Simulating the discharge of the Chao Phraya River taking into account reservoir operation

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Abstract A simple reservoir operation model for Total Runoff Integrating Pathways (TRIP), which is one of the global river routing network models, is introduced. To overcome the shortage of reservoir operating rule information, the model is designed to set an operating rule for each reservoir using globally available data sets and few parameters. The model is applied to the Chao Phraya River in Thailand to validate its performance. The correspondence between the model results and observations is judged to be good enough for applying the model in global and continental studies.

Key words Chao Phraya River (Thailand); global river discharge simulation; reservoir operation model; TRIP

INTRODUCTION

Reliable assessment of current and future global water resources has received increasing attention because the growth of population and economy are expected to cause serious water shortage in the world. In assessments, global river routing network models (GRRNMs) have been widely used to estimate the global distribution of river discharge, which is regarded as the most fundamental and sustainable water resources (Vörösmarty et al., 2000; Oki et al., 2001). One of the technical issues of current GRRNMs is that they cannot deal with flow regulation by reservoirs; nevertheless their impacts on the river discharge and water resources in the basin are sometimes too large to neglect. Therefore, it was decided to develop a reservoir operation model (ROM) for GRRNM to represent its flow regulation function in the river network. Vörösmarty et al. (1997) assigned the locations of 622 large reservoirs to their GRRNM. However since they did not have ROM, they just indicated the significant increase in the standing store of natural river water and the residence time due to impoundment by comparing the total storage capacity and the annual inflow of each reservoir. They also pointed out that a major problem in developing ROM is caused by the shortage of available operating rule information for individual reservoirs. To overcome this, a ROM has been designed to perform with commonly available information, and incorporated into Total Runoff Integrating Pathways (TRIP; Oki & Sud, 1998) which is one of the GRRNMs. This paper reports the results of model application to the Chao Phraya River in Thailand.
AVAILABLE RESERVOIR DATA

Information on reservoirs was obtained from the *World Register of Dams 1998* (WRD98; ICOLD, 1998) which is, practically, the only comprehensive global reservoir dataset. In consideration of the spatial resolution of TRIP (1° × 1° and 0.5° × 0.5° grid), only large reservoirs with capacities of more than or equal to $10^9$ m$^3$ are considered. The database contains a total of 593 such reservoirs. WRD98 provides us with the names of dams, storage capacities and purposes in decreasing order, but the geographical coordinates, inflow data and operating rules for the listed dams are not provided. The geographical coordinates are necessary to assign each reservoir to a corresponding location on TRIP’s digital river network. The information provided in WRD98, i.e. names of dam, river, nearest city, was used in conjunction with published world atlases to locate the relevant entries of each dam. Of the total of 593 reservoirs, the locations of 511 reservoirs were identified on the digital river network of TRIP. The annual inflow discharge was obtained from the simulation results of TRIP, made by inputting global grid runoff data provided by the Global Soil Wetness Project (GSWP; Dirmeyer *et al.*, 1999). The data was the output of an offline run of the Simplified Biosphere model (SiB; Sellers, 1986) operated by the Japan Meteorological Agency (JMA), using the International Satellite Land Surface Climatology Project (ISLSCP) Initiative I dataset which is global, 24-month period (1987–1988), monthly, 1° × 1° grid, near surface meteorological data provided by NASA (Meeson *et al.*, 1995). More details of the simulation procedure are described in Oki *et al.* (2001). Since operating rule data associated with individual reservoirs are quite difficult to collect globally, they were estimated from several available global data.

MODEL DESCRIPTIONS

This section introduces the structure of ROM, a special flow calculation scheme for GRRNMs to represent reservoir operation, used when a reservoir is assigned on the calculating grid. In reality, flow regulation at each dam is determined by its unique operating rule. However, it seems impractical to collect rules for all the large reservoirs. Therefore ROM is designed to set an adequate operation rule for each reservoir automatically. Since globally obtainable reservoir data is also limited, as described above, the structure of ROM should be kept simple. ROM consists of two modules, namely the Basic Operation Module (BOM) whose function is to reduce seasonal/annual fluctuation of river discharge, and the Unique Operation Module (UOM) which considers the purpose of the reservoir (i.e. hydropower, irrigation, etc.). Both modules set the operation rule every year and calculate releases. The calculation interval is monthly.

Basic Operation Module (BOM)

The Basic Operation Module (BOM) aims to reduce seasonal and inter-annual discharge fluctuation. BOM is applied to every reservoir because it is assumed that this is the fundamental function of large dams.
Based on the data at each dam, all the months of a year are classified as “high-discharge season” and “low-discharge season”. If the monthly discharge is larger than the annual mean, the month is classified as “high-discharge season” and vice versa. The first month of the low-discharge season was considered as the first month of the hydrological year. In the first month of the hydrological year, BOM sets three parameters: the release coefficient ($k_{rls}$), the normal release ($r_{\text{norm}}$), and flood discharge ($r_{\text{flood}}$) from the information on the reservoir storage, total capacity and the mean annual inflow. These coefficients behave as the operating rule. The release coefficient ($k_{rls}$) is defined as:

$$k_{rls} = S / [k_{\text{norm}} \times C]$$  \hspace{1cm} (1)

where $S$ is the storage in the first month of the hydrological year $[\text{m}^3]$, $C$ is the total storage capacity $[\text{m}^3]$, $k_{\text{norm}}$ is the normal-year coefficient $[0-1]$ and invariable to season or year. It corresponds to the ratio of total storage capacity excluding surcharge and dead storage, to total storage capacity. The release coefficient judges the storage condition of the reservoir and is designed so as to reduce the release under storage shortage condition ($S < k_{\text{norm}} \times C$) or to allow abundant supply under storage excess condition ($S > k_{\text{norm}} \times C$). Then the normal release ($r_{\text{norm}}$)$[\text{m}^3 \text{month}^{-1}]$ is defined as:

$$r_{\text{norm}} = k_{rls} \times Q / 12$$  \hspace{1cm} (2)

where $Q$ is the mean annual inflow $[\text{m}^3 \text{year}^{-1}]$. The normal release is the target value to release. The flood discharge ($r_{\text{flood}}$)$[\text{m}^3 \text{month}^{-1}]$ is defined as:

$$r_{\text{flood}} = (C - S + k_{rls} \times Q) / M_{\text{flood}}$$  \hspace{1cm} (3)

where $M_{\text{flood}}$ is the number of months classified as high-discharge season. The flood discharge is the threshold of the monthly inflow. The inflow is judged as “flood discharge” when it exceeds $r_{\text{flood}}$ and the excess amount is also released.

Finally, the operating rule is set as follows:

$$i \geq r_{\text{flood}} \quad r_{\text{BOM}} = r_{\text{norm}} + (i - r_{\text{flood}})$$  \hspace{1cm} (4)

$$i < r_{\text{flood}} \quad r_{\text{BOM}} = r_{\text{norm}}$$  \hspace{1cm} (5)

where $r_{\text{BOM}}$ is the monthly target release set by BOM and $i$ is monthly inflow. The evaporation from the reservoir is neglected in this study.

**Unique Operation Module (UOM)**

UOM controls any additional release or storage, taking account of the purpose of the reservoir and water demand in the lower reach. In this paper, a scheme for irrigation water supply is introduced. The monthly irrigation water demand ($d$) is a function of crop type, rainfall and irrigated area in the basin, described as:

$$d = \sum_{\text{crop}} (k_{\text{dip}} \times ET_{\text{crop}} - p) \times a$$  \hspace{1cm} (6)

where $ET_{\text{crop}}$ is the monthly water requirement for the cultivated crop $[\text{mm month}^{-1}]$, $p$ is the monthly rainfall, $a$ is the irrigated area. $k_{\text{dip}}$ is the dependency coefficient, which indicates the degree of dependence of agriculture on irrigation water. It varies between 1 for agriculture fully dependent on irrigation, to 0 for rain-fed agriculture.
The CROPWAT program developed by Smith (1992) was used to estimate the monthly crop water requirement \( (ET_{\text{crop}}) \). CROPWAT calculates monthly crop water requirement \( (ET_{\text{crop}}) \) as:

\[
ET_{\text{crop}} = k_c \times ET_0 + L_{\text{perc}}
\]

where \( k_c \) is the crop coefficient determined by month and the growing stage of crops, \( ET_0 \) is the potential evapotranspiration and \( L_{\text{perc}} \) is the percolation loss which is a special term for paddy field.

The irrigated area \( (a) \) was estimated using a global map of irrigated areas (Döll & Siebert, 2000). It provides us information of global irrigated area distribution at 0.5° x 0.5° resolution. It was observed that not all the area reported is actually under cultivation, some areas may be left as fallow. Therefore, the monthly cultivated area \( (a) \) was defined as:

\[
a = k_{\text{area}} \times a_{\text{org}}
\]

where \( k_{\text{area}} \) is the planted area coefficient, the ratio of the actually cultivated area to the total irrigated area, \( a_{\text{org}} \) is the original data derived from Döll & Siebert (2000).

Finally, the monthly target release set by UOM \( (r_{UOM}) \) is calculated as:

\[
r_{UOM} = k_{\text{rls}} \times d
\]

The \( r_{UOM} \) value can be smaller than 0 and in which case the total monthly release is saved (see equation (10)).

The total monthly release from a reservoir \( (r) \) is described as:

\[
r = r_{BOM} + r_{UOM}
\]

STUDY AREA

The model was applied to the Chao Phraya River in Thailand as a case study. Figure 1 shows the river system in TRIP. Two reservoirs are assigned their location in the digital river network: the Bhumibol and Sirikit dams. The discharge is validated at Nakhon Sawan where a gauging station is located. Table 1 shows the discharge simulation by TRIP without consideration of reservoirs. The catchment area is well represented. However, the discharge at the dam location or the upper reach is lower than observed. The input parameters for BOM are listed in Table 2. The observed value for the mean annual inflow was used in the study, since it has a critical impact on the release calculation. It is indispensable for improving the discharge simulation, especially in the upper reach or in a small catchment area. The normal-year coefficient \( (k_{\text{norm}}) \) was set to 0.85 for the both reservoirs. We assume \( k_{\text{norm}} \) as a global parameter. However it might need some regional modification in global application.

The agriculture in the basin is adapted to the tropical monsoon climate. The main crop is rice, so it is assumed that all the irrigated area in the basin is paddy. The typical cropping pattern is to sow and transplant in July and harvest in November (rainy season crop). It is rain-fed and irrigation water is supplied as a supplementary, and almost all the irrigated area is cropped. If sufficient water is available, a second crop is raised, transplanted in February and harvested in June (dry season crop). It is completely dependent on irrigation water supply, and its cropped area varies in
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Fig. 1 Chao Phraya River in TRIP. ★ Bhumibol dam, ■ Sirikit dam, ○ Nakhon Sawan (river gauging station), shading = catchment area.

Table 1 Chao Phraya River hydrological information.

<table>
<thead>
<tr>
<th></th>
<th>Catchment area ($10^6$ km$^2$):</th>
<th>Annual discharge ($m^3 s^{-1}$):</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TRIP</td>
<td>Obs.</td>
</tr>
<tr>
<td>Bhumibol dam</td>
<td>26 400</td>
<td>23 442</td>
</tr>
<tr>
<td>Sirikit dam</td>
<td>13 300</td>
<td>11 753</td>
</tr>
<tr>
<td>Nakhon Sawan (gauging station)</td>
<td>110 600</td>
<td>117 200</td>
</tr>
</tbody>
</table>

TRIP*: Average of simulation result (1987–1988, runoff data source: JMA SiB with ISLSCP I dataset)
Obs.**: Average of 1987–1988
Obs.***: Average of 1980–1996

Table 2 Parameters for BOM.

<table>
<thead>
<tr>
<th></th>
<th>Bhumibol dam</th>
<th>Sirikit dam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage capacity, $C$ ($10^6$ m$^3$)</td>
<td>13 500</td>
<td>9 500</td>
</tr>
<tr>
<td>Mean Annual inflow, $Q$</td>
<td>163</td>
<td>166</td>
</tr>
<tr>
<td>Normal-year coefficient, $k_{nara}$</td>
<td>0.85</td>
<td>0.85</td>
</tr>
<tr>
<td>High-discharge season months</td>
<td>Aug, Sep, Oct, Nov</td>
<td>Jul, Aug, Sep, Oct</td>
</tr>
</tbody>
</table>

Table 3 Parameters for UOM.

<table>
<thead>
<tr>
<th>Month</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature(°C)</td>
<td>23.6</td>
<td>25.8</td>
<td>27.2</td>
<td>28.3</td>
<td>27.8</td>
<td>26.4</td>
<td>26.0</td>
<td>26.2</td>
<td>26.4</td>
<td>25.3</td>
<td>24.0</td>
<td>21.0</td>
</tr>
<tr>
<td>Rain (mm month$^{-1}$)</td>
<td>0</td>
<td>22</td>
<td>20</td>
<td>78</td>
<td>199</td>
<td>159</td>
<td>126</td>
<td>148</td>
<td>316</td>
<td>269</td>
<td>88</td>
<td>0</td>
</tr>
<tr>
<td>$ET_0$ (mm day$^{-1}$)</td>
<td>5.7</td>
<td>5.8</td>
<td>7.0</td>
<td>7.0</td>
<td>5.8</td>
<td>6.1</td>
<td>6.1</td>
<td>5.4</td>
<td>4.8</td>
<td>4.3</td>
<td>5.1</td>
<td>6.3</td>
</tr>
</tbody>
</table>

Crop season

<table>
<thead>
<tr>
<th></th>
<th>Dry season crop</th>
<th>Rainy season crop</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_{dep}$</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>$k_{area}$</td>
<td>0.3</td>
<td>1</td>
</tr>
<tr>
<td>$k_c$</td>
<td>0.5 1 1 1 0.5</td>
<td>0.5 1 1 1 0.5</td>
</tr>
<tr>
<td>$I_{pred}$ (mm day$^{-1}$)</td>
<td>3 3 3 3 3</td>
<td>3 3 3 3 3</td>
</tr>
<tr>
<td>$ET_{crop}$ (mm day$^{-1}$)</td>
<td>5.9 10.0 10.0 8.8 3.1</td>
<td>6.1 8.4 7.8 7.3 5.6</td>
</tr>
</tbody>
</table>

Temperature, Rain, $ET_0$ data are derived from ISLSCP I data set for 100°30' E, 14°30' N.
proportion to the storage in reservoirs. On average, about 30% of the total irrigated area is cropped in the dry season. However, the timing and the cropped area vary largely according to weather and rainfall.

Using the information, parameters for UOM were prepared (Table 3). Daily potential evapotranspiration ($ET_0$) for every $1^\circ \times 1^\circ$ grid square of the basin is calculated using the method introduced by Kondo (2000). The method is to solve the surface energy balance equation by iterative calculation. This method was applied because it was more theoretical and better suited for the input data than that used by the CROPWAT program. The air temperature, surface pressure, vapour pressure, wind speed and short/longwave downward radiation were provided by the ISLSCP Initiative I data set and used as input data. Agricultural parameters were set following the information described in the previous paragraph. At first, each 150-day period of the dry/rainy cropping season is classified. Next the dependency coefficient ($k_{dep}$) and the planted area coefficient ($k_{area}$) are set to 1 and 0.3 respectively for dry seasons, and 0.5 and 1 for rainy seasons. These values were fixed in the simulation. The year-to-year fluctuations of these values are represented with the coefficient $k_{r/s}$ in equations (1) and (9). Finally, the values of $k_r$ and $L_{perc}$ are set by simplifying the values in Smith (1992). Originally, $k_r$ is a function of days and $L_{perc}$ depends on soil type or slope. However, they were assumed to be monthly fixed values in this study. This warrants future work on the method of theoretical parameter determination.

RESULTS AND DISCUSSION

At first, ROM was applied to the Bhumibol dam and the Sirikit dam to validate its performance. In each case, the initial storage (in January 1980) and 17-year (1980–1996) observed monthly inflow data was input into ROM. The observed data was provided by the Royal Irrigation Department of Thailand and GAME-T Data Center (http://hydro.iis.u-tokyo.ac.jp/GAME-T). The results are shown in Fig. 2. Although the model has a simple structure, the long-term trend of the annual peak release and monthly storage are well represented. The calculation of monthly release is sometimes subject to major error. However, the release coefficient which varies yearly, damps such error. Since the purpose of this study is to develop a simple model which works with commonly available global data, the model is judged adequate.

Next, ROM was coupled with TRIP at $1^\circ \times 1^\circ$ spatial resolution. In the flow computation, ROM is used if reservoirs were assigned on the calculating grid, otherwise the original routing scheme was used. The input global grid runoff data is the same as that of described earlier. Figure 3 shows the resultant discharge at Nakhon Sawan. The observed discharge (broken line with star) has two peaks in a year, a large one in September and a small one in March. The former is due to rainfall in the rainy season. However, the latter is formed without distinct rainfall. When reservoir operation was not considered (solid line with squares), the dry season peak was not formed and discharge tended to be underestimated in the dry season and over-estimated in the rainy season. With incorporation of ROM into TRIP (solid line with diamonds), the hydrograph compares well with the observations, especially in the dry season. Also the rainy season peak was reduced. This is due to the function of reservoir, to store inflow in rainy season and to release in dry season. The reservoir storage simulation
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Fig. 2 Calculated/observed monthly release (upper, $m^3/s$) and storage ($10^6 m^3$) for (a) the Buinoh dam, and (b) the Sirikit dam. — calculated, - - observed, 1980–1990.

Fig. 3 Calculated/observed discharge at Nakon Sawan. • TRIP+ROM (with dam), ■ original TRIP (without dam), * observed.
has some discrepancies. Figure 4 shows the result of Sirikit dam storage calculation. This is due to the underestimation of inflow, especially in 1988, and the storage has not recovered in the high-discharge season. It should be noted, that the simulation carried out in this study assumes that the original discharge simulation has a certain degree of accuracy. However, the current grid runoff data (i.e. the input for GRRNMs) should be improved, especially in the upper stream where the catchment area is relatively small and the topographic effect has a dominant impact on runoff formation.

CONCLUSION

A simple reservoir operation model designed for application with GRRNM is described. To overcome the shortage of information on reservoir operating rules, the model is designed to set operation rules for each reservoir using available global data sets and few parameters. Despite its simple structure, the model represents the actual operation of two large dams and the discharge of the Chao Phraya River adequately. However, the performance of ROM, especially in reservoir storage simulation, is strongly dependent on the accuracy of the inflow discharge. It warrants future work on the improvement of the grid runoff calculation which is the input data to TRIP. Nonetheless, the newly developed framework will allow us to simulate global river discharge taking account of reservoir operation, which provides us more reliable estimation of the seasonal distribution of global water resources and their inter-annual fluctuation. For the next step, it is proposed to apply the model to various reservoirs in the world to validate its performance. It is also necessary to develop other UOMs such as hydropower or water-supply modules and to validate their global applicability.
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REFERENCES


