Establishing a Physically-based Representation of Groundwater Re-evaporation Parameter in SWAT

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EXTENDED ABSTRACT

For the soil and soil water system, when the top soil is dry, water in the capillary fringe that separates the saturated and unsaturated zones will diffuse upward. The SWAT (Soil and Water Assessment Tool) simulates the movement of soil water from the saturated zone into overlying unsaturated soil layers as a function of water demand for potential evaporation. To avoid confusion with soil evaporation and transpiration from the topsoil, in the SWAT model, this process has been termed re-evaporation. The model employed a parameter, called a re-evaporation coefficient, to estimate groundwater re-evaporation, and normally the parameter needs calibration.

However, calibration of spatially varied model parameters, such as the groundwater re-evaporation coefficient in the SWAT, needs some relevant observations, and may not be easy for applying such a model to many areas. Therefore, if the relationship between a model parameter and a physical representation can be identified, it would be preferred to determine the parameter value according to the physically-based representation.

After intensive calibration, the SWAT model was applied to the East River basin in southern China. It is found that the re-evaporation coefficient value varies spatially corresponding to the change of topography. In a mountainous area, the coefficient value is small, and is large in the downstream areas. Physically, it is observed that the larger the saturated contributing area, the more significant the groundwater re-evaporation. According to a topography related model, TOPMODEL, the saturated fraction can be estimated based on the statistics of topographic index, which is the logarithm of the ratio of the controlled drainage area for a unit width and the tangent of its local slope. Figure 1 shows the means of all subbasin topographic indices for the whole East River basin. In the TOPMODEL, water table depth of each subbasin is also needed for the calculation of saturated fraction. Since water table depth will vary with time, the saturated fraction will be a time varying parameter, which should be more reasonable for representing the groundwater re-evaporation in the SWAT.

Using calibrated re-evaporation coefficient and new re-evaporation parameter (saturated fraction) developed based on the concept of TOPMODEL, the SWAT simulated the streamflow at Boluo gauging station in the East River basin (see Figure 1). The results show that the simulation using the saturated fraction is better than the simulation from the calibrated re-evaporation coefficient in the SWAT.

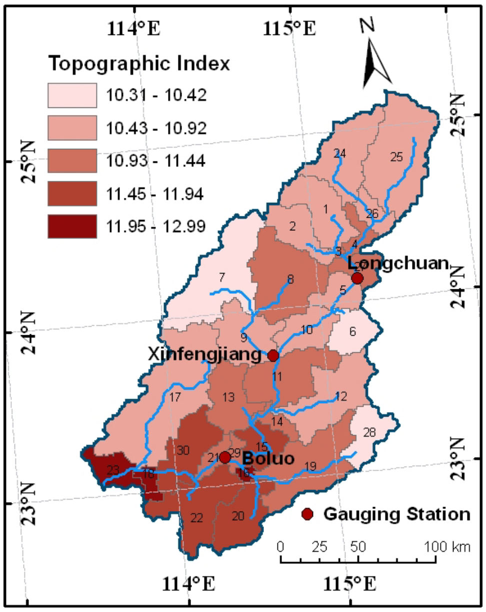

Figure 1. Topographic index of each subbasin of the East River basin in southern China.

1. INTRODUCTION

In the SWAT (Soil and Water Assessment Tool) (Arnold *et al*. 1998), groundwater depletion through evaporation due to a shallow water table can be an important component of a regional scale water balance. Water that moves upwards through capillary rise from a shallow water table can enter the atmosphere through plant transpiration or direct evaporation from bare soil (Young *et al*. 2007). Groundwater models representing regions with shallow water tables need to account for this important path of groundwater discharge (Belitz *et al*. 1993). Zammouri (2001) developed a finite-difference groundwater flow model based on Gardner's equation to quantify the groundwater budget and the losses via evaporation from bare soil.

SWAT models the movement of water into overlying unsaturated layers as a function of water demand for evapotranspiration. As water is removed from the capillary fringe by evaporation, it is replaced by water from the underlying aquifer. This process is significant in watersheds where the saturated zone is near to the ground surface (Neitsch *et al*. 2001). However, the estimation of groundwater re-evaporation in the SWAT involves a parameter, called groundwater re-evaporation coefficient, which is related to model's streamflow and is one of the model crucial parameters involved in the calibration process (Misgana and Nicklow 2005).

Since the groundwater re-evaporation in the SWAT model is related to the size of saturated areas of a basin or the water table depth, it should be possible to replace the re-evaporation coefficient with the saturated fraction. The saturated fraction can be obtained using the TOPMODEL (Beven and Kirkby 1979) based on the topographic index and daily water table depth. The TOPMODEL is a physically based catchment model for modeling runoff generation, and may offer a way of providing spatially distributed hydrological information with readily available input requirements (Seibert *et al*. 1997).

For avoiding the calibration of the groundwater re-evaporation coefficient in the SWAT, this study integrates the concept of the TOPMODEL into the SWAT and examines the performance of the physically based groundwater re-evaporation over the East River in southern China.

2. STUDY AREA

The East River basin (named Dongjiang in Chinese) located between latitudes 22°34′ and 25°12′N and longitudes 113°24′ and 115°53′E, is one of the four main drainage areas comprising the Pearl River basin (Chen and Chau 2000, Chen and Wu 2007) (see Figure 2). The mainstem of the River is 562 km long, and the drainage area is 35,340 km^2. In the study, the observed streamflows at Longchuan and Boluo flow gauging stations in Guangdong Province (Figure 2) have been used to calibrate the model. The controlled drainage area of Longchuan station is about 7,743 km^2 at the headwater area in the East River basin. The controlled drainage area of the Boluo station is 25,325 km^2, and the long-term average annual discharge at the station is about 739 m^3/s (23.3 billion m^3/yr).

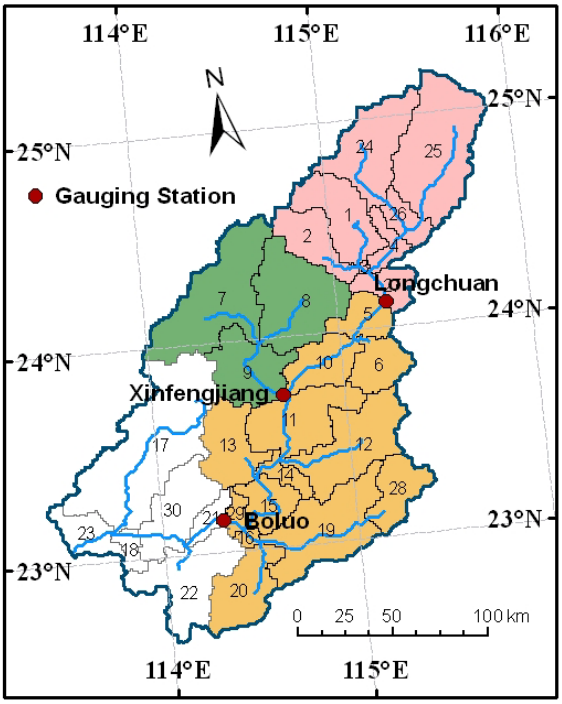

Figure 2. Three subbasins in the East River basin.

3. RESEARCH DATA

3.1. DEM, Land Use and Soil Data

In the study, the GTOPO30 DEM data at 1 km resolution were adopted to discretise the catchment into sub-catchments (Chen and Wu 2007). This discretisation resulted in the definition of 30 sub-basins (see Figure 2). For parameterizing the SWAT hydrology model, the land cover data with 1 km resolution obtained from Chinese Academy of Sciences were used, and the land uses were divided into six groups. They are agriculture, forest, pasture, range, urban area and water surface. In addition, the FAO (Food and Agriculture Organization of the United Nations) soil map with 0.5 km resolution was used for the description of major soils in the East River basin.

3.2. Meteorological Data

The available time series of daily meteorologic forcings including precipitation, maximum and minimum surface air temperatures, wind speed and relative humidity (Feng *et al*. 2004) are used in the study. The data covers the period from January 1, 1951 to December 31, 2000. This dataset with one degree spatial resolution is derived based on long-term observed data over the mainland of China (Feng *et al*. 2004). In the study, there are eight 1°×1° grids covering the East River basin.

3.3. Streamflow Observations

In the study, daily stream flow observations at Longchuan station for the period January 1952 to December 1974 and at Boluo station for the period January 1954 to December 1974 are used, while only monthly flow at Shuntian station (denoted as ST) located in Xinfengjiang Reservoir catchment for the period January 1967 to December 1974 were available.

Table 1. Five calibrated SWAT parameters used over the East River basin.

Parameter	Range	Catchment LC	Catchment XFJR (ST)	Catchment BL
Baseflow alpha factor (days)	0.001 - 1	0.003	0.0054	0.0054
Soil evaporation compensation factor	0.001 - 1	0.999	0.999	0.999
Plant uptake compensation factor	0.001 - 1	0.001	0.001	0.001
Groundwater "revap" coefficient	0.02 – 0.2	0.05	0.02	0.2
Deep aquifer percolation fraction	0 - 1	0.1	0.016	0.5
Correlation coefficient	Calibration	0.82	0.93	0.96
Correlation coefficient	Validation	0.78	0.89	0.91

The SWAT model was calibrated at sub-watershed levels using daily measured streamflows from Longchuan station during January 1, 1952 through December 31, 1972 for drainage area above it, and from Boluo station during January 1, 1954 through December 31, 1972. Monthly streamflows from Shuntian station January 1967 to December 1972 were used to calibrate the parameters for XFJR catchment. Field monthly and daily data from Longchuan (denoted as LC) and Boluo (denoted as BL) during January 1, 1973 through December 31, 1974 were used for validation. Table 1 lists five calibrated parameters for these three sub-watersheds (see Figure 2). The unit of baseflow alpha factor is days, while others are dimensionless. The correlation coefficients of monthly observed flows and simulated flows at the three gauges during the calibration period and the validation period can also be found in Table 1.

4. METHOD

4.1. SWAT Groundwater Re-evaporation

In the SWAT model, the groundwater re-evaporation is calculated as follows:

$$w_{revap} = \beta_{rev} \cdot E_o \qquad (1)$$

where w_{revap} is the amount of water moving upwards from the groundwater in response to water deficiencies (mm). β_{rev} is the re-evaporation coefficient, and the E_o is the potential evapotranspiration (mm). A daily time scale is used.

As β_{rev} approaches 0, movement of water from the groundwater (shallow aquifer) to the root zone is restricted. On the contrary, as β_{rev} approaches 1, the rate of transfer from the shallow aquifer to the root zone approaches the rate of potential evapotranspiration. The range of re-evaporation coefficient is suggested to be between 0.02 and 0.20 by Neitsch *et al*. (2001).

4.2. Saturated Fraction Using TOPMODEL

TOPMODEL (Beven and Kirkby 1979) is a physically based catchment model for simulating runoff generation. The model uses topographic information in the form of an index that describes the tendency of water to accumulate and to move down slope by gravity. Since the early 1990's, the model has been widely used because it can provide spatially distributed hydrological information (e.g. saturated contributing area) with readily available input requirements (e.g. Digital Elevation Model) (Seibert *et al*. 1997).

Saturated fraction of a catchment is the ratio of the saturated contributing area, A_c, where all rainfall contributes to overland runoff without any infiltration loss, to the area A of a basin. It is given as (Chen and Kumar 2001):

$$fr_{sat} = \frac{A_c}{A} = \int_{x \geq (\xi \cdot \bar{z} + \lambda)} f(x)dx \qquad (2)$$

where $f(x)$, the probability distribution of the topographic index, is normally parameterized as a three-parameter gamma distribution (Sivapalan *et al*. 1987). The variable x is topographic index which is given as:

$$x = \ln \frac{a}{\tan \beta} \tag{3}$$

where α is the upstream contributing area, from the watershed divide, per unit contour length, and $\tan\beta$ is the local slope.

In equation (2), threshold defining area is function of average water depth (Chen and Kumar 2001). $\bar{z}$ is the basin average water table depth, and has the relationship with the local water table depth z (positive downward from the surface) as follows:

$$z = \bar{z} - \frac{1}{\xi}(x - \lambda) \tag{4}$$

The factor ξ, the soil decay factor, is a hydrogeologic constant which is a measure of the decline of the saturated hydraulic conductivity with increasing soil depth; in the study, the value 1.8 m^{-1} is used according to Chen and Kumar (2001). The parameter λ is the mean value of the topographic indices over the basin.

5. RESULTS AND DISCUSSION

5.1. Comparison of Two Methods

From Table 1, we can see that the groundwater re-evaporation coefficient of 0.2 in downstream drainage area (see Figure 2.) is larger than that (0.02 for Xinfengjiang catchment and 0.05 for drainage area controlled by Longchuan, respectively) in upstream drainage area. This reflects the fact that saturated fraction (or saturated contributing area) generally is small in upstream areas and large in downstream.

At a subbasin scale, spatially varied saturated fraction can be calculated using equations (2) using the statistics of the topographic index (Figure 1) for the whole East River basin. Then, similar to the computation in the original SWAT, the groundwater re-evaporation will be computed using the equation below:

$$w_{revap} = fr_{sat} \cdot E_o \tag{5}$$

Dynamics of water table depth used in the calculation of saturated fraction is obtained from the daily soil water content contained in the SWAT. Therefore, the water table depth (m) used in this study is taken as the difference between the entire depth of soil profile (assumed to be 2m for the East River basin) and daily soil water height (m) which is simply given as below:

$$SWHT = \frac{SWC}{1000 \cdot Porosity} \tag{6}$$

where *SWHT* is an assumed height of saturated soil where the porosity of soil is full of water (m), *SWC* is the volume of water in the soil profile (mm), and *Porosity* is the soil porosity. All variables in equation (6) are used at a subbasin level. The average soil water height during the validation period from January 1, 1973 to December 31, 1984 is shown in Figure 3. From this figure, it can be seen that soil water height in the downstream is generally larger than that in upstream. The figure also displays that in the headwater area controlled by Longchuan, soil water height is even larger than that in the mid-stream. According to the soil types used in the simulation, this may be caused by the larger conductivity of soil used in the mid-stream, as water exceeding saturated capacity can easily seep into the shallow aquifer.

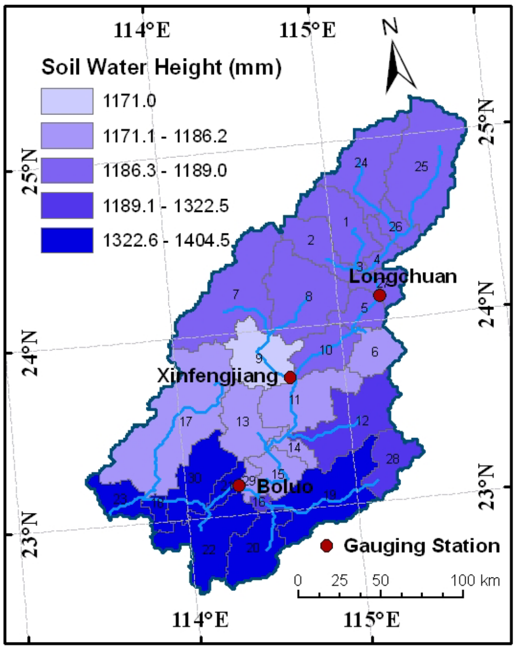

Figure 3. Average soil water height of each subbasin during validation period.

5.2. Physically-based Parameter

Figure 4 shows the daily streamflow observations and the comparison of the two-streamflow simulations at Boluo station. One is from the SWAT integrating the concept of TOPMODEL, and the other from the SWAT using calibrated groundwater re-evaporation coefficient. From the figure, it can be seen that the two simulations match closely with the observations in 1979. In addition, during some periods in 1979, the simulation from the saturated fraction method is even closer to the observations.

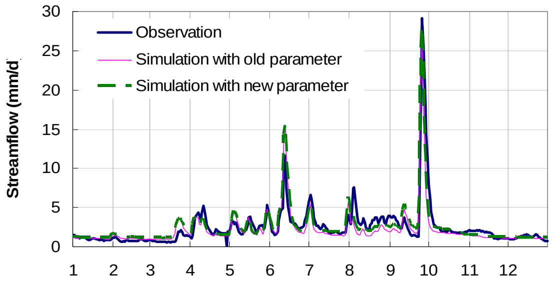

Figure 4. Comparison of SWAT simulated daily streamflow at Boluo using groundwater re-evaporation coefficient and TOPMODEL saturated fraction with the observations in 1979.

Figure 5 shows the SWAT simulated daily groundwater re-evaporation volume in 2000 using the old parameter (re-evaporation coefficient) and the new parameter (saturated fraction) developed from the concept of TOPMODEL, respectively. From the figure, it can be seen that the new simulation of re-evaporation is generally smaller than that from the old simulation, and the range of variation of new simulation is also smaller than that of the original one. That is why the average simulated streamflow at Boluo station using the new re-evaporation parameter is a little larger than that using the old parameter.

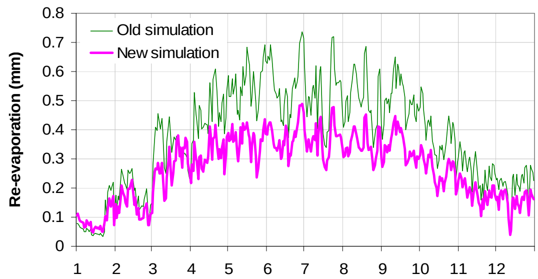

Figure 5. Comparison of simulated groundwater re-evaporations using the old parameter and the new parameter.

Table 2 gives the statistics (Chen and Wu 2007) of the two simulations using the streamflow observations. The table shows that the simulation using the concept of TOPMODEL has correlation coefficient 0.87, which is the same as the simulation using the calibrated re-evaporation coefficient. Compared with the simulation from the original SWAT, the relative deviation of the new simulation improved slightly, and relative bias improved significantly. Consequently, we may infer that the saturated fraction computed using the concept of TOPMODEL may be suitable to represent the groundwater re-evaporation coefficient in the SWAT. In addition, since the saturated fraction concept is based on physical understanding the runoff generation, the new scheme of computing the groundwater re-evaporation should have a more solid basis for applying the revised SWAT to study catchment hydrology.

Table 2. Comparison of the simulated daily flow at Boluo streamflow gauging station during validation period using the calibrated re-evaporation coefficient and the saturated fraction.

Statistics Terms	Relative Bias	Relative Deviation	Correlation Coefficient
Old parameter	-0.16	0.27	0.87
New parameter	0.08	0.26	0.87

6. CONCLUSION

An approach for estimating the spatially varied and time varying parameter - saturated fraction - is presented in this paper. The numerical model SWAT is calibrated by the observed flow at three gauging stations (Longchuan, Xinfengjiang and Boluo). Then the model is used to estimate the groundwater re-evaporation using the re-evaporation coefficient and the saturated fraction, respectively. The comparison indicated that the saturated fraction may be suitable to represent the groundwater re-evaporation in the SWAT and may perform better than the original method in the SWAT, using the re-evaporation coefficient.

Furthermore, considering the characteristics of saturated fraction which is spatially varied, time varying and related to dynamics of water table depth, this physically based parameter can be an appropriate replacement of the re-evaporation coefficient which is time-invariant and needs calibrating. However, there are still some limitations, such as computing the water table depth and even the consistency between the computations of water table and the baseflow with the concept of TOPMODEL, that need to be improved in future study.

7. ACKNOWLEDGEMENTS

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