Runoff Simulation of Three Gorges Area in the Upper Yangtze River during 1998 Flood Season*

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(Received September 27, 2004; revised December 6, 2004)

ABSTRACT

The contribution of areal precipitation of the catchment from Cuntan to Yichang (Three Gorges area) to eight flood peaks of the Upper Yangtze River (the upper reaches of the Yangtze River) is diagnosed for 1998 flood season. A rainfall-runoff model is employed to simulate runoffs of this catchment. Comparison of observed and simulated runoffs shows that the rainfall-runoff model has a good capability to simulate the runoff over a large-scale river and the results describe the eight flood peaks very well. Forecast results are closely associated with the sensitivity of the model to rainfall and the calibration processes. Other reasons leading to simulation errors are further discussed.

Key words: areal precipitation, rainfall-runoff model, the Upper Yangtze River (the upper reaches of the Yangtze River), 1998 flood

1. Introduction

The Yangtze River is the largest river in China, with a large drainage area of 1808 x 10³ km². Due to its special geographic location and atmospheric circulation pattern, rainstorm occurred frequently over the Yangtze River, with concentrated, stable, lasting and large rainfall and covered a vast rainfall region, leading to a huge discharge and even flooding. Therefore flooding is one of the most devastating natural disasters in the Yangtze River. In the 20th century, major flood events have occurred over the Yangtze River in years 1931, 1954, 1991, 1993, 1996, and 1998, with increasing frequency and severity during 1990s. Despite of flood control and protection measures, the societal impact of floods has been increased as a result of increasing economic development along the Yangtze River. Given the flood prediction and warning in advance, it is possible to undertake all necessary measures to prevent the loss of life and the damage to property, in such a way that the flood-induced destruction can be reduced to the minimum. Consequently, flood forecasts are one of the most important aspects of flood control and prevention.

There have been a lot of recent researches in runoff simulation and flood forecasting with hydrological models. TOPMODEL has been applied to a variety of catchments and hydrological modeling problems (Freer and Beven, 1996; Valeo and Moin, 2000). Moreover, an expanding use of TOPMODEL over a relatively large catchment has also been done in the Huaihe River Basin of China (Guo et al., 2000). Liu et al. (2003) used a rainfall-runoff model (TOPMODEL) to simulate runoffs of the Meishan and Nianyushan catchments during the summers of 1998 and 1999 in the GAME/HUBEX project. Zhang et al. (2003) used a high-resolution Regional Integrated Environmental Model System (RIEMS), and a Large-scale Routing Model (LRM) to simulate the stream-flow over the Yellow River Basin. Fan et al. (2001) introduced the precipitation-runoff modeling system (PRMS) of U.S. Geological Survey and successfully replanted it to the Luanhe Basin and studied the impacts of the climate change on the water resources in the Luanhe Basin. The Xin'anjiang Model is used as the basic model to develop a monthly grid-based macroscale hydrological model for the assessment of the effects of climate change on water resources of the Huaihe River Basin.

*Supported by the National Natural Science Foundation of China under Grant Nos. 40175028 and 40475045.
(Hao et al., 2002), and also used by Jiang et al. (1998) to simulate the stream runoff of Xinjiang. Ren and Liu (2001) applied the Digital Elevation Drainage Network Model (DEDNM) to simulate the hydrological processes during the intensified observation period of 1998/1999 HUBEX.

As an operational system, the significant character of GAPI rainfall-runoff model is to describe the state of moisture in the catchment area by use of the Antecedent Precipitation Index, which simplifies the input data and makes up the absence of humidity observation. There are some problems in the model, e. g., the effect of topography, vegetation and soil was not taken into account. However, operational experimentation and researches show that the model is of a good capability of simulating the runoff (Bálint and Gauzer, 1994) for the relative small basins of Europe. In this paper, this model is applied to the Three Gorges area of the Upper Yangtze River (the upper reaches of the Yangtze River), with a relative large discharge, to simulate the eight flood peaks during 1998 flooding season. The paper is organized as follows. The first part of the paper is introduction; the second part gives details of the rainfall-runoff model. Aiming at the 1998 flood, precipitation and flow regime of the Upper Yangtze River and the contribution of areal rainfall of the basin to its inflow and flood are analyzed in the third part. And then, the application of GAPI rainfall-runoff model to the basin from Cuntan to Yichang in Three Gorges area (Fig.1) of the Upper Yangtze River is described and a comparison of observed and simulated runoffs is presented. Finally the conclusions and a summary are given.

2. Structure and basic equations of the model and its approach

2.1 The GAPI rainfall runoff model

The GAPI rainfall-runoff model is a forecasting system developed by the Water Resources Research Center of Hungary. API represents the Antecedent Precipitation Index, which is utilized to describe the state of moisture in the catchment area, and the probability of the API is assumed to be Gamma distribution. Thus GAPI is named after the acronym of Gamma Antecedent Precipitation Index.

The GAPI model consists of two modules. Module 1 estimates the rainfall losses and separates surface, subsurface and base runoffs; Module 2 performs the routing of surface, subsurface and base flow, while taking into account the effect of surface and underground storage capacity.

For a given period, part of rainfall, forming surface and subsurface runoffs, can be expressed through a volumetric runoff coefficient

$$\alpha = \frac{\sum_{i=1}^{T} Q_i - TQ_o}{\sum_{i=1}^{T} P_i},$$

(1)

where $\alpha$ is a volumetric runoff coefficient, $Q_o$ is the minimum value of runoff, $t$ is the time lag of runoff to rainfall in unit day, $T$ is the period of rainfall and runoff integration, $Q$ is the discharge at the downstream river station and $P$ is the rate of precipitation in unit m$^3$ s$^{-1}$.

The rate of effective rainfall largely depends on seasonal changes of catchment humidity conditions, i.e., indirectly on characteristics of antecedent effective rainfall. GAPI model employs an exponential form of rainfall to depict the antecedent precipitation index such as

$$\text{API}_t = \sum_{i=0}^{N} P_{t-i} e^{-t\alpha},$$

(2)

where $N$ is the length of API window, i.e., $e^{-t\alpha}$ is 0.05 or less within this period. It denotes an impacting period of the antecedent precipitation on the humidity
conditions of the catchment.

The API is calculated on the basis of effective rainfall values, i.e., the value of daily loss is subtracted from the actual value of precipitation. The ratio of surface runoff is expressed through the probability of API. The distribution of API in different lengths was investigated on a variety of river basins and the results showed that the following form served as the most suitable expression for the density function

$$f_k(\text{API}) = \frac{\lambda^k \text{API}^{k-1}}{\Gamma(k)} e^{-\lambda \text{API}}. \quad (3)$$

This distribution approaches an exponential distribution for the case $k = 1$ and practically Gaussian for the cases when $k > 50$. Assuming that there is a dependence of the effective catchment area on the probability of API, the ratio of surface runoff can be estimated if the probability of API is known

$$A_{f,i} = f[P(\text{API}_i)], \quad (4)$$

and the interflow ratio

$$A_{w,i} = 1 - A_{f,i}. \quad (5)$$

Module 1 separates the total volume of runoff into three parts:

- surface flow
  $u_{1,t} = u_t A_{f,t} \alpha_t, \quad (6)$

- subsurface flow
  $u_{2,t} = u_t (1 - A_{f,t}) \alpha_t (1 - \alpha_b), \quad (7)$

- and base flow
  $u_{3,t} = u_t (1 - A_{f,t}) \alpha_t \alpha_b, \quad (8)$

where $u_t$ is the total volume of runoff, $\alpha_t$ is volumetric runoff coefficient, and $\alpha_b$ is the ratio of base flow to infiltration.

After the determination of surface, subsurface and base flow volumes for each time sequence $t$, the routing of these volumes follows. This operation is performed by Module 2, which consists of three parallel cascades. The first cascade with parameters $n_1, K_1$ routes surface flow; the second with parameters $n_2, K_2$ routes subsurface flow and the third with parameters $n_3, K_3$ routes base flow. The resulting flow for each discrete time step produced by GAPI model is the sum of the routed values of surface, subsurface and base flows.

### 2.2 Discrete Linear Cascade Model (DLCM)

A flood routing model based on DLCM combined with rainfall-runoff models (GAPI) is taken as tool for daily forecasting. To give a better explanation of DLCM, first the single reservoir, then reservoirs in series (basic assumptions of Nash cascade) and finally the discretization of continuous model will be analyzed.

#### 2.2.1 Single reservoir

A single reservoir with inflow $u(t)$ and outflow $y(t)$ is one whose storage $x(t)$ is linearly related to its output $y(t)$ by storage constant $k$, i.e., $x(t) = ky(t)$, thus the output equation is $y(t) = k^{-1}x(t)$. Due to continuity, the change of the storage water $x(t)$ is given by the storage equation $\frac{dx(t)}{dt} = -y(t) + u(t)$. Therefore the state equation of linear time-invariant reservoir is

$$\frac{dx(t)}{dt} = -k^{-1}x(t) + u(t). \quad (9)$$

#### 2.2.2 Linear reservoirs in series

Linear cascade model consists of the linear time-invariant reservoirs in series. A watershed may be represented by a series of $n$ identical linear reservoirs each having the same storage constant $k$ (Chow, 1988). By routing a unit-volume inflow through the linear reservoirs, a mathematical model for the instantaneous unit hydrograph (IUH) of the series can be derived. Output of the one linear reservoir is the input to the next one as shown in Fig.2.

![Fig.2. Schematic diagram of the linear reserviors in series (K = k⁻¹).](image)

State variable representation of the Nash cascade is as follows.

Introducing $k = 1/K$ and $x_i(t)$ as the amount of water stored in the $i$th reservoir at time $t$, then

$$\dot{X}(t) = FX(t) - Gu(t) \quad (10)$$
and

\[ y(t) = HX(t) \]  

 constitute the continuous state variable model of the Nash cascade, where

\[
F = \begin{bmatrix}
-k & 0 & \cdots & 0 & 0 \\
0 & -k & \cdots & 0 & 0 \\
\vdots & \vdots & \ddots & \vdots & \vdots \\
0 & 0 & \cdots & k & -k
\end{bmatrix},
\]

\[
X(t) = \begin{bmatrix}
x_1(t) \\
x_2(t) \\
\vdots \\
x_n(t)
\end{bmatrix},
\]

\[
G = \begin{bmatrix}
1 \\
0 \\
\vdots \\
0
\end{bmatrix}, \quad \text{and} \quad H = [0 \ 0 \cdots k].
\]

It is seen from above that \( F \) is an \( n \times n \) matrix of Toeplitz type, and \( X(t) \) is an input matrix.

In solving the linear continuous state equation and expanding the discrete model, a State Transition Matrix (STM) is very important. Since the continuous model is time-invariant, the STM is the matrix exponential of \( F \), i.e., \( \Phi(t) = e^{Ft} = \exp(Ft) \). This can be written as (Szollosi-Nagy, 1982)

\[
\Phi(t) = e^{Ft} = 
\begin{bmatrix}
e^{-kt} & 0 & \cdots & 0 \\
kte^{-kt} & e^{-kt} & \cdots & 0 \\
\frac{(kt)^2}{2!}e^{-kt} & kte^{-kt} & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
\frac{(kt)^{n-1}}{(n-1)!}e^{-kt} & \frac{(kt)^{n-2}}{(n-2)!}e^{-kt} & \cdots & e^{-kt}
\end{bmatrix} u(t). \tag{12}
\]

The computation of STM enables the determination of the impulse response function of a continuous dynamic system \( h(t) = H \exp(Ft)G \). The runoff \( u(t) \) can be computed from the convolution of two functions as follows:

\[
y(t) = \frac{1}{K(n-1)!} \int_0^t \left( \frac{\tau}{K} \right)^{n-1} e^{-\tau/K} u(t-\tau) d\tau. \tag{13}
\]

2.2.3 Discrete formulation of the continuous Nash cascade

If both inputs \( u(t) \) and output \( y(t) \) of the Nash cascade model are sampled at equidistant sampling intervals \( \Delta t \), then the discrete input-output sequences \( u_t \) and \( y_t \) will be also defined at \( t = 0, \Delta t, 2\Delta t, \cdots \). Then the discrete state model at the sample points will be

\[
X_{t+\Delta t} = \Phi_t(\Delta t)X_t + \Gamma_t(\Delta t)u_t \]

with discretization scheme, where \( \Phi_t(\Delta t) \) is the STM corresponding to the sampling interval \( \Delta t \), \( \Phi_t(\Delta t) = \Phi_t(t + \Delta t, t) = \exp[F_t(t + \Delta t, t)] = \exp(Ft\Delta t) \), and \( \Gamma(\Delta t) \) is the input transition matrix. The corresponding discrete output equation remains unchanged in form, \( y_t = Hx_t \).

It should be noted that the first step, before using DLCM model, is to define model parameters \( n \) and \( K \), where \( n \) is the number of linear reservoirs and \( K \) is the storage coefficient.

2.3 Watershed network scheme for model

The catchment from Cuntan to Yichang is located in the Upper Yangtze River with an altitude of 40 m and a length of about 320 km. It has three sub-basins which are taking into account: Cuntan-Wanxian, Wanxian-Fengjie, and Fengjie-Yichang. The sub-basin areas are 26400, 16800, and 18400 km\(^2\), respectively.

Because of lacking the observation of discharge in tributaries, fictitious tributaries will be designed between each two cross sections. The network of catchment is such as shown in Fig.3.

![Fig.3. The network illustration of catchment from Cuntan to Yichang.](image)

For an ungauged tributary, the discharge is not available. Taking into account the huge discharge of the Yangtze River, it is necessary to estimate the lateral inflow of ungauged tributary. The estimation is
performed by the optimization of DLCM model, which transforms the discharge of one cross section to the second cross section, and a transformed discharge value is obtained. In comparison of the transformed discharge and the observation of the second cross section, the difference between them is just the inflow of ungauged tributary.

2.4 Estimation of areal precipitation of sub-catchments

Areal precipitation describes the state of mean rainfall of a given area or watershed and is defined as the precipitation of unit area. The weight of stations is considered when Thiessen polygon method is used to calculate the areal rainfall, thus this method with higher precision is suitable for the catchment with uneven station (Xu et al., 2001). Consequently, the Thiessen polygon method is chosen to determine areal precipitation in this paper. First the areal weight coefficient of each station is determined, and multiplied by the corresponding rainfall, and then accumulated to obtain areal precipitation.

The relative weights for each gauge are determined from the corresponding areas of Thiessen polygon network, the boundaries of the polygons being formed by the perpendicular bisectors of the lines joining adjacent gauges. These intersected bisectors divide the catchment into some polygons, with only one rain gauge within a polygon. If there are $n$ rain gauges in the catchment, and the assigned area of the $i$th gauge within the watershed is $A_i$, and the rainfall is $P_i$, then the area average precipitation for the watershed is $\bar{P} = \frac{1}{A} \sum_{i=1}^{n} A_i P_i$, where the watershed area $A = \sum_{i=1}^{n} A_i$.

Usually the stations are plotted on a map and the perpendicular bisectors of the connecting lines between two stations form polygons around each station. The area of each polygon is measured by the planimeter. At present, with the advent of GIS, Thiessen polygons can be created in the Arcview GIS system and each area is determined, which requires the corresponding GIS data of basin. Here, despite the lack of GIS data, the boundaries of each sub-basin can be determined in a Meteorological Information Comprehensive Analysis Prediction System (MICAPS), the area of polygon can be obtained by solving the mathematical problem through making program.

3. Synoptic background and characteristics of the 1998 Flood

During the summer of 1998, both the subtropical high and the westerly circulation were stable, and the cold airs were very active. With the confrontation of cold and warm air masses, stable heavy rain belts formed over the Yangtze River.

At Yichang Station on the main stem, there appeared altogether eight flood peaks (Fig.4). On July 2, the first flood peak at Yichang in 1998 appeared, which resulted from the heavy rains over the Upper Yangtze River from the end of June. On July 18, the second flood peak formed. In the subsequent days, another six flood peaks occurred successively at Yichang. The maximum discharge peak at Yichang was 63300 m$^3$ s$^{-1}$.

In order to explain the relationship between heavy rains in the Upper Yangtze River and eight flood crests at Yichang Station, Table 1 shows the duration of the heavy rainfall and the corresponding time of storm-induced flood peaks (National Meteorological Center et al., 1998) and the areal precipitation amounts of the catchment from Cuntan to Yichang three gorges area in the Upper Yangtze River, where basin area-average precipitation was obtained by taking Thiessen-weighted averages of the rainfall data from 7 rainfall gauges in the watershed. It is found that most flood peaks are corresponding to the large areal precipitation in this catchment except the 7th flood peak. The time series of daily area precipitation and water level (Fig.4b) also indicate the coincident relationship between each heavy rain process and the fluctuation of flood. There is a flood peak associated with each heavy rain process previously, while there is a fall of water level coincident with the decreased or intermittent period of the heavy rain. Flood peaks lag behind the duration of the heavy rainfall about 1-3 days. From Table 1 and Fig.4, we can see that some flood crests result from one rainfall process, while other flood crests are the result of two rainfall processes. Meanwhile, from the areal precipitation totals...
(Table 1) of each process we can find that the heavier areal rainfall leads to a sharp increase of water level, e.g., the 1st and the 4th time with the areal precipitation of 206.1 and 124.8 mm respectively and the corresponding water level from 47.46 m, 49.45 m to 52.41 m, 53.53 m, and vice versa. As a result, storm rain processes which happened in the basin from Cuntan to Yichang have a direct contribution to the flood peaks at Yichang Station. Meanwhile, it is noted that a few heavy rain processes (from July 3 to July 7, from August 19 to August 20 and from August 22 to August 24, as shown in Table 1) occurred in the upper reaches of Cuntan, which play an in-negligible role in the 2nd and 7th flood crests of Yichang. In the following, GAPI rainfall-runoff model and the DLCM model will be applied to simulate eight flood peaks.

4. Application of GAPI rainfall-runoff model combined with DLCM model for the test catchments

The input data of models include discharge and areal precipitation. The valid period for forecasting of the model is 6 days. In order to show the general characteristics of models, the data series of 2001, a usual year without severe flood occurring in the

![Fig. 4](image-url)

**Fig. 4.** (a) Time series of daily average discharge (m$^3$ s$^{-1}$) at Yichang during summer 1998 (1 Jun.–9 Sep.). (b) Time series of daily average water level $H$ (m) at Yichang and daily areal precipitation (mm) of the basin from Cuntan to Yichang during summer 1998 (1 Jun.–9 Sep.). Numbers 1–8 depict eight flood peaks, respectively.
Table 1. Duration of the heavy rainfall corresponding to the flood peak of 8 times in the Upper Yangtze River and the area rainfall of the catchment from Cuntan to Yichang

<table>
<thead>
<tr>
<th>Number</th>
<th>Duration of the heavy rainfall</th>
<th>Area rainfall of the catchment</th>
<th>Time of peak flood at Yichang</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Cuntan (mm)</td>
<td>Yichang (mm)</td>
</tr>
<tr>
<td>1</td>
<td>June 27-30</td>
<td>119.5</td>
<td>206.1</td>
</tr>
<tr>
<td></td>
<td>June 30-July 2</td>
<td>86.6</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>July 3-7</td>
<td>3.7*</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td>July 12-16</td>
<td>45.3</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>July 19-21</td>
<td>44.9</td>
<td>44.9</td>
</tr>
<tr>
<td>4</td>
<td>August 1-3</td>
<td>59.7</td>
<td>124.8</td>
</tr>
<tr>
<td></td>
<td>August 4-7</td>
<td>65.1</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>August 8-12</td>
<td>106.4</td>
<td>106.4</td>
</tr>
<tr>
<td>6</td>
<td>August 13-17</td>
<td>73.4</td>
<td>73.4</td>
</tr>
<tr>
<td>7</td>
<td>August 19-20</td>
<td>0.02*</td>
<td>1.56</td>
</tr>
<tr>
<td></td>
<td>August 22-24</td>
<td>1.54*</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>August 26-28</td>
<td>63.5</td>
<td>63.5</td>
</tr>
</tbody>
</table>

4.1 Parameter optimization

Parameter optimization was performed by an optimization program developed in the National Forecasting Service of Vituki. Parameters of GAPI rainfall-runoff model and DLCM are listed respectively in Tables 2 and 3.

From Tables 2 and 3, we can see that the travel time of surface runoff from the test watershed to the outlet at Yichang is mostly shown on the travel time from tributaries to main stem, about 1-3 days, which is well matched with lag time of flood peaks behind areal precipitations as mentioned above.

4.2 Forecast results

To evaluate the runoff simulation, the average of absolute errors between forecast value and observation (|\(\bar{E}\)|) and the forecast efficiency coefficient (\(\eta\)) (Table 4) are used. They are

\[
|\bar{E}| = \frac{1}{N} \sum_{t=1}^{N} |Q_{t}^{\text{sim}} - Q_{t}^{\text{obs}}|, \quad (\text{m}^3 \text{s}^{-1})
\]
where $Q_{t}^{\text{sim}}$ is runoff simulation, and $Q_{t}^{\text{obs}}$ is observed runoff; and

$$
\eta = \sqrt{1 - \frac{\sigma_e}{\sigma_d}}, \tag{15}
$$

where $\sigma_e = \frac{1}{N} \sum_{t=1}^{N} (Q_{t}^{e} - \bar{Q}_{t})^2$ (in m$^3$ s$^{-1}$) is the standard deviation of errors, $Q_{t}^{e} = Q_{t}^{\text{sim}} - Q_{t}^{\text{obs}}$ is errors between forecast value and observation; $\sigma_d = \frac{1}{N} \sum_{t=1}^{N} (Q_{t}^{d} - Q_{t}^{d})^2$ is the standard deviation of the change in observed runoff during the time lag $(i = 1, 2, \cdots, 6 \text{ d})$, $Q_{t}^{d} = Q_{t}^{\text{obs}} - Q_{t+i}^{\text{obs}}$ is the change of observed runoff between time $t$ and $t+i$, $t = 1, 2, \cdots, N$.

To explain contrastively the forecast results during summer 1998 and from summer 1998 to next spring, forecast errors and efficiency coefficients are presented in Table 4. It is apparent that errors between forecast and observation increase with increasing days of forecast as expected. Meanwhile, the forecast efficiency coefficients are almost in excess of 0.82. Moreover, it is notable that the average values of absolute errors in summer 1998 are much bigger than the concerning results of one year, whereas the forecast efficiency is lower.

Table 4. Forecast results in the periods of summer 1998 and of June 1998 to May 1999

| Section | Forecast days | $|E|$ (m$^3$ s$^{-1}$) | $\eta$ |
|---------|---------------|----------------------|--------|
|         |               | Whole year | Summer 1998 | Whole year | Summer 1998 |
| Wanxian | 1             | 484        | 1539       | 0.845      | 0.833       |
|         | 2             | 777        | 2554       | 0.886      | 0.877       |
| Fengjie | 1             | 420        | 1201       | 0.872      | 0.868       |
|         | 2             | 673        | 1907       | 0.892      | 0.886       |
| Yichang | 1             | 468        | 1345       | 0.836      | 0.827       |
|         | 2             | 725        | 2168       | 0.885      | 0.876       |

The time series of runoff simulation at Yichang are illustrated in Figs.5 and 6. In general, simulated runoff has a good tendency with the observation. However, it should be noted that the forecast during the period of July 23-28 is much lower than the observation and for the time period of August 3-20, the forecasting presents scattered distributions, which denotes the sensitivity of the model to the rainfall. From the comparison of the rainfall observation and the runoff forecast, it can be found that if heavy rainfall occurred in the basin, runoff rose very quickly (e.g., Aug. 9-11). When rainfall decreased or ceased for a period of time, then runoff decreased sharply (e.g., July 22-28 and Aug. 6-8). In practice, if the rainfall increases and the soil is saturated, the surface runoff would increase and some part of rainfall could be converted into subsurface runoff when the soil is unsaturated. Contrarily, owing to the previous rainfall process, the soil moisture is high enough that the amount of infiltration would be lower than before. Therefore, although the rainfall decreases, the surface runoff would still increase. As a result, just the over-sensitivity of the model to the rainfall leads to the big departure between simulation and observation during those periods mentioned above.

From the viewpoint of forecast validation, the forecasting with lead-time of 1 or 2 days is well matched with the observation (Fig.6). Results describe the 8 flood peaks very well. The best forecast periods are from July 7 to 22 and from August 24 to September 4. The deviations are smaller even though the peaks of forecast results lag behind the corresponding observation of July 2, July 23, and August 12, while the departures of forecast of 3 to 6 days are much bigger, especially during the periods of 4th, 5th, and 6th flood peaks, i.e., from August 3 to 20 (Fig.5).

4.3 Verification of parameters

In order to confirm the reliability of parameters, which are determined by optimization by means of automatically calibrating the data in 2001, the same parameters are used to simulate the runoff of summer 1999. Figure 7 shows the results from July 1 to August 10, with obvious flood fluctuations during this period.
Fig. 5. Flood hydrograph observation and forecast (1-6 days) at Yichang as well as the areal precipitation of corresponding sub-basin during summer 1998 (29 Jun. -9 Sep.).

Fig. 6. Flood hydrograph observation and forecast (1-2 days) at Yichang as well as the areal precipitation of corresponding sub-basin during summer 1998 (29 Jun. -9 Sep.).
Fig. 7. Flood hydrograph observation and forecast (1-6 days) as well as the areal precipitation of corresponding sub-basin during summer 1999 (1 Jul. -10 Aug.).

Table 5. Forecast results in the periods of summer 1999 and of June 1999 to May 2000

| Section | Forecast days | $|E|$ (m$^3$ s$^{-1}$) | $|E|$ (m$^3$ s$^{-1}$) | $\eta$ | $\eta$ |
|---------|--------------|------------------|------------------|------|------|
|         |              | Whole year | Summer 1998 | Whole year | Summer 1998 |
| Wanxian | 1            | 523        | 1250        | 0.888 | 0.890 |
|         | 2            | 804        | 1906        | 0.920 | 0.923 |
| Fengjie | 1            | 397        | 893         | 0.919 | 0.918 |
|         | 2            | 719        | 1641        | 0.917 | 0.920 |
| Yichang | 1            | 442        | 842         | 0.920 | 0.930 |
|         | 2            | 793        | 1601        | 0.911 | 0.917 |

The forecast result is quite good, indicating the relative stability of the parameters. Table 5 presents the forecast error and efficient coefficient. Comparing with the results of 1998, it is attractive that there are not much more differences with regard to the forecast efficiency coefficient between summer 1999 and the whole year. The forecast efficiency coefficients are almost over 0.9 and much higher than that of 1998. It is likely to have a bearing on the calibration process. In the case study, the calibration is made automatically by the model. It is possible that the optimization of parameters is not perfect. In operational forecast, a manual optimization will be done after automatical optimization to obtain the optimal parameters. In addition, only one-year time series of data in 2001 is used for calibration, in such a way that model was not able to learn about enough knowledge pertinent to flood events. Regarding the relative normal flood of 1999, the parameters are capable of dealing with it. While for the unprecedented flood of 1998, the parameters without enough information have not enough capacity to forecast it. As a result, only when more information of flood cases the model learns, the more stable is the parameter and the higher is the forecast capacity.

5. Conclusions and discussion

One of the major causes for the 1998 extraordinary flood in the Yangtze River was the rainstorm. On the main stem, at Yichang Station there appeared altogether eight flood peaks, which were closely associated with areal precipitation of the basin from Cuntan to Yichang.
Simulated runoffs of the three gorges area using rainfall-runoff model turn out to be almost identical to the observations. Forecasting with lead-time of 1 or 2 days is well matched with the observation and the results describe the eight flood peaks very well. And forecast results reflect the sensitivity of the model to the rainfall.

Comparison of the forecast results of 1999 and 1998 shows that the optimal parameters are closely associated with the calibration process. More information of flood cases the model learns, the more stable is the parameter and the higher is the forecast capacity.

Flood forecasts are very useful for flood prevention and protection. Application of rainfall-runoff model in the Yangtze River is a successful attempt. Even though the forecast results are in disagreement with the observation completely, except some reasons about model mentioned above, other reasons should be taken into account, such as the effect of topography, uneven distribution of rain gauge and heavy rain, arithmetic method of areal precipitation and so on. As shown in Fig.1, the rain gauges distribute unevenly along the main stem of the river, but those gauges are considered more representative of the area and then relative weights may be assigned to the gauges in computing the area average. As a matter of fact, the effects of topography make the rainfall distribute unevenly in the regions of plain and plateau, which results in the error of forecast to a certain extent. Meanwhile, as mentioned in the 3rd part, storm rain processes in the basin from Cuntan to Yichang have a direct contribution to the flood peaks. However, some heavy rain processes occurring in the upper reaches of Cuntan are not considered into model, which indirectly caused the flood crest of Yichang. In addition, the observation of tributaries is not available.

In a word, this study provides the test and extensions of the rainfall-runoff development process and its potential application of flood forecast and warning. Better results would be obtained if more information is taken into consideration. Some problems existed in this paper need to be investigated further, such as a contrastive experiment of choosing different data of flood years and general years for calibration, or taking into account larger convergence water area to compute the areal precipitation and so on. However, due to the reasons of schedule and data during staying in Hungary, these problems would be considered in the research work in the future.

Acknowledgments. This study was supported by the 34th international post-graduate course on hydrology with special regard to IWRM (Integrated Water Resource Management), which was held in Budapest, Hungary from 7 April to 31 July, 2003. The authors are grateful to Mr. Michal Ceran for his valuable assistance.

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