (days). The production store (X1) is storage in the soil, which includes evapotranspiration and percolation and is dependent on the soil types in the river basin. The groundwater exchange coefficient (X2) is a function of groundwater exchange, which influences routing store. When X2 is a negative value, water enters the deep aquifer. When it is a positive value, water exits the aquifer to storage. Routing storage (X3) is the amount of water that can be stored in porous soil and depends on the type and humidity of soil. Time peak (X4) is the time when the ordinate peak of the flood hydrograph is created in the GR4J modelling. The ordinate of this hydrograph is created from runoff, where 90% of flow is slow flow that infiltrates into the ground and the remainder is fast flow that flows onto the surface.

Parameter optimization

The optimization algorithm used in SWAT is the Particle Swarm Optimization (PSO). It is a built-in technique in SWAT-CUP, which is a population-based stochastic optimization technique developed by Eberhart and Kennedy (1995) that uses the social behaviour of bird flocking.

For parameter optimization in the two simpler models, Shuffled Complex Evolution (Duan *et al.*, 1992; 1993) algorithms are used. We used the simpler conceptual models and optimization algorithms in the Hydromad package (Andrews *et al.*, 2011), which is a powerful package that contains various hydrological models, optimization algorithms, and statistical tools for analysis. The objective function applied in estimating the three rainfall-runoff model parameters is the Nash-Sutcliffe Efficiency (Nash and Sutcliffe, 1970) method:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \quad (1)$$

where P_i is the simulated value, O_i is the measured value, and $\overline{O}$ is the average measured value.

Performance measure

To compare the three hydrological models we used two approaches. First, a day-to-day comparison of the observed and simulated flows, for reproducing the exact hydrograph, was conducted. Second, a flow duration curve-based model comparison was carried out to assess how well the models reproduce the discharge frequency distribution.

The period of available data for the study watershed was 13 years, which was not sufficiently long for model warm-up, calibration, and validation of models as in Yapo *et al.* (1996), Anctil *et al.* (2004), and Kim *et al.* (2011). Therefore, a k-fold cross validation method was used with six 10-year calibration and 2-year validation periods. The year preceding each calibration period was used as a warm-up period.

SWAT model parameter sensitivity and uncertainty analysis

Over-parameterization is a well-known and frequent problem with hydrological models (Box and Jenkins, 1976), especially distributed models (Beven, 1989). Sensitivity analysis methods designed to reduce the number of parameters that require fitting with input–output data are common (e.g., Spear and Hornberger, 1980). Therefore, parameter sensitivity and uncertainty analyses were conducted for the SWAT model. Sensitivity analyses are often referred to as either "local' or 'global'. A local analysis addresses sensitivity relative to point estimates of parameter values, whereas a global analysis determines sensitivity with regard to the entire distribution of a parameter. Global sampling methods randomly or systemically scan the entire range of possible parameter values and sets. The sampled parameter sets can provide the user with the importance of each parameter. These can then be used to quantify the global parameter sensitivity and uncertainty of parameters and outputs. The sampling strategy is essential to this method (van Griensven *et al.*, 2006). One sampling strategy uses Latin hypercube simulations (McKay *et al.*, 1979; Iman and Conover, 1980; McKay, 1988), which are based on Monte Carlo simulations, but a stratified sampling approach is used that allows efficient estimation of the output statistics. The distribution of each parameter is subdivided into N strata with a probability of occurrence equal to 1/N.

In this study, the Soil and Water Assessment Tool – Calibration and Uncertainty Program (SWAT-CUP) was used for the global sensitivity and uncertainty analyses. The parameter sensitivities were determined by calculating the multiple regression systems that regress the Latin hypercube-generated parameters against the objective function values. A t-test was then used to identify the relative significance of each parameter.

The selected sensitive flow parameters for SWAT were then optimized using the default values for the insensitive flow parameters. The uncertainties in parameters, expressed as ranges, account for all sources of uncertainty, such as the uncertainty in deriving variables, e.g., rainfall and temperature, the conceptual model, parameters, and measured data (Abbaspour, 2012). Propagation of uncertainties in the parameters leads to uncertainties in the model output variables, which are expressed as the 95% probability distributions. These uncertainties were calculated at the 2.5% and 97.5% levels of the cumulative distribution (disallowing the worst 5% of the simulations) of the output variables generated by the propagation of parametric uncertainties using Latin hypercube sampling (Abbaspour, 2012). The percentage of observations covered by the 95% prediction uncertainty (95PPU) (P-factor) and the relative width of a 95% probability band (r-factor) to quantify the fit between simulation results expressed as 95PPU and observational data expressed as a single signal were used. A P-factor of 1 and an r-factor of zero represent a simulation that exactly corresponds to the measured data.

Application

Application of the physically-based, semi-distributed model SWAT

From the sensitivity analysis results of 13 flow parameters in the SWAT model using PSO, seven parameters were found to be most sensitive, i.e., P-values were less than 0.05. The effective hydraulic conductivity in the main channel alluvium (CH_K2) was the most sensitive parameter followed by the baseflow alpha factor for bank storage (ALPHA_BNK). Based on the sensitivity analysis, seven flow parameters, CH_K2, ALPHA_BNK, SOL_BD, SOL_K, ALPHA_BF, CN2, and CH_N2, showed significant impacts on streamflow. The default values of the non-sensitive parameters were used to simulate streamflow. Therefore, the calibration of SWAT was performed using the most sensitive seven parameters.

The percentage of observations within the 95PPU (P-factor) and the relative width of the 95% probability band (r-factor) were used as performance indicators for the model in the uncertainty estimation. In the SWAT-CUP manual, it is suggested that a P-factor value of greater than 0.7, and an r-factor of around 1, are acceptable. Therefore, the P-factor and r-factor values for the study watershed were found to be acceptable, which indicates that the parameter uncertainties were within the desired ranges for this watershed.

Application of the simple conceptual rainfall-runoff models IHACRES and GR4J

The results for the average of all folds were used to compare the models' performance. The Nash–Sutcliffe coefficient values obtained for all four folds using the GR4J model structure fall within the ranges of 0.81–0.87 and 0.68–0.90 for the calibration and validation time periods, respectively. The Nash–Sutcliffe coefficients obtained using the IHACRES model structure fall within the ranges of 0.74–0.82 and 0.60–0.90 for the calibration and validation time periods, respectively. In general, these two conceptual models have comparable performance results for the Yongdam watershed.

Comparison of model performance between the SWAT, IHACRES, and GR4J models

Comparison of models in the time domain

The performance results based on the time domain (i.e., hydrograph) comparison of the three models are provided in Table 1; these results show that GR4J yielded better results than SWAT and IHACRES in reproducing the exact hydrograph. IHACRES performed comparably to the more complex model, SWAT, for daily streamflow simulation hydrograph. Because GR4J proved to have better performance in the day-to-day streamflow simulation it is considered a more robust hydrological model for reproducing the exact hydrograph.

Comparison of models in the quantile domain

Figures 2 and 3 show the flow duration curve for high and low flow, respectively, and the performance metrics are provided in Table 2. The performance of SWAT was improved by manually changing the most sensitive flow parameter, the curve number (*CN*), for each phase of the flow duration curve. This is done by fixing the optimal values of the other sensitive parameters, which were found during the calibration of the rainfall-

Table 1 – Performance measure values for each model for the entire flow range

Fold number	Calibration			Validation		
	SWAT	GR4J	IHACRES	SWAT	GR4J	IHACRES
1	0.77	0.83	0.78	0.81	0.78	0.72
2	0.74	0.81	0.74	0.86	0.90	0.90
3	0.77	0.83	0.77	0.77	0.85	0.78
4	0.77	0.83	0.77	0.81	0.86	0.81
5	0.81	0.87	0.82	0.64	0.68	0.60
6	0.54	0.82	0.76	0.76	0.83	0.79
Average	0.73	**0.83**	0.77	0.78	**0.82**	0.77

runoff model, in order to reproduce the exact hydrograph in the time domain. The model comparison results show the improved SWAT (SWAT Imp.) performed better than the other modelling approaches in simulating the mid-range, dry-condition and low flows. IHACRES performed best in the simulation of moist flow, whereas the SWAT Imp. and GR4J performed best in reproducing the high flow.

Discussion and conclusions

We compared two conceptual rainfall–runoff models and one physically-based rainfall–runoff model in terms of time domain- and quantile domain-based model performance. The results of the time domain-based comparison showed that GR4J produced superior results to SWAT and IHACRES. The assessment of model performance in the quantile domain revealed that the improved SWAT flow output results, obtained by manually changing the most sensitive parameters for different aspects of the flow phase, were better than the simple conceptual models (GR4J and IHACRES) for simulating high flow, mid-range flow, dry condition flow and low flows. The simple conceptual models were better than SWAT at simulating moist flow. All three models generally captured the magnitude and variability of the observed streamflow in the Yongdam watershed, and the results did not indicate that any of these hydrologic models were superior to the others for all measures of model performance. The

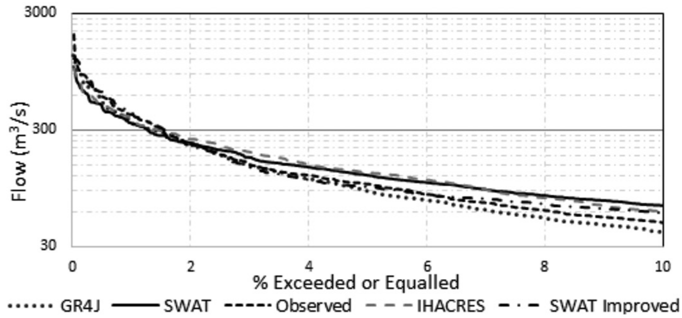

Figure 2 – Observed and modelled flow duration curves for high flow

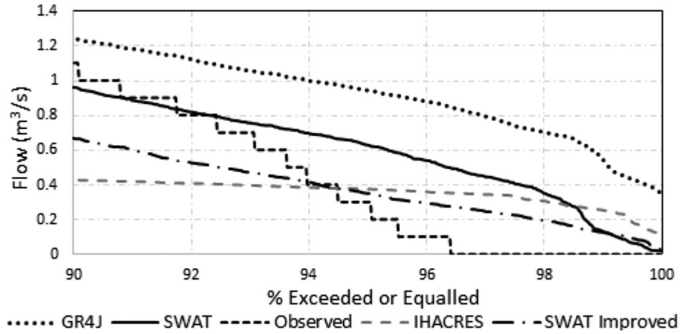

Figure 3 – Observed and modelled flow duration curves for low flow.

Table 2 – Flow duration curve-based model performance measure values for categorised flow range

Flow Range	Model	Performance measure values R-Bias	R^2	Best Model
High Flow	SWAT Imp.	**0.01**	0.96	GR4J, SWAT Imp.
	GR4J	-0.09	**0.97**	
	IHACRES	0.02	0.96	
	SWAT	-0.02	0.97	
Moist Flow	SWAT Imp.	0.24	0.90	IHACRES
	GR4J	-0.25	0.99	
	IHACRES	**0.06**	**0.99**	
	SWAT	0.66	0.97	
Mid-Range Flow	SWAT Imp.	**0.01**	**0.99**	SWAT Imp.
	GR4J	-0.34	0.99	
	IHACRES	-0.56	0.99	
	SWAT	0.30	0.99	
Dry Condition	SWAT Imp.	**0.00**	**0.99**	SWAT Imp.
	GR4J	0.26	0.99	
	IHACRES	0.74	0.92	
	SWAT	0.07	0.99	
Low Flow	SWAT Imp.	**-0.03**	**0.91**	SWAT Imp.
	GR4J	1.43	0.77	
	IHACRES	-0.04	0.55	
	SWAT	0.55	0.78	

Note: 'SWAT Imp.' indicates the improved results in the SWAT flow output due to manually changing the most sensitive parameters for different aspects of the flow phase.

selected simple conceptual models, GR4J and IHACRES, performed comparably to the more complex model (SWAT) at a daily time step. . Furthermore, there are strong positive correlations between the outcomes of the two simple conceptual models (GR4J and IHACRES), whereas these two conceptual models correlate moderately to weakly with the more complex physically-based, semi-distributed model (SWAT). Therefore, our results suggest that a multi-model ensemble approach with the SWAT model and either the GR4J or the IHACRES model could be used for regional water resource assessment.

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