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Original Article

Application of Modified Tank Model to Simulate Groundwater Level Fluctuations in Kabul Basin, Afghanistan

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ABSTRACT

Groundwater management is a significant task to have sustainable groundwater sources in Afghanistan especially in Kabul Basin. In this study, the groundwater level fluctuation simulation and forecast by a traditional tank model, snow tank + traditional tank model (S + traditional tank), combined tank model and snow combined tank model (SC-tank model) were compared. The variables (precipitation, groundwater level, temperature and evaporation) were utilized to simulate and forecast groundwater level fluctuations at a representative observation well (CKB1-W) in Kabul Basin from 2005 to 2013. Shuffled Complex Evolution-University of Arizona (SCE-UA) algorithm was utilized to find the best parameter for the models. Accuracy of model estimation was evaluated by coefficient of determination, Nash-Sutcliffe efficiency (NSE) coefficient and root-mean-square error (RMSE). Consequently, the SC-tank model provided the most accurate result in simulation and forecast of groundwater level fluctuations at the representative observation well in Kabul Basin. The result indicated that the SC-tank model constructed in this study could be applied for groundwater management in Kabul Basin, Afghanistan.

Keywords: groundwater level, precipitation, tank model, Kabul Basin

INTRODUCTION

Afghanistan is a nation located in central and southern Asia. It is a mountainous country in a dry part of the world which has extreme climate and weather. There are five big river basins, including the most important one, Kabul River Basin.

Afghanistan, especially Kabul City extremely depends on groundwater resources for drinking and household domestic consumptions, agriculture, construction, factories and other activities. The groundwater potential in the Kabul Basin is not sustainable to supply the whole water demand of Kabul City [1]. Groundwater is overused owing to increasing population and industrial activities in Kabul City. Groundwater extraction is greater than the recharge, which caused groundwater drawdown. Since 1982, groundwater tables have declined about 10 m in Kabul's aquifers [2]. Increase of water use has reduced groundwater table, which has given rise to dry wells. Also during recent droughts, more than 25% of shallow wells have gone dry [2].

A number of investigations have been conducted in surface water and groundwater. However, there is not enough reliance in the groundwater resources estimation of the Kabul Basin. There is still a need for a better understanding of the major groundwater systems and a developmental strategy to sustain current use and meet future demand. The vitality of integrated planning and effective management of groundwater resources is largely liable on the accurate simulation and forecast of the groundwater levels.

There are several models [3–8] including conceptual models and numerical models related to this study, which described groundwater system. Numerical methods are used to simplify physical flow of subsurface and boundary conditions. However, in the above-mentioned models, not only a few quantitative data are needed to calibrate the simulation parameters to get reliable predictions.

For example, the model proposed by Xu *et al.* [7] needs soil type, land use and other data to calibrate models but in this case study the required data are difficult to collect in Afghanistan because there are only limited data in the country.

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In addition, climate conditions are different in each country. Thus, simple and suitable model should be designed based on the regional situation of each country. In this study, the model based on the tank model would be valuable to cover the concerned points with consideration of hydrometeorological situation of Afghanistan, especially Kabul Basin although it only requires a limited data.

Developed conceptual rainfall-runoff models simulate the rainfall process. These models [tank model, HBV model, the Sacramento model, and MIKE 11/NAM model [9] were considered for physical processes of water flow in the whole catchment area where, the model performs with the nonlinear streamflow quickly illustrates correlations. However, the rainfall-runoff models are not appropriate to simulate groundwater level fluctuation.

Therefore, in this study, four different types of models based on tank model were introduced to simulate the relationship between precipitation and groundwater level fluctuation of observation well in Kabul Basin. The objective of this paper is to provide a simple approach using only precipitation, temperature, evaporation and groundwater level data to simulate and predict groundwater level fluctuations by comparing 1) traditional tank model, 2) snow tank + traditional tank model (S + traditional tank model), 3) combined tank model and 4) snow combined tank model (SC-tank model). The best set of parameter values were calculated by Shuffled Complex Evolution-University of Arizona (SCE-UA) algorithm. In addition, to evaluate the quality of the simulation and forecast result, Nash-Sutcliffe efficiency (NSE) coefficient, correlation coefficient (R^2) and root-mean-suare error (RMSE) were used.

MATERIALS AND METHODS

Traditional Tank Model

In this study, traditional tank model contained three tandem tanks that the first tank was used to simulate the precipitation, surface runoff and penetration; the second tank was used to simulate the intermediate runoff and penetration and the third tank was used to simulate the base flow and discharge as shown in **Fig. 1**.

The capacity balance equations for the tank model containing three tanks were calculated by the following formulae:

$$h1_{k+1} = h1_k + r_k - q1_k \quad Q11_k \quad Q12_k - Evap_k \tag{1}$$

$$h2_{k+1} = h2_k + q1_k - Q21_k \quad q2_k \tag{2}$$

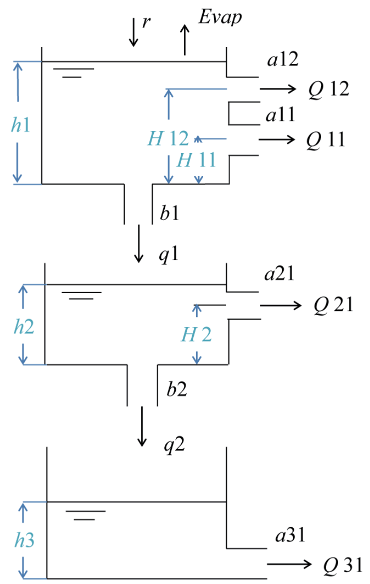

Fig. 1 Traditional tank model concept.

$$h3_{k+1} = h3_k + q2_k - Q31_k \tag{3}$$

where $h1_k$, $h2_k$ and $h3_k$ are the storage (mm) of three parallel tandem tanks in month k, respectively; r_k is the rainfall amount (mm) in month k; $Evap_k$ is the amount of evaporation (mm) from first tank in month k; $q1_k$, $q2_k$ are the penetration rates (mm) of the first and second tank in month k respectively; $Q11_k$ and $Q12_k$ are the constituents of surface runoff (mm) from the first tank, in month k respectively; $Q21_k$ represents the intermediate runoff (mm) from the second tank in month k; and $Q31_k$ represents the base discharge (mm) from the third tank in month k. The amount of runoff or infiltration through an outlet was linearly proportional to the head of water and could be stated as:

$$Q11_k = \begin{cases} a11 \times (h1_k - H11) & h1_k > H11 \\ 0 & h1_k \le H11 \end{cases} \tag{4}$$

$$Q12_k = \begin{cases} a12 \times (h2_k - H12) & h1_k > H12 \\ 0 & h1_k \le H12 \end{cases} \tag{5}$$

$$Q21_k = \begin{cases} a21 \times (h2_k - H2) & h2_k > H2 \\ 0 & h2_k \le H2 \end{cases} \tag{6}$$

$$Q31_k = a31 \times h3_k \tag{7}$$

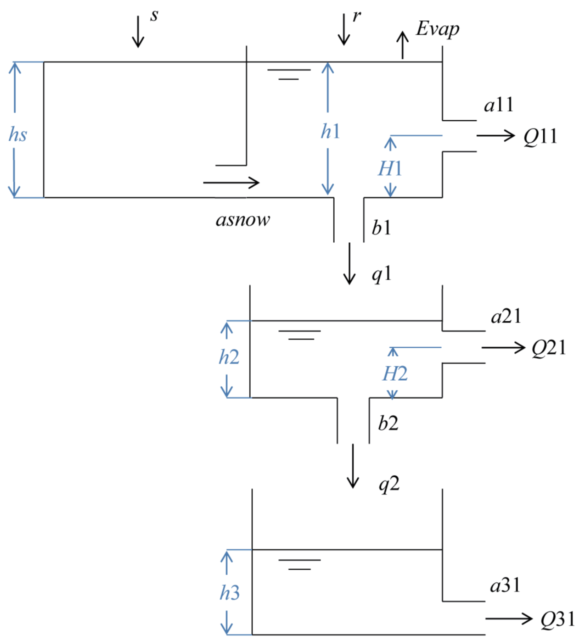

Fig. 2 Principle of S + traditional tank model.

$$q1_k = b1 \times h1_k \tag{8}$$

$$q2_k = b2 \times h2_k \tag{9}$$

where $a11$ and $a12$ are the lateral holes output coefficients (dimensionless) in the first tank, $a21$ and $a31$ are the lateral output coefficients (dimensionless) for the second and third tanks, respectively; $b1$ and $b2$ are the penetration coefficients (dimensionless) for the first and second tanks, respectively; $H11$ and $H12$ are the heights (mm) of runoff outlet of the first tank, respectively; and $H2$ is the height (mm) of runoff outlet of the second tank. The third tank storage ($h3_k$) was used to calculate the base flow of groundwater level in month k.

S + traditional tank model

The snow tank was added with traditional tank in the model is called S + traditional tank (**Fig. 2**). In this model, precipitation measured as snow in the winter season was considered related with temperature.

The capacity balances equations for the first tank tandem parallel with snow tank were calculated by the following formulae:

$$h1_{k+1} = \begin{cases} h1_k - q1_k - Q11_k & Temp \le 0 \\ h1_k + r_k + hs_k \times asnow - q1_k - Q11_k - Evap_k & Temp > 0 \end{cases} \tag{10}$$

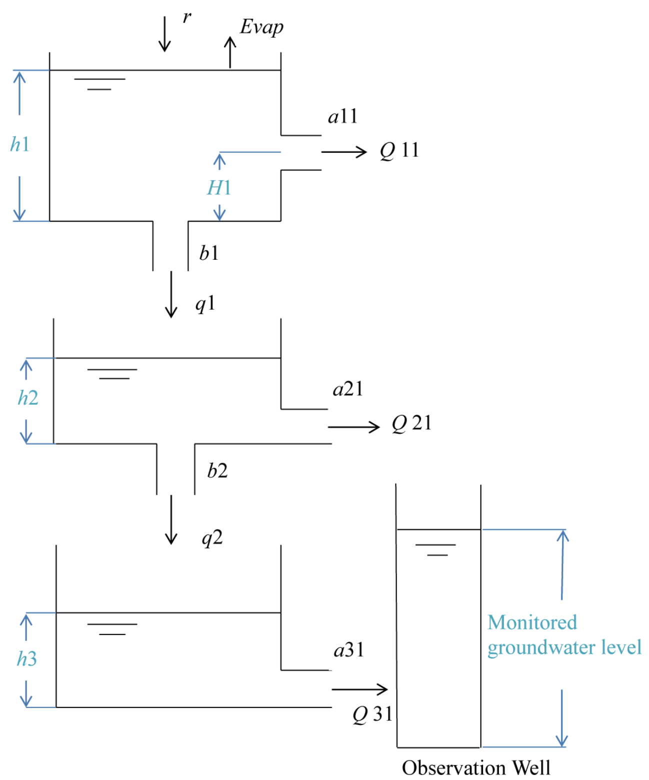

Fig. 3 Principle of combined tank model.

$$hs_{k+1} = \begin{cases} hs_k + s_k & Temp_k \le 0 \\ hs_k - hs_k \times asnow & Temp_k > 0 \end{cases} \tag{11}$$

where s_k is the snow precipitation in month k, hs_k is the snow storage (mm) tank along the first tank in month k, and *asnow* is the lateral outlet coefficient (dimensionless) from snow tank to first tank. The capacity balances for the second tank and third tank were calculated by the same formulae as those of traditional tank model: formulae (2) − (9) with the exception of formula (5). The third tank storage ($h3_k$) was used to calculate the groundwater level in month k.

Combined tank model

The principle of combined tank model is shown in **Fig. 3**. The combined tank model has a conceptual “observation well”. Water storage in observation well can be regarded as the combination of partial runoff of the second and third tank (**Fig. 3**). The capacity balance equations for the combined tank model containing three tanks were calculated by formulae (1) to (9) except formula (1) and formula (5).

There are two hypotheses in the calculation of groundwater level fluctuation: First, the contribution water level bears a linear relationship to runoff of each tank. This can be expressed by the following formulae:

$$HH2_k = C_{a2} \times Q21_k + C_{b2} \tag{12}$$

$$HH3_k = C_{a3} \times Q31_k + C_{b3} \tag{13}$$

where $HH2_k$ and $HH3_k$ are the contribution water levels in the second and third tanks in month *k*, respectively; C_{a2}, C_{b2}, C_{a3} and C_{b3} are conversion coefficients of the second and third tanks, respectively.

Second, the monitored groundwater level fluctuation is the combination of contribution water level in the second and third tanks. The combination is calculated by the following formulae:

$$GL_k = X_k \times HH2_k + (1 - X_k) \times HH3_k \tag{14}$$

where X_k is the mixing ratio of the two water table fluctuations as a linear function of three months of precipitation accumulation, and

$$X_k = \sum_{i}^{N=3} r_k / p \tag{15}$$

where *p* is the translation coefficient for r_k. It was calibrated with the combined tank model parameters at the same time.

SC-tank model

Kabul Basin is located in the semi-arid region of Afghanistan, and the groundwater levels in the study area fluctuate according to the precipitation situation. The fluctuations of the groundwater level were related to the natural weather condition in this observation well. The traditional tank model, S + traditional tank model and combined tank model have not yet been applied separately for Kabul Basin. Therefore, SC-tank model which combined the three models above was newly developed and proposed in this study.

Where the SC-tank model has three tandem tanks with a parallel snow tank along with the first tank. The SC-tank was introduced to simulate the relationships between precipitation and groundwater level fluctuation with consideration of temperature and evaporation. The first tank was used to simulate the precipitation, surface runoff and infiltration (if the temperature is higher than 0°C, it is infiltration; otherwise, the precipitation is snow type). Water storage in the observation well was regarded as the combination of partial runoff of the second and third tank. Water storage height in the observation well was defined as monitored groundwater level (**Fig. 4**). The entire formulae (1) − (15) except formula (1) and (5) were used for calculations.

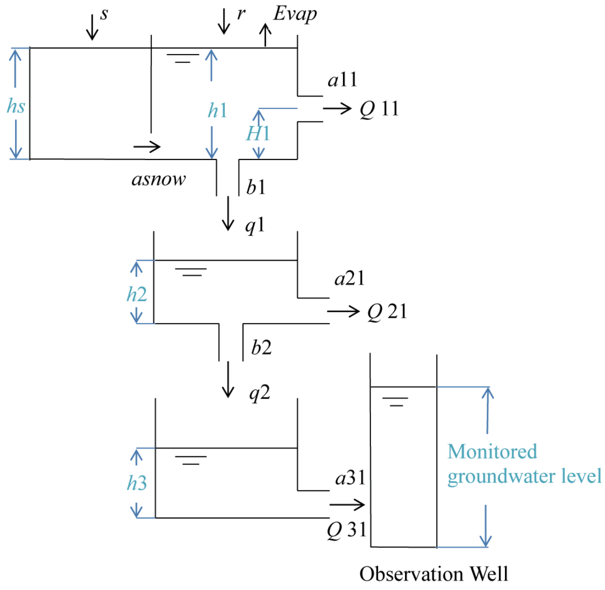

Fig. 4 Principle of SC-tank model.

Parameter identification

The selection of suitable parameters is extremely important for modeling especially in rainfall-runoff model to calibrate the objective function. The SCE-UA algorithm proposed by Duan *et al.* [10,11] is an automatic calibration algorithm. This algorithm has performed well in many previous studies.

In this study, the parameter values recommended by Duan *et al.* [10] and Sorooshian *et al.* [12] were used for the SCE-UA algorithm as follows:

1) m = 2n+1, where m is the number of points in each complex and n indicates the parameters of the model;
2) q = n + 1, where q is the simplex or number of points in an array.
3) α = 1, which shows the number of repetitions; and
4) β = 2n + 1 in the competitive complex evolution included in the SCE method.

Definition of optimization function

In this study the simulation and forecast results were evaluated by RMSE [13], NSE coefficient [14], and R^2 [13].

Change of errors assessment which is done individually by sample size was calculated by RMSE as follows:

$$RMSE = \sqrt{\frac{1}{N}\sum\left(H_{ci} - H_{oi}\right)^2} \tag{16}$$

In order to measure the predicative power of hydrological models, NSE method was used.

$$NSE = 1 - \left[\frac{\sum\left(H_{ci} - H_{oi}\right)^2}{\sum\left(H_{oi} - H_{\overline{oi}}\right)^2}\right] \tag{17}$$

To evaluate the correlation of observed data and calculated data, R^2 was used.

$$R^2 = 1 - \frac{\sum(H_{ci} - H_{oi})^2}{\sum H_{oi}^{\ 2} - \frac{\sum H_{ci}^{\ 2}}{N}} \tag{18}$$

where H_{ci} is the calculated result; H_{oi} is the observed data; $H_{\overline{oi}}$ is the average value of observed data; N is the number of observed data. Which NSE specifies the difference between observed and calculated values.

Study area

Kabul Basin is located in the valley between Paghman and Kohe-Safy mountains, extended from the upper part of Logar and Paghman Rivers. Also it is confluence of Kabul River to Ghorband and Salang River with Panjsher River to Sayad area. Kabul Basin is divided into six sub-basins (**Fig. 5**) as follow: Central Kabul sub-basin, Paghman and upper Kabul sub-basin, Logar sub-basin, Dehsabz sub-basin, Shomali sub-basin and Panjsher sub-basin.

Surface water drainage basins generally differ from borders among sub-basins. Geology of the sub-basins consists of rocks and quaternary and tertiary sediments. Also the surrounding mountains and inter-basin ridges cover uplifted crystalline and sedimentary rocks. The quaternary deposits are characteristically in the valleys which have less than 80 m thickness. The underlying tertiary deposits in Kabul City have around 800 m thickness, but more than 1000 m thickness [15] in some areas of the valley.

Groundwater in Kabul Basin predominantly flows through the saturated alluvium layer and other basin-fill sediments. Groundwater flows in the same direction with surface flows. The mean annual precipitation was about 291 mm in 2013; while the mean annual evaporation is greater than precipitation (1600 mm). Snow in the upstream mountains is an important source of surface water. The main source of groundwater recharge is infiltration from rivers and irrigated agricultural lands in Kabul Basin [15]. In addition, local precipitation in the wet monsoon storms can also recharge the groundwater in sub-basins.

Kabul Basin recharge can be through a river bed; direct precipitation infiltration; recharge at a foothill associated with snow melt; recharge from irrigation channels; and recharge due to leakage from sewage or septic tanks. In particular, the river beds and irrigation canals might be the main recharge sources during the period of high peak flow of Kabul River, Logar River and other sub-basin streams [2]. Usually, the highest groundwater table is observed in April and May, and the lowest groundwater is observed in October to December through Kabul Basin.

In this study, Matlab R2015a (MathWorks, Natick, USA) was utilized to search parameter sets, which provided the lowest RMSE by SCE-UA algorithm between simulated and observed groundwater level for observation well. Traditional tank model, S + traditional tank model, combined tank model and SC-tank model calibrations were conducted using formula (1) − (15) of CKB1-W observation well during the period from Jan 2005 to Jun 2013.

Observation Data

The precipitation data from Agromet Project in the Ministry of Agriculture, Irrigation and Livestock (MAIL) in cooperation with USGS were used. The temperature and evaporation data were collected from Kabul meteorological station. The groundwater level data monitored for 2004 − 2013 in Kabul Basin provided from USGS [16] were used. In this study, the central Kabul Basin groundwater levels were considered. Thus, one representative observation well was selected to simulate the groundwater level. Kabul River which originated from upstream has a key role for recharging the selected observation well. Precipitation data of Paghman precipitation station was used for model simulation because it is located in upstream.

The Central Kabul sub-basin has 419 km^2 area where Kabul City is located. The sub-basin comprises Kabul River downstream from the point of confluence with the Paghman stream. In this sub-basin, 23 monitoring wells had been observed by the USGS study team for monitoring the groundwater table. In this study, CKB1-W (the original name of the well is “well 64 in side of Afghanistan Geological Survey”) which is located in the middle sub-basin was simulated and forecasted. Furthermore, this observation well is located at government official area where groundwater level in the well was not affected by over pumping as residential area.

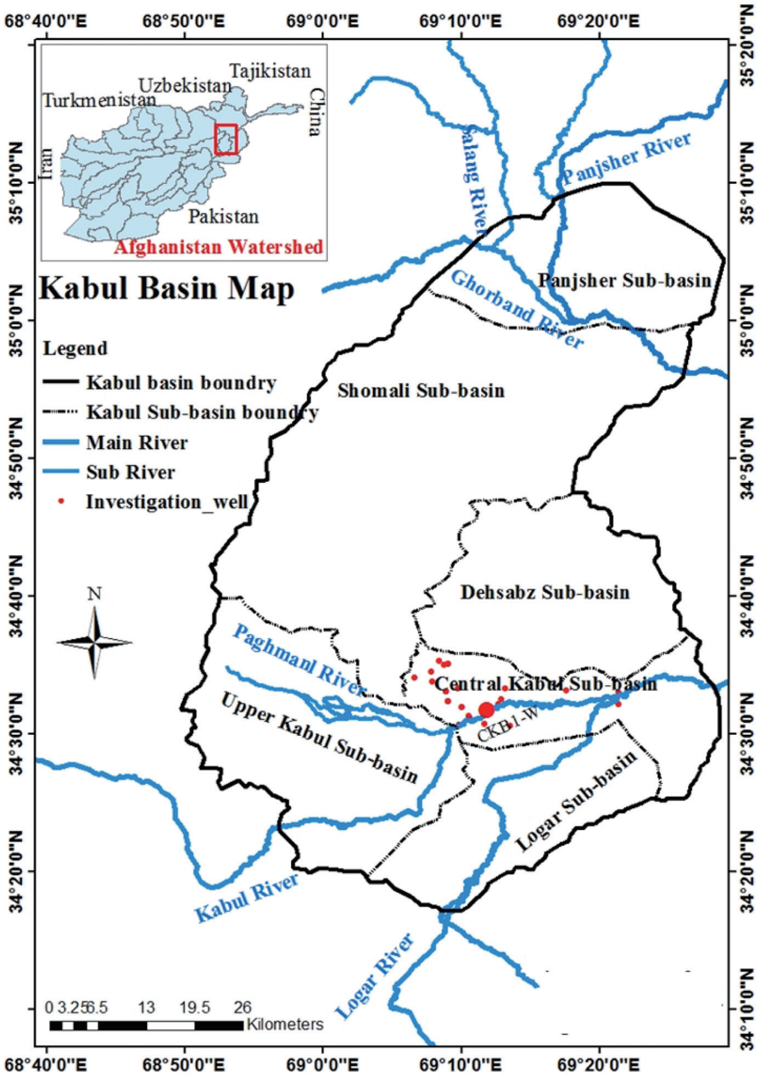

Fig. 5 Location of Kabul Basin study area in Afghanistan created in this study.

In this study the data for Jan 2005 to Dec 2009 were used for the simulation and the data for Jan 2010 to Jun 2013 were considered for forecasting groundwater level fluctuations for the evaluation of the model performance.

RESULTS AND DISCUSSION

Simulation and Forecast Results

In this study the traditional tank model, S + traditional tank model, combined tank model and SC–tank model simulation and forecast results were compared by consideration of variables (precipitation, evaporation and temperature). The monthly precipitation was lower than monthly evaporation. Also when the temperature was low precipitation occurred and where there was high temperature evaporation was dramatically increased. However, when the temperature was increased, the water level was also increased because of snow melting and surface flow happened to recharge groundwater from river bed (**Fig. 6**). The groundwater level has been reduced since 2009 because there were less precipitation and high evaporation.

The traditional tank model and S + traditional tank model simulation and forecast results were not accurate. The combined tank model simulation result looks good than the traditional tank model and S + traditional tank model but the forecast result was not accurate. On the other hand, the SC-tank model is the best among the models in both simulation and forecast results. These results indicate that the SC-tank model can be applied for simulation and forecast of groundwater level fluctuations in representative observation

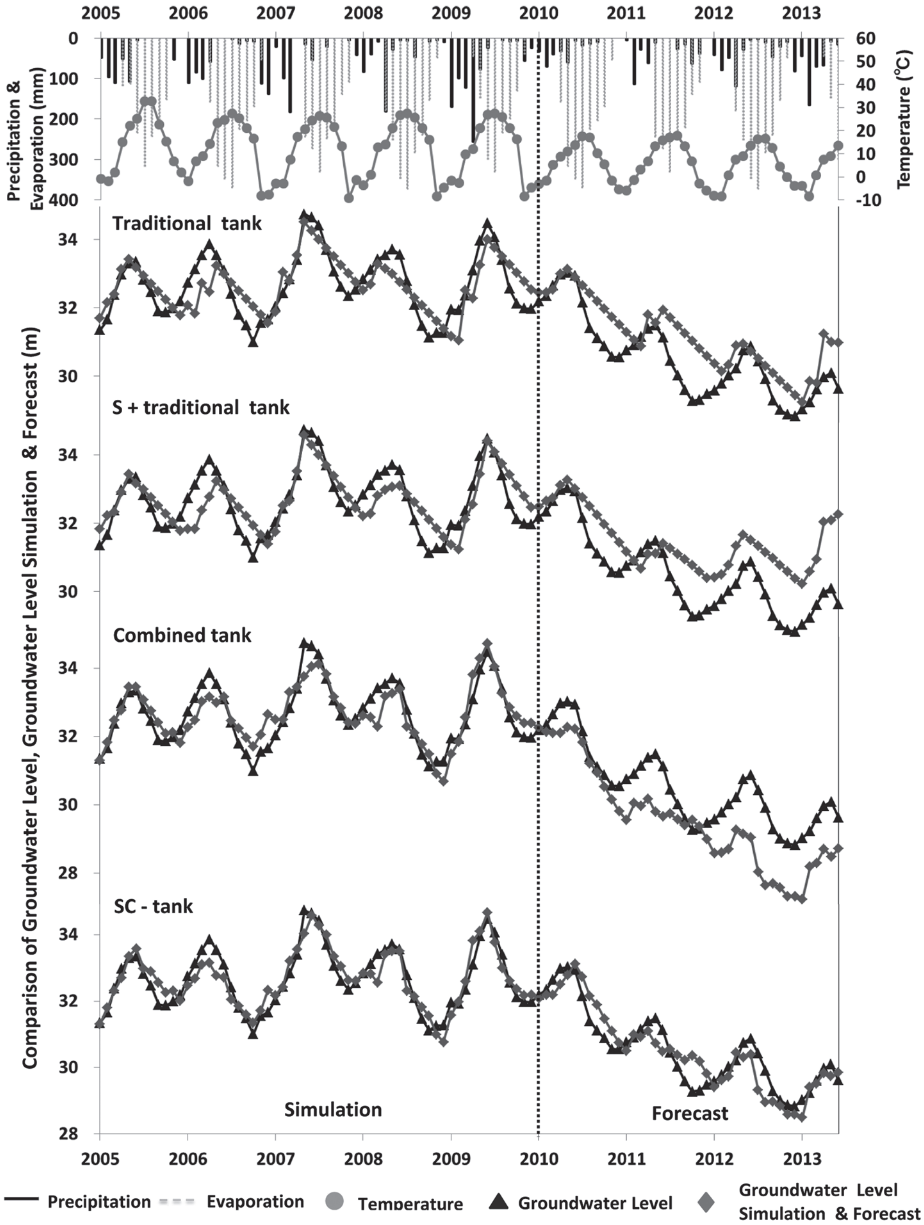

Fig. 6 Comparison of the simulation and forecast results of traditional tank, S + traditional tank, combined tank and SC-tank models.

well (**Fig. 6**).

In addition, SC-tank model parameters were stable when the simulation period increased and decreased. The parameter values were also almost the same which proved the affectivity of the model. However, in other models especially in the combined tank model parameters were not stable when the simulation period was changed. These results indicate that the SC-tank model is acceptable in a different condition for the simulation and forecast of groundwater level fluctuations in Kabul Basin.

Evaluation of Model Results

The statistical competencies of the traditional tank model, S + traditional tank model, combined tank model and SC-tank model for the simulation period and forecast period are summarized in **Table 1**. It is observed from **Table 1** that the SC-tank model performance is more significant than other models and the SC-tank model has validated the groundwater level with reasonable accuracy in terms of all the statistical indices during simulation and forecast periods.

Generally, by increasing the number of parameters for the

Table 1 Evaluation of simulation and forecast results.

Models	Number of parameters	Simulation period			Forecast period		
		R^2	NSE	RMSE	R^2	NSE	RMSE
Traditional tank	12	0.999	0. 646	0.551	0.999	0.507	0.827
S + traditional tank	12	0.999	0. 637	0.558	0.998	0.083	1.128
Combined tank	14	0.999	0.784	0.430	0.998	0.031	1.159
SC-tank	16	0.999	0.852	0.356	0.999	0.827	0.490

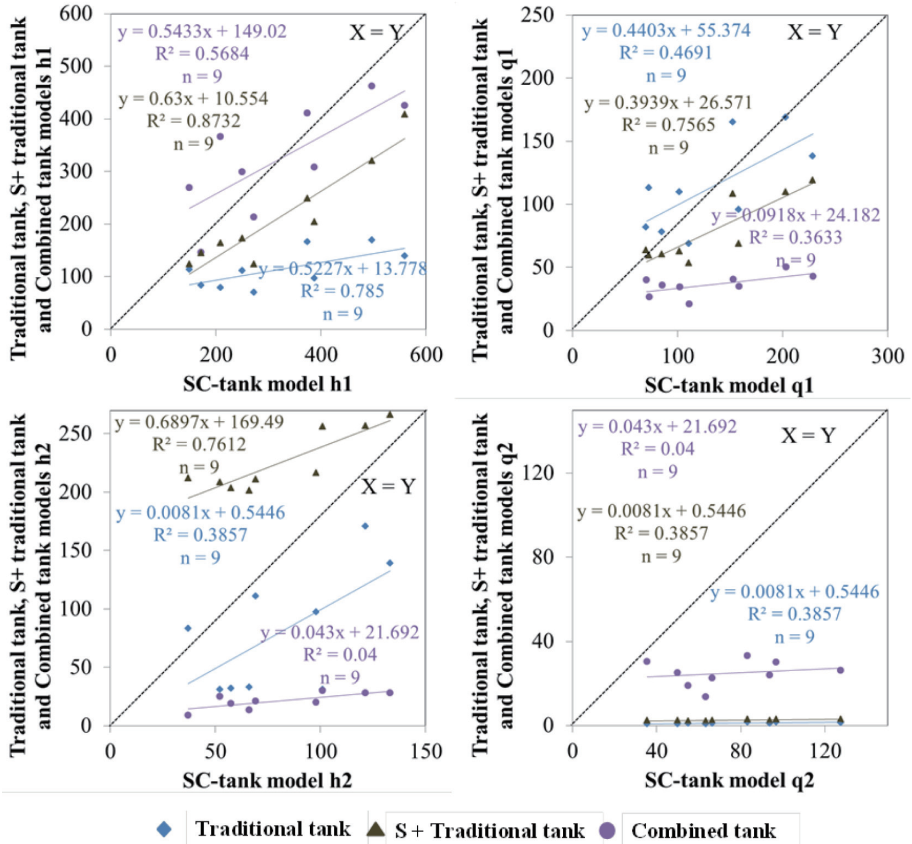

Fig. 7 Comparison of the annual peaks obtained from the simulation using traditional tank, S + traditional tank and combined tank models with those obtained from SC-tank model.

model calibration, the accuracy of calculation results would be better. In this study by slightly increasing the number of parameters, there was a significant improvement in the results. It indicated that the added parameters provided a more thorough description of hydrometerlogical situation of Afghanistan especially in Kabul Basin.

The annual peaks obtained from the simulation using the traditional tank, S + traditional tank and combined tank models were compared with those of SC-tank model. This comparison indicated that traditional tank, S + traditional tank (except for the h2 value) and combined tank model values are less than those of SC-tank model (**Fig. 7**). The results indicated that the other models` values are less than SC- tank model and SC-tank model is the most effective in sufficiently simulating and forecasting groundwater level fluctuations.

In SC-tank model, the parameters were stable even though the simulation period was changed. The traditional tank model (without the consideration of snow as precipitation) could not simulate well the groundwater level fluctuation. This result indicates that contributions of snow and rain to the groundwater level should be considered separately in winter season in Kabul Basin.

The S + traditional tank model which considered snow as precipitation also could not simulate the groundwater level fluctuations so well in Kabul Basin because that the representative observation well of Kabul Basin is situated along Kabul River. Kabul River has a significant role groundwater recharge especially during heavy rain. However, the S + traditional tank model could not respond to such irregular precipitation event.

In the combined tank model, water storage in the observation well was regarded as the combination of partial runoff from the second and third tanks. The simulation result was better than traditional tank and S + traditional tank models but was not highly accurate. The forecast result was also not good compared with other models. The reason could be the non-consideration of snow as precipitation in the winter season.

The SC-tank model which combined with the S + traditional tank and combined tank models consisted of all concepts associated with accurate simulation and forecast results. In this model, both rainfall and snow were considered as precipitation depending on temperature. Furthermore, infiltration from surface flow was calculated as precipitation accumulation for three months and a combination of partial runoff of the second and third tanks. The popular runoff in Kabul River occurred associated with snow melting and monsoon precipitation in spring season. Therefore, the SC-tank model which has the capability to respond to snow-melting condition and deluge situation could easily simulate the groundwater level fluctuations in representative observation well of Kabul Basin.

CONCLUSION

In this study, traditional tank, S + traditional tank, combined tank and SC-tank models were compared for simulation of groundwater level fluctuation in Kabul Basin, Afghanistan. The SC-tank model, which has snow tank and the conceptual observation well, showed the best results. It also provided a simple approach to simulate and predict groundwater level fluctuations. Thus, simulation and forecasting of the groundwater level fluctuations using the SC-tank model would be proposed to water resource administrators for groundwater resource management in Kabul Basin, Afghanistan.

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