Abstract

This paper presents the terrestrial hydrological features of the Pearl River basin in South China by using a macro-scale hydrological model, the Variable Infiltration Capacity (VIC) model, and a routing scheme. Without calibration, the VIC model is used to simulate streamflow, evapotranspiration and soil moisture change at a daily time step for the period 1951–2000. After aggregation of daily output, it is observed that the VIC streamflow simulation is comparable to the observation at a month step. Moreover, from the model simulation, the study reveals that the monthly soil moisture change varies dynamically for maintaining the basin water balance, and both of the streamflow and evapotranspiration are dominant hydrological processes over the basin. With the routing scheme, the hydrological simulation from the VIC model is investigated at a daily step. It is observed that the scheme can improve the simulation of the timings and magnitudes of the daily streamflow peaks significantly, and the temporal scale of the influence of the routing on the streamflow simulation is less than 2–3 weeks in the Pearl River basin.

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Keywords: Hydrological features; Streamflow simulation; VIC; Routing; Pearl River

1. Introduction

Floods and droughts are natural hazards that occur frequently over the Pearl River basin in South China (Pearl River Water Resource Commission, 2005; Cui et al., 2007). In order to develop mitigation measures to attenuate the damages of these hazards, it is important to know the features of hydrological processes in the basin, which would provide a sound basis for a variety of water resource diagnostic studies.

Since the 1980s, in order to study hydrological processes at basin and continental scales, macro-scale hydrological models (MHMs) have been developed to simulate the land surface hydrology through modeling physical processes of the terrestrial water cycle (e.g. Sellers et al., 1986; Dickinson et al., 1986; Russell and Miller, 1990; Chen and Kumar, 2001; Nijsen et al., 2001a). The advancement of MHMs was closely related to the development of land surface parameterization schemes (LSPs) for general circulation models (GCMs) (e.g. Sellers et al., 1986; Dickinson et al., 1986), but focused more on modeling soil moisture change, evapotranspiration and runoff generation (Chen and Kumar, 2001; Nijsen et al., 2001b). Subsequently, MHMs can be useful for exploring the hydrological features through assessing the terrestrial hydrological responses to topography, vegetation covers and soil characteristics at basin and continental spatial scales.

This study applies the Variable Infiltration Capacity (VIC) model (Liang et al., 1994), one of the MHMs, to the Pearl River basin in South China to study the hydrological features. The VIC model has been used for a number of modeling studies over large-scale river basins (e.g., Abdulla et al., 1996; Nijsen et al., 1997, 2001b; Su and Xie, 2003; Chen and Wu, 2008). Nijsen et al. (2001b) reported the study of discharge simulation for 26 continental river basins over the globe, which include one tributary of the Pearl River, the West River, by using the VIC model at a spatial resolution of $2^\circ \times 2^\circ$ grids. Su and Xie (2003) studied runoff simulation for the regions over Mainland China, especially over the Huaihe River and the Yellow River, at a spatial resolution of 60 km $\times$ 60 km by using the VIC model. In addition, the hydrological processes...
of the East River, one tributary of the Pearl River basin, were investigated by using the VIC model (Chen and Wu, 2008). However, the VIC model has not been specifically applied to the whole Pearl River basin for studying its terrestrial hydrological features, which is imperative to mitigate water-related natural hazards in the basin. Furthermore, the studies of Su and Xie (2003) and Chen and Wu (2008) did not use the routing scheme (Lohmann et al., 1996, 1998a,b), which was developed specifically for routing the runoff simulated by the VIC model, to study the effects of routing on the timings and magnitudes of peak flows, which is critical for studying floods. It is worth noting that the VIC model developed by Liang et al. (1994) does not include any river channel routing schemes. Generally, a proper flow routing can effectively improve the accuracy of streamflow simulation (Lian et al., 2007), especially for daily flow simulation. Nijssen et al. (2001b) used the routing scheme of Lohmann et al. (1996, 1998a,b) to simulate river discharges; however, the spatial resolution (2° × 2°, i.e. one grid cell with the area of about 40,000 km²) used in the study might be too coarse to model hydrological processes for the West River properly.

Therefore, the objectives of this paper are to apply the VIC model and the routing scheme to the whole Pearl River basin with 1° × 1° spatial resolution, and to explore the terrestrial hydrological features over the basin. The paper is organized as follows. Section 2 introduces the models and objective functions. The description of the study area and data is given in Section 3. The study results are presented in Section 4.

2. Models and objective functions

2.1. Variable infiltration capacity (VIC) model

The VIC macro-scale model (Liang et al., 1994, 1996) is used to simulate surface and subsurface hydrological processes on a spatially distributed (grid cell) basis. The land surface in the model is grouped into different land cover types, and the soil column in a grid cell is specified by using averaged soil characteristics with a number of soil layers (Liang et al., 1994). Compared to other MHMs, the main feature of the VIC model is the application of the variable infiltration curve developed by Zhao et al. (1980) and Zhao (1984, 1992), which can scale the infiltration by a non-linear function of the fractional grid cell area.

The variable infiltration curve in the VIC model is defined over a grid cell as follows (Liang et al., 1994):

\[
i = i_m \left[1 - (1 - A)^{1/B}\right] \tag{1}
\]

where \(i\) and \(i_m\) are the infiltration rate and maximum infiltration rate within the grid cell, respectively. \(A\) represents the fraction of a grid cell for which the infiltration rate is equal to \(i\), and \(B\) is an infiltration rate shape parameter, which is a measure of the spatial variability of the infiltration rate (Liang et al., 1994). Using Eq. (1), the direct runoff (i.e., overland flow) is computed from the areas where precipitation exceeds the storage capacity of the soil column.

The soil moisture transport mechanism of the soil column in the VIC model consists of gravity drainage in each soil layer, which is a function of the soil moisture storage and the hydraulic conductivity. The ARNO baseflow model (Todini, 1996) is used to represent subsurface runoff generation from the deepest soil layer (Liang et al., 1994). Basically, the baseflow is specified as a function of soil moisture in the lowest soil layer, which is non-linearly related to high soil moisture content and linearly related to low soil moisture content (Liang et al., 1994) of the deepest soil layer. The total runoff is the sum of direct runoff and baseflow for each grid cell.

2.2. Flow routing for VIC

The VIC model provides the simulation of overland flow and baseflow, but the scheme for routing the runoff from the upstream to downstream over a basin is not available (Liang et al., 1994). Thereafter, a stand-alone routing scheme was developed by Lohmann et al. (1996, 1998a,b). The flowchart of simulation procedure for VIC and the routing scheme is shown in Fig. 1. The main task of this routing scheme is to simulate the lateral travel time of water within each grid cell as well as the transport time in river channels.

The routing scheme consists of two impulse response functions. One is for river channels, and the other for grid cells (Lohmann et al., 1996, 1998a,b). The river channel impulse response function (Lohmann et al., 1996, 1998b) can be represented as follows:

\[
h(x, t) = \frac{x}{2\sqrt{\pi}Dt} \exp\left(-\frac{(Ct-x)^2}{4Dt}\right) \tag{2}
\]

![Fig. 1. Flowchart of simulation procedure for VIC and the routing scheme.](attachment:flowchart.png)
where $C$ and $D$ are flow wave velocity and wave diffusivity, respectively. Both parameters can be determined by field measurements or estimated by using streamflow observations (Lohmann et al., 1996). $x$ and $t$ are the channel length and time, respectively. The boundary and initial conditions of Eq. (2) are $h(x,0) = 0$ for $x > 0$ and $h(x,t) = \delta(t)$ for $t \geq 0$.

The ranges of wave velocity $C$ and the diffusivity $D$ were suggested to be $1\text{–}3 \text{ m/s}$ and $200\text{–}4000 \text{ m}^2/\text{s}$, respectively, in the Weser River basin in Germany by Lohmann et al. (1996). In that study, $C$ and $D$ were optimized with a least-square solution based on 1 year period of hourly interpolated streamflow data for grid cells with the spatial resolution of $0.125^\circ \times 0.125^\circ$ (about $15 \text{ km} \times 15 \text{ km}$) in the basin. Nijssen et al. (1997) calibrated the value of $C$ for two river basins in the United States. One is the Columbia River basin with $1^\circ \times 1^\circ$ grid cells with the range of $0.5\text{–}2 \text{ m/s}$, and the other the Delaware River basin with $0.5^\circ \times 0.5^\circ$ grid cells with 1 m/s. These two parameters for the Pearl River are estimated by using a sensitivity analysis (see Section 4.2 for details). Then, the discharge through channels can be computed by using convolution integrals as below:

$$Q(x,t) = \int_0^t U(t-s)h(x,s)ds \quad (3)$$

where $U$ is the flow volume from a grid cell. In the VIC model, the simulated flow exits a grid cell in only one of eight possible directions, and the flow volume from a grid cell is weighted by the fraction of the grid cell within the study basin. Then, the grid cell impulse response function can be computed via deconvolution of the catchment impulse response function, which can be derived from observed hydrograph and related hyetograph, and the river channel impulse response function (Lohmann et al., 1998a). In this study, the catchment impulse response function is derived from several flood events.

Reservoir operations and water extractions from river channels are not modeled in this routing scheme. Therefore, the simulated flow from the VIC and the routing scheme is natural flow (which refers to the streamflow in channels without the anthropogenic influences).

2.3. Objective functions

In order to evaluate the simulation results, several objective functions are employed. Among them, relative bias (RB) is used to test whether the model has the ability to simulate the observation mean of the variable $Q$.

$$\text{RB} = \frac{\sum_{i=1}^{n} (Q_{\text{sim}}(t) - Q_{\text{obs}}(t))}{\sum_{i=1}^{n} Q_{\text{obs}}(t)} \quad (4)$$

Furthermore, the Relative Root Mean Square Error (RRMSE) and Nash–Sutcliffe efficiency coefficient (NSE) (Nash and Sutcliffe, 1970) are used as objective functions. RRMSE is the average of the squared errors for the simulation divided by the observation mean, which provides an objective measure of the difference between observation and simulation for every simulation step. NSE can indicate the simulation quality by comparing both volume and shape of observed and simulated hydrographs. The computations of RRMSE and NSE are given as below:

$$\text{RRMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (Q_{\text{obs}}(t) - Q_{\text{sim}}(t))^2/Q_{\text{obs}}} \quad (5)$$

$$\text{NSE} = 1 - \frac{\sum_{i=1}^{n} (Q_{\text{sim}}(t) - Q_{\text{obs}}(t))^2}{\sum_{i=1}^{n} (Q_{\text{obs}}(t) - Q_{\text{obs}})^2} \quad (6)$$

NSE ranges from $-\infty$ to 1, and the value of 1 refers to a perfect match of model simulation to the observation.

In addition, to examine the influence of the routing scheme on streamflow simulation, especially on the simulation of peak flows, LPTE and LPV are defined. Local peak flow is defined as its value is larger than both the streamflow values at the previous time step and next time step. The correct simulated peak flow refers to the simulated local peak flow occurs on the same day when the observed local peak flow occurs. LPTE is the ratio of the number of the times of correct simulated peak flow ($\text{LPTE}_{\text{sim}}$) to the total number of times of peak flow occurred in an observation dataset ($\text{LPTE}_{\text{obs}}$). To evaluate the simulation of peak flow volume, LPV is defined through calculating the observed and simulated peak flow discharges. The equations for LPTE and LPV are given as follows:

$$\text{LPTE} = \frac{\text{LPTE}_{\text{sim}}}{\text{LPTE}_{\text{obs}}} \quad (7)$$

$$\text{LPV} = 1 - \frac{1}{\text{LPTE}_{\text{obs}}} \sum_{j=1}^{\text{LPTE}_{\text{obs}}} \left( \frac{|Q_{\text{obs}}(T_p(j)) - Q_{\text{sim}}(T_p(j))|}{Q_{\text{obs}}(T_p(j))} \right) \quad (8)$$

where $T_p$ is the time of observed peak occurrence. A perfect peak flow simulation refers to that the values of LPTE and LPV are equal to 1.0.

3. Study area and data

The total area of the Pearl River basin in South China is $0.45 \times 10^6 \text{ km}^2$. The basin consists of four major river basin systems, the East river, North river, West River and Pearl River Delta (Fig. 2), in which the West River includes 8 sub-basins. Fig. 2(a) shows the natural shape of the Pearl River basin over the digital elevation map, and Fig. 2(b) displays the $1^\circ \times 1^\circ$ grid cells of the basin for applying the VIC model and the river reaches and direction for using the routing scheme. The East River flows to the Pearl River Delta directly, while the West River and North River are confluent before discharging into the Pearl River Delta. Ultimately, the Pearl River runs into the South China Sea through eight outlets. As a whole, the water system of the Pearl River is uniquely characterized by three inluxes and eight outward-fluxes (Cui et al., 2007).

Over the basin, average annual precipitation is about $1480 \text{ mm/yr}$, and annual runoff generation is about $0.74 \times 10^6 \text{ m}^2/\text{km}^2/\text{yr}$, which is about half of the total annual
precipitation (Cui et al., 2007). However, inter-annual variation of runoff is rather large. For the period 1951–2000, the runoff ratio of the wettest year to the driest year can reach 6–7, while the related precipitation ratio of them is less than 3 (Niu and Chen, 2008). The seasonal variation of runoff is also high. In the wet season (April–September), the runoff is about 80% of the total annual runoff (Niu and Chen, 2008). Therefore, water-related natural hazards, namely floods and droughts, occur frequently over the basin. For example, from the historical records, local, regional and basin-scale floods have occurred over the Pearl River Basin (Pearl River Water Resource Commission, 2005). Meanwhile, drought is another natural hazard in the Pearl River basin; especially in 1963, 5% of the total area of the basin was subjected to severe drought (Pearl River Hydraulic Research Institute, 2007).

This study uses the streamflow observations at six gauge stations (i.e., Gaoyao, Wuzhou, Shijiao, Boluo, Xinfengjiang, and Longchuan) over the West River, North River and East River (see Fig. 2) to evaluate the performance of the VIC model and the routing scheme. The control drainage areas of these six gauge stations are given in Table 1. To delineate the Pearl River basin, GTOPO30 DEM dataset with 1 km spatial resolution (Verdin and Verdin, 1999) is used. For running the VIC model, the soil and vegetation data over the basin are

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**Table 1**

Streamflow simulation results at a monthly step for six gauge stations over the three tributaries of the Pearl River (Fig. 2).

<table>
<thead>
<tr>
<th>River</th>
<th>Station</th>
<th>Control area (km²)</th>
<th>Period</th>
<th>RB</th>
<th>RRMSE</th>
<th>NSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>West River</td>
<td>Gaoyao</td>
<td>351,525</td>
<td>1980–2000</td>
<td>0.06</td>
<td>0.27</td>
<td>0.88</td>
</tr>
<tr>
<td>West River</td>
<td>Wuzhou</td>
<td>329,705</td>
<td>1981–1985</td>
<td>0.01</td>
<td>0.20</td>
<td>0.90</td>
</tr>
<tr>
<td>North River</td>
<td>Shijiao</td>
<td>37,872</td>
<td>1980–2000</td>
<td>−0.19</td>
<td>0.32</td>
<td>0.85</td>
</tr>
<tr>
<td>East River</td>
<td>Boluo</td>
<td>25,325</td>
<td>1980–2000</td>
<td>0.56</td>
<td>1.21</td>
<td>−3.17</td>
</tr>
<tr>
<td>East River</td>
<td>Xinfengjiang</td>
<td>5734</td>
<td>1951–1958</td>
<td>−0.07</td>
<td>0.42</td>
<td>0.83</td>
</tr>
<tr>
<td>East River</td>
<td>Longchuan</td>
<td>7699</td>
<td>1952–1972</td>
<td>−0.21</td>
<td>0.41</td>
<td>0.82</td>
</tr>
</tbody>
</table>

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Fig. 2. The Pearl River basin, the river network and six streamflow gauge stations. (a) The natural shape of the basin over the digital elevation map. (b) The grid cells at 1° × 1° spatial resolution of the basin with the river routing reaches and direction.
extracted from two datasets, global soil and vegetation from Nijssen et al. (2001a). Detailed information of these two datasets can be found in Nijssen et al. (2001a). For completeness, a brief review is provided below.

In the global soil dataset, two VIC soil parameters, soil texture and soil bulk density, were derived from the 5-min FAO-UNESCO (Food and Agriculture Organization–United Nations Educational, Scientific, and Cultural Organization) digital soil map of the world and the WISE (World Inventory of Soil Emission Potentials) pedon database (Nijssen et al., 2001a). The remaining soil parameters in the VIC model, such as porosity, saturated hydraulic conductivity, and the exponent for the unsaturated hydraulic conductivity equation were obtained based on the study of Cosby et al. (1984). For the Pearl River basin, the soil column in each grid cell is divided into three layers. The depth of soil layer is specified by sampling the WISE database (Nijssen et al., 2001a). The thickness of the near-surface layer is 0.3 m, the second layer 1.0–2.5 m, and the bottom layer 0.2 m.

In the global vegetation dataset for the VIC model, vegetation types were taken from the Advanced Very High Resolution Radiometer (AVHRR)-based, 1-km, global land classification from Hansen et al. (2000), which includes 11 vegetation types, and other two land cover types, bare ground and urban built-up area. Vegetation fractions were determined as the area occupied by a vegetation type divided by the total land area in each 1°×1° grid cell. Vegetation-related parameters for the VIC model such as vegetation height, and minimum stomatal resistance were assigned to each vegetation type, and roughness lengths and displacement heights were calculated from assumed average vegetation heights following Calder (1993). Architectural resistances were taken from Ducoudré et al. (1993). Leaf Area Index (LAI), used in the calculation of interception storage and evapotranspiration for the VIC model, was based on Myneni et al. (1997). In the VIC model, the LAI values were allowed to vary by month.

In this study, the VIC model is applied for the period January 1951–December 2000. The daily meteorological data, including precipitation, maximum and minimum air temperatures, wind speed and relative humidity reported in Feng et al. (2004) are used. The daily meteorological observations for the period 1951–2000 from 726 weather stations over Mainland China are gridded to 1°×1° grids (Feng et al., 2004), and, therefore, the spatial resolution of 1°×1° grids is used for the Pearl River basin (see Fig. 2(b)). It is worth noting that a daily time scale is used for driving the VIC model and the routing scheme.

The study period for the comparison of observations and simulations at a monthly step is from January 1980 to December 2000 for Gaoyao station in the West River, Shijiao station in the North River and Boluo station in the East River. In addition, at a monthly step, the study periods for Wuzhou station in the West River, Xinfengjiang station and Longchuan station in the East River are from January 1981 to December 1985, from January 1951 to December 1958, and from January 1952 to December 1972, respectively. The study period of daily streamflow is from 1 January 1980 to 31 December 1985 for Gaoyao, from 1 January 1980 to 31 December 1988 for Shijiao, and from 1 January 1954 to 31 December 1988 for Boluo.

4. Results

4.1. VIC simulation

The VIC simulation can provide various hydrological processes, such as streamflow, soil moisture variation and evapotranspiration. Since a routing scheme mainly improves streamflow simulation at sub-monthly temporal scales (see Section 4.2), the VIC daily simulation results without the routing scheme are compared with the observation at a monthly scale after aggregation of daily data.

Table 1 gives the comparison results between the streamflow observations and simulations over the period 1980–2000 at a monthly time step by using the objective functions to compute the statistical terms of RB, RRMSE and NSE. The values of these statistical terms listed in Table 1 indicate that VIC model can properly simulate the streamflow of the West River and the North River but not the East River according to the general performance rating guidelines (which recommend that the model performance at monthly scale with NSE > 0.50 and RB < ±0.25 can be roughly evaluated as a ‘satisfactory’ rating) suggested by Moriasi et al. (2007). To further develop the comparison results, Fig. 3 shows the relationships between the observed and simulated values in the scatter plot of the monthly streamflow for the period 1980–2000 for these three gauge stations. That the linear regression line slopes for Gaoyao station (1:0.95) with \( R^2 = 0.91 \) and for Shijiao station (1:1.09) with \( R^2 = 0.90 \) are close to 1:1 reveals that the model has the capability of simulating the dynamics of monthly runoff series.
over the West River and the North River. However, the slope of 1:0.44 with $R^2$ of 0.76 for Boluo station indicates that the streamflow simulation in the East River from the VIC model is much higher than the observation, which is consistent with the statistical results of RB and NSE in Table 1.

With inspection of the East River basin and the study of Wu and Chen (accepted for publication), it is observed that the Boluo monthly streamflow is significantly influenced by the operation of the reservoirs in the upstream of the station. The reservoirs can attenuate the peak flow and increase the low streamflow, which is the reason of the regression slope of 1:0.44 (namely the simulated streamflow is much larger than the observation at Boluo station). Therefore, the observations from two streamflow gauge stations, Xinfengjiang and Longchuan (see Fig. 2), upstream of the Boluo station are used to investigate the streamflow simulation without the reservoir influence. Due to the availability of the streamflow data, for Xinfengjiang station, there is the Xinfengjiang Reservoir operated since 1959, and then the study period 1951−1958 is used. For Longchuan station, Fengshuba Reservoir operated since 1973 is located at its upstream, and the study period 1952−1972 is used. Table 1 lists the statistical results for these two stations, and it can be found that the monthly simulation results are comparable to the simulation at the North River. Therefore, the VIC model can provide reasonable streamflow simulation for the East River also, and the study indicates that the reservoir operation in the East River can influence the streamflow at a monthly scale significantly.

In Nijssen et al. (2001b), the VIC simulation for five year monthly streamflow at Wuzhou station in the West River (see Fig. 2) was investigated and the values of $R_{RMSE}$ and RB are 0.44 and $-0.16$, respectively. The VIC simulation for Wuzhou station over the period 1981−1985 is compared with the result from the study of Nijssen et al. (2001b). The $R_{RMSE}$ and RB are 0.20 and 0.01 (see Table 1), respectively, which are considerably improved. It can be inferred that the improvement of the simulation is mainly due to using the $1° \times 1°$ spatial resolution, which is finer than the spatial resolution used in Nijssen et al. (2001b). Therefore, the spatial resolution used in this study should be more suitable than that in Nijssen et al. (2001b) to study the hydrological processes over the basin.
After validating the VIC model in the simulation of streamflow over the Pearl River, the features of the different water components from the VIC model simulation are analyzed. Fig. 4 shows monthly means of precipitation, evapotranspiration, runoff and soil water change averaged over the period 1980–2000 for the West River (Fig. 4(a)), North River (Fig. 4(b)), and East River (Fig. 4(c)), respectively. From Fig. 4, it can be found that the model results reveal that the monthly soil water change oscillates dynamically for maintaining the basin water balance. For all three tributaries, according to the magnitudes of these water components, the dominant terrestrial hydrological processes are evapotranspiration and runoff. This indicates that the water balance in the VIC model simulation is confirmed.

Furthermore, Fig. 4 displays that monthly precipitation is above 200 mm in June and July for the West River, from April to June for the North River and from April to August for the East River, and the runoff generally is the governing component in the water balance for these months. When the sum of evapotranspiration and runoff exceeds precipitation in a month, it reflects that soil water is extracted out in the month. Fig. 4 shows that soil water storage would be continuously extracted from July to December in the West River, from June to December in both of the North River and East River, for contributing to the evapotranspiration and runoff over the basin. Meanwhile, Fig. 4 indicates that the monthly maximum soil water recharge occurs in May for the West River, and in February for both the North River and East River. With the information of the soil water recharge and extraction, it can be deduced that soil condition would be the wettest in June for the West River and in May for both the North River and East River, and the driest in December for these three tributaries, which are useful for the study of floods and droughts over the basin.

### 4.2. Routing results

The VIC model simulates the volume of runoff at a daily step from each grid cell over the whole Pearl River basin (Fig. 2), and the routing scheme is used to model the lateral travel time of water within each grid cell and river channels. The flow directions in the 1° × 1° grid cells for indicating the path of routing, and the locations of the six gauge stations are shown in Fig. 2(b).

Fig. 5(a) shows the catchment impulse response functions (see Section 2.2) for the three tributaries of the Pearl River, which are derived from the study of several flood events occurred over the tributaries. For the river channel impulse response function, a sensitivity study is used to evaluate the values of parameters $C$ and $D$ (see Eq. (2)). Using the streamflow observation at Gaoyao station in 1976, the sensitivity of the parameter $C$ on the streamflow simulation is given in Fig. 5(b). The figure shows that the parameter can influence the hydrograph shape on both the flow travel time and volume. The simulation with $C$ of 3 m/s matches the observation better than other two values, 1 m/s and 2 m/s (Fig. 5(b)). Similar analysis about parameter $D$ shows that the sensitivity of the streamflow to the parameter $D$ is small (the change is within ±0.16% for daily streamflow value corresponding to the changing $D$ value from 2000 to 3000 m²/s). Therefore, the routing parameter $C$ is estimated as 2–3 m/s for the West River, 3–3.5 m/s for the North River and 3 m/s for the East River; parameter $D$ of 2000 m²/s is used.

With the routing scheme, the VIC simulated daily runoff is routed from the upstream to the downstream for these three tributaries. Table 2 lists the comparison results of streamflow at a daily time step from the VIC model with and without the

<table>
<thead>
<tr>
<th>Station</th>
<th>Period</th>
<th>RB</th>
<th>RRMSE</th>
<th>NSE</th>
<th>LPTE</th>
<th>LPV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaoyao</td>
<td>1980–1985</td>
<td>0.06/0.03</td>
<td>0.76/0.30</td>
<td>−0.06/0.84</td>
<td>0.17/0.53</td>
<td>0.39/0.77</td>
</tr>
<tr>
<td>Shijiao</td>
<td>1980–1988</td>
<td>−0.18/−0.15</td>
<td>0.79/0.52</td>
<td>0.50/0.78</td>
<td>0.14/0.57</td>
<td>0.22/0.65</td>
</tr>
<tr>
<td>Boluo</td>
<td>1959–1988</td>
<td>−0.01/−0.02</td>
<td>1.16/0.69</td>
<td>−0.29/0.54</td>
<td>0.14/0.45</td>
<td>0.02/0.53</td>
</tr>
<tr>
<td>Boluo</td>
<td>1954–1958</td>
<td>−0.05/−0.02</td>
<td>1.15/0.60</td>
<td>0.39/0.83</td>
<td>0.11/0.61</td>
<td>−0.39/0.49</td>
</tr>
</tbody>
</table>

Fig. 5. (a) Catchment impulse response functions (IRF) for the three tributaries of the Pearl River. (b) Sensitivity of the routing parameter $C$ for the streamflow simulation at Gaoyao station in the West River in 1976 (parameter $D$ is 2000 m²/s).
routing scheme for Gaoyao, Shijiao, and Boluo (see Fig. 2(b)). From the table, it can be observed that the routing scheme can effectively improve the simulation at the daily scale through reducing the values of RB and RRMSE and increasing NSE to approaching 1.

To view the simulation results from the routing scheme, Fig. 6 shows the comparisons of observations and simulations from the VIC model with and without the routing scheme. Fig. 6(a)—(c) displays the daily streamflow in 1984 for the three gauge stations, Gaoyao, Shijiao and Boluo, respectively; Fig. 6(d) gives the daily streamflow in 1957 for Boluo station only (for the consideration of without the reservoir effects on streamflow). From the figure, it is observed that the dots are effectively converged to the linear regression lines for the simulation with the routing scheme, which results in the increase of $R^2$ from 0.46 (without the routing scheme) to 0.89 (with the routing scheme) in Fig. 6(a), from 0.64 to 0.83 in Fig. 6(b), from 0.55 to 0.73 in Fig. 6(c), and from 0.47 to 0.88 in Fig. 6(d). It is believed that the increase of $R^2$ is due to the correction of flow peak timings and magnitudes by using the routing scheme, which can be confirmed by inspecting LPTE and LPV in Table 2. The table shows that the times of local peak occurrences are corrected with increasing LPTE value and the simulations of local peak magnitudes are improved with increasing LPV value. Nevertheless, Fig. 6(c) shows that according to the linear regression lines the routing scheme cannot improve the simulation of streamflow considerably, and both of the line slopes are 1:0.59 and 1:0.61, respectively, which rather over-simulate the streamflow. This is consistent with the monthly comparison result in Fig. 3 and Table 1, and reflects the effect of the reservoir operation. Therefore, the simulated streamflow in 1957 before the operation of the Xinfengjiang Reservoir is routed, and the results are given in Fig. 6(d) and Table 2. It is observed that the performance of
streamflow simulation at a daily time step is improved by the routing scheme, and the statistical term of NSE increases from 0.39 to 0.83. Therefore, the routing scheme has its capability of preserving lateral travel time of water flow, and is very effective in daily hydrological process simulation of streamflow.

To evaluate the effects of the routing scheme on temporal scales of streamflow simulation, Fig. 7 shows the performance of model simulation with and without routing by comparing NSE value at different time scales ranging from 1 day to 6 weeks for the three tributaries over three study periods given in Table 2 (the period of 1954–1958 for Boluo). From the figure, it is observed that the effect of the routing scheme is very significant for Gaoyao at small time scales (less than 1 week). The NSE value reaches to a certain flat level after 2 weeks for the North River and East River and after 3 weeks for the West River, which indicates the routing scheme would not be effective for a temporal scale beyond.

5. Conclusions

The hydrological processes of the Pearl River basin in South China, which consists of four sub-basin systems, the West River, North River, East River and Pearl River Delta, for the period 1951–2000, were simulated by using the VIC model and a routing scheme. The simulation was carried out at the $1^\circ \times 1^\circ$ spatial and daily temporal resolutions. Over the basin, the daily meteorological forcings, including precipitation, maximum and minimum temperatures, and wind speed, were used, and the soil and vegetation parameter values were extracted from the soil and vegetation global datasets. Without calibration, the VIC model was applied to the Pearl River basin.

Comparison with the streamflow gauge observations from the West River, North River and East River revealed that the monthly variation in runoff was well captured by the VIC simulation. However, the model could not model the streamflow well for the period 1980–2000 at Boluo station in the East River, which was influenced considerably by the upstream reservoir operation. It is concluded that the $2^\circ \times 2^\circ$ grid resolution for the Pearl River basin is coarse, and the $1^\circ \times 1^\circ$ grid resolution would be enough at a monthly time scale. However, the degree of fine resolutions for producing proper simulation at shorter temporal scales needs further research. From the analysis of the simulated water components, streamflow, evapotranspiration and soil water change, it was observed that over the Pearl River basin the soil moisture change is important for maintaining the water balance, and the streamflow and evapotranspiration are two dominant hydrological processes. Furthermore, the streamflow and evapotranspiration vary seasonally according to the seasonal variation pattern of precipitation.

The routing scheme was used to route the streamflow simulated by the VIC model. Two parameter values in the routing scheme were determined by using a sensitivity study, and then the VIC simulated streamflow was analyzed at a daily time step. The study indicated that the routing scheme could improve the simulation of the peak flow significantly. Moreover, the analysis of the influence of the routing scheme on different temporal scales disclosed that the routing can improve the streamflow simulation for the time steps less than 2–3 weeks. In other words, if the temporal scale is more than about 3 weeks, for the Pearl River basin, the effects of the routing scheme can be neglected.

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