Runoff Analysis of the 1998 Songhuajiang River Flood using the Distributed Hydrological Model

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ABSTRACT: The objective of this study is to investigate the applicability of re-analysis data in hydrological forecasting. In this study, flood runoff analysis of the historical 1998 flood occurred in Songhuajiang River basin in northeastern China has been carried out by using the Global Energy and Water Cycle Experiment (GEWEX) Asian Monsoon Experiment (GAME) re-analysis products (version 1.5). For the continental river basin, the distributed hydrological model with 0.5 by 0.5 degree spatial resolution is built by using our distributed modeling system. For this basin, calculated hydrographs are derived at three hydrological stations, namely Pulanji, Dalai and Harbin. They are compared with the observed ones. It is shown that the flood volume and timing of peak discharge are well represented. This shows that GAME re-analysis data is fully applicable. And this also implies the possibility to apply re-analysis data to hydrological forecasting on the continental scale river basins.

1 INTRODUCTION

In the summer of 1998, the greatest flood in the past fifty years occurred in the Songhuajiang River basin in northeastern China (Hayakawa et al., 1999). The possibility of forecasting of such flood disasters have been examined. The runoff analysis based on spatially distributed hydrologic modeling is one of the most prime approach for flood forecasting. In such runoff analysis, the spatially and temporally distributed inputs are required. Therefore, the Global Energy and Water Cycle Experiment (GEWEX) Asian Monsoon Experiment (GAME) re-analysis products (Yamazaki et al., 2000; Yatagai et al., 2000) version 1.5 was used in this study. The objective of this study is to investigate the applicability of these re-analysis data in hydrological forecasting.

2 MODEL DESCRIPTION

The distributed hydrological model consists of the rainfall-runoff process submodel and the channel routing submodel. The study basin is divided into lots of computational grid cells with user-defined spatial resolution. The rainfall-runoff process model evaluate runoff generated in each grid cell. The channel network for study basin can represent a set of imaginary channels linked between two grid points (center of grid cell). The channel routing model produces time-series of discharge at all grid points. In this section, the characteristics of two submodels are summarized as follows.

2.1 Rainfall-runoff process model

In this study, the Xinanjiang model (Zhao et al., 1980; Zhao, 1992) was introduced as a model for runoff estimation on each grid cell. Because of the subgrid scale spatial variability (SSSV) of water storage capacity, one can divide every computational grid cell into local storage elements, characterized by their local storage capacity \( W_{m} \) (ranging from zero to a maximum value \( W_{mm} \)). The storage capacity of the whole grid cell \( W_{m} \) is average of all the local storage capacities. The distribution function of \( W_{m} \) for a grid cell \( F(W_{m}) \) gives the fraction of the grid cell in which storage capacity is less than or equal to
Figure 1. Schematic of runoff production with a SSSV of water storage capacity. The curve plots $W'_m$ against $F(W'_m)$, and represents the maxima of the local water contents.

$W'_m$: 

$$F(W'_m) = 1 - (1 - F_{imp}) \left[1 - \frac{W'_m}{W_{mm}}\right]^b,$$  \hspace{1cm} (1)

where, $b$ is a shape parameter; $F_{imp}$ is the impervious area fraction of grid cell. With this distribution, the maximum local storage capacity $W_{mm}$ is related to the mean storage capacity in the grid cell $W_m$:

$$W_{mm} = \frac{1 + b}{1 - F_{imp}} W_m.$$  \hspace{1cm} (2)

Figure 1 shows that the SSSV of water storage capacity allows the smallest local storage elements to saturate, and runoff to occur before the saturation of the whole grid cell. $F(W')$ is the saturated fraction of the grid cell at one time. The maxima of local water content on the saturated area $W'$ is represented such that

$$W' = W_{mm} \left[1 - (1 - W/W_m)^{1/b}\right],$$  \hspace{1cm} (3)

where $W$ is the total water content in the grid cell. For each grid cell, we defined the net precipitation such that $P_n = P - E_p$, where $P$ and $E_p$ are precipitation and potential evaporation respectively. When $P_n > 0$, runoff $R$ is represented such that

$$R = \int_{W'}^{W' + P_n} F(W'_m) dW'_m$$

$$= \begin{cases} P_n - W_m + W + W_m \left[1 - (W' + P_n)/W_{mm}\right]^{1+b} & W' + P_n < W_{mm} \\ P_n - W_m + W & W' + P_n \geq W_{mm}. \end{cases}$$  \hspace{1cm} (4)

2.2 Channel routing model

In the Songhuajiang River basin, river flow subject to diffusional effects is characterized due to the small river bed slope. Therefore, the Muskingum-Cunge model (Cunge, 1969) equivalent to the diffusion wave approximation of the one-dimensional St. Venant equation is adequate for channel routing in this study. The routing equation is the following:

$$Q_{j+1}^{n+1} = C_1 Q_j^{n+1} + C_2 Q_j^n + C_3 Q_{j+1}^n,$$  \hspace{1cm} (5)
where \( j \) and \( n \) are spatial and temporal indexes, respectively. The routing coefficients, \( C_1 \), \( C_2 \) and \( C_3 \), are the following:

\[
C_1 = \frac{-1 + C + D}{1 + C + D}, \quad C_2 = \frac{1 + C - D}{1 + C + D}, \quad C_3 = \frac{1 - C + D}{1 + C + D},
\]

(6)

where \( C \) and \( D \) are Courant and cell Reynolds numbers, respectively (Ponce, 1989). The Courant number is the ratio of the flood wave celerity \( c \) to the numerical celerity \( \Delta x/\Delta t \), such that

\[
C = \frac{\Delta t}{\Delta x},
\]

(7)

where \( \Delta x \) is computational space step (equal to channel length); \( \Delta t \) is computational time step. The cell Reynolds number is the ratio of the hydraulic diffusivity \( Q/(2BS) \) (Hayami, 1951) to the numerical diffusivity \( c\Delta x/2 \) (Ponce and Yevjevich, 1978), such that

\[
D = \frac{Q}{BSc\Delta x},
\]

(8)

where \( Q \) is mean discharge; \( B \) is channel width; and \( S \) is channel slope. The flood wave celerity \( c \) is the following:

\[
c = \frac{5}{3} \frac{S^{1/10}Q^{2/5}}{n^{3/5}B^{2/5}},
\]

(9)

where, \( n \) is Manning’s roughness coefficient in m\(^{-1/3}\)/s. The routing parameters are based on average values of \( Q \) at each computational grid cell. This can be achieved by a iterative four-point average, which includes the unknown grid point \((j + 1, n + 1)\) (Ponce and Chaganti, 1994).

3 DATA

3.1 Channel network

In this study, the global 30-minute drainage direction map, DDM30 (Döll and Lehner, 2001) was used as channel network information. In addition, we used the global 30-second elevation data, GTOP30. The parameters for channel routing, such as channel length, channel slope, local grid area and drainage area, were calculated at each grid point. Figure 2 shows the channel network extracted from DDM30 for the Songhuajiang River.

3.2 Atmospheric boundary conditions

The GAME re-analysis products version 1.5 released in June 2002 (Yamazaki et al., 2003) are introduced as atmospheric boundary conditions for runoff analysis in this study. The objective of GAME re-analysis is to collect off-line data during the GAME Intensive Observation Period (IOP) and to obtain re-analysis of higher quality using the most updated assimilation system and the off-line data as well as on-line data through the Global Telecommunications System (GTS) (Yamazaki et al., 2000; Yatagai et al., 2000). These products are available at 6-hour time interval covering the period from 1 April to 31 October 1998. From GAME re-analysis products, 3-dimensional analyzed variables (anal_0.5) and 2-dimensional forecasted variables (2dmon_1.25) are used. The anal_0.5 can represent the 3-dimensionally analyzed fields with 0.5 by 0.5 degree horizontal resolution over Asian and Pacific regions. Air temperature, specific humidity, surface pressure and wind speed are used from anal_0.5. The 2dmon_1.25 can represent the global 2-dimensionally forecasted fields with 1.25 by 1.25 degree spatial resolution. The 2dmon_1.25 contains 12 to 18 hour forecasts. Precipitation and downward shortwave and longwave fluxes at surface are used from 2dmon_1.25.

The GAME re-analysis data are spatially interpolated to the 0.5 by 0.5 degree, our model resolution. A bilinear interpolation procedure is used for all variables. The data are then temporally interpolated from 6-hour temporal resolution to the hourly time step. Linear temporal interpolation algorithms are


Figure 2. Channel network with 0.5 by 0.5 degree spatial resolution for the Songhuajiang River. The basin boundary is shown as a thin solid line. The thick solid lines are the channel reaches. Three black dots show the hydrological stations, namely Fulaerji, Dalai and Harbin.

Table 1. List of hydrological stations.

<table>
<thead>
<tr>
<th>Station Name</th>
<th>Longitude &amp; Latitude</th>
<th>Drainage Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fulaerji</td>
<td>123.58°E, 47.17°N</td>
<td>152×10^3 km²</td>
</tr>
<tr>
<td>Dalai</td>
<td>124.28°E, 45.53°N</td>
<td>254×10^3 km²</td>
</tr>
<tr>
<td>Harbin</td>
<td>126.67°E, 45.78°N</td>
<td>434×10^3 km²</td>
</tr>
</tbody>
</table>

applied to all variables. Total precipitation was calculated as the sum of convective precipitation and large-scale condensation.

Figure 3 shows time-series of precipitation, air temperature, and wind speed at Harbin. The thin solid lines show time-series extracted from GAME re-analysis data. The thick solid lines show observed time-series.

3.3 River discharge

The river discharge data provided by the Hydrology and Water Resources Survey Bureau of Heilongjiang Province and/or the Ministry of Water Resources, P. R. China were used. Table 1 shows longitude/latitude and drainage area of each hydrological station. Three points namely Fulaerji, Dalai and Harbin are adopted to compare the model output against the observed discharge.

4 RUNOFF ANALYSIS

The runoff analysis of the 1998 flood in Songhuajiang River basin was carried out with 0.5 by 0.5 degree spatial resolution and hourly time step covering the period from 1 April to 31 October 1998. The hindcast accuracy of calculated hydrographs at three hydrological stations is validated by comparing with observed ones.
Figure 3. Time-series of precipitation, air temperature, and wind speed at Harbin. The thin solid lines show time-series extracted from GAME re-analysis data. The thick solid lines show observed time-series.

4.1 Model parameters

For rainfall-runoff process modeling, values of $W_m$, $b$ and $F_{imp}$ were specified based on empirical studies: $W_m = 120$ mm, $b = 0.3$ and $F_{imp} = 0.02$. For channel routing, channel width $B_{i,j}$ and Manning’s roughness coefficient $n_{i,j}$ at grid point $(i, j)$ are the following:

\begin{align*}
B_{i,j} &= B_0 \left( \frac{A_{i,j}}{A_0} \right)^\alpha, \\
n_{i,j} &= n_0 \left( \frac{A_{i,j}}{A_0} \right)^\beta,
\end{align*}

where $A_{i,j}$ is drainage area at grid point $(i, j)$; and $A_0$, $B_0$ and $n_0$ are drainage area, channel width and Manning’s roughness coefficient at reference point, respectively. Values of $\alpha$ and $\beta$ are adopted $\alpha = 0.5$ and $\beta = -0.314$ respectively (Lu et al., 1991).

4.2 Initial conditions

The model requires the initial conditions for several variables, such as surface temperature, water storage and river discharge. For model initialization, the near-surface meteorological analyzed and hybrid products included the International Satellite Land Surface Climatology Project (ISLSCP) Initiative I CD-ROM (Meeson et al., 1995) were used. Concretely, air temperature, dew-point temperature, surface pressure, wind speed magnitude, hybrid shortwave and longwave downward radiation at surface and hybrid total precipitation were used as atmospheric boundary conditions for initialization. Those variables are available at 6-hour temporal resolution covering the period from 1 January 1987 to 31 December 1988.
For both year 1987 and 1988, cyclical repetitive calculations using our distributed hydrological model were carried out. The judgment index for finishing the calculation is the absolute relative error of state value at 24Z 31 December to one at 00Z 1 January. One can repeat the calculation until one find the absolute relative error within 1% at all grid cells. For several variables, the average of monthly mean values for April 1987 and 1988 was adopted as the initial condition.

4.3 Potential evaporation

The Xinanjiang model requires the spatially distributed inputs of precipitation and potential evaporation. On each computational grid cell, potential evaporation \( E_p \) is determined by iteratively solving the energy balance at the infinitely thin skin of the surface,

\[
R_n = H + lE + G, \tag{12}
\]

where \( R_n \) is net radiative flux at the surface; \( H \), \( lE \) and \( G \) are sensible heat, latent heat and ground heat fluxes at the surface, respectively.

The net radiative flux is the following:

\[
R_n = (1 - A)S^1 + L^1 - \varepsilon \sigma T_s^4, \tag{13}
\]

where \( S^1 \) and \( L^1 \) are the downward shortwave and longwave fluxes at the surface, respectively. \( A \) is surface albedo; \( \varepsilon \) is emissivity; \( \sigma \) is Stefan-Boltzmann constant; and \( T_s \) is surface skin temperature.

The sensible and latent heat fluxes are calculated by using a bulk formula,

\[
H = \rho c_p C_H |v|(T_s - T_a), \tag{14}
\]

\[
lE = \rho C_E |v|(q_s - q_a) = \rho \beta C_H |v|(q_s - q_a), \tag{15}
\]

where \( T_a \) is air temperature; \( q_s \) and \( q_a \) are surface and air specific humidity; \( \rho \) is air density; \( c_p \) is specific heat at constant pressure; \( l \) is latent heat of vaporization; \( \beta \) is the evaporation efficiency; \( |v| \) is wind speed magnitude at the surface; and \( C_H \) and \( C_E \) are the bulk coefficients for heat and water transfer. Here, the coefficient \( C_H \) depending on wind speed and atmospheric stability is based on Louis (1979). The potential evaporation is determined without the effect of surface water stress (\( \beta = 1 \)).

The ground heat flux at the surface is evaluated by following:

\[
G = G_0 \cos \left( \omega t + \frac{\pi}{4} \right), \tag{16}
\]

\[
G_0 = \Delta T_s \omega^{1/2} (c_g \rho_g \lambda_g)^{1/2}, \tag{17}
\]

where \( \Delta T_s \) is daily amplitude of surface temperature; \( c_g \) is specific heat of soil; \( \rho_g \) is soil density; and \( \lambda_g \) is soil thermal conductivity. Here, we take that \( \omega = 2\pi/86400 \text{ s}^{-1}, c_g \rho_g \lambda_g = 2 \times 10^6 \text{ J m}^{-2} \text{ K}^{-1} \text{ m}^{-2} \).

5 RESLUT

Model performance was evaluated using the Nash and Sutcliffe (1970) efficiency coefficient (NS score). NS score \( e \) is evaluated as follows:

\[
e = 1 - \frac{\Sigma(Q_{obs} - Q_{cal})^2}{\Sigma(Q_{obs} - \bar{Q}_{obs})^2}, \tag{18}
\]

where \( Q_{cal} \) is calculated discharge; \( Q_{obs} \) is observed discharge; and \( \bar{Q}_{obs} \) is mean observed discharge. NS score is the proportion of the variance of the observed values accounted for by the model. Its values can range from minus infinity to one. A negative value indicates that the observed mean does better prediction of \( Q_{obs} \) than the model does.

Figure 4 shows hydrographs at three hydrological stations: Fulaerji, Dalai and Harbin. Table 2 shows flood volume, timing of peak discharge and NS score at three hydrological stations. The evidence in Figure 4 and Table 2 suggests that the flood volume and timing of peak discharge are well represented. The result at downstream hydrological stations tends to have better representations.
Table 2. Flood volume, timing of peak discharge and NS score at three hydrological stations.

<table>
<thead>
<tr>
<th>Station Name</th>
<th>Peak Discharge [m^3·s^{-1}] (Timing)</th>
<th>NS Score</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Calculated</td>
<td>Observed</td>
</tr>
<tr>
<td>Dalai</td>
<td>10660 (Aug. 19, 1998)</td>
<td>14560 (Aug. 18, 1998)</td>
</tr>
<tr>
<td>Harbin</td>
<td>16285 (Aug. 25, 1998)</td>
<td>17400 (Aug. 21, 1998)</td>
</tr>
</tbody>
</table>

6 CONCLUSIONS

In this study, flood runoff analysis of historical 1998 flood occurred in Songhuajiang River basin in China has been carried out by using the GAME re-analysis products (version 1.5). The calculated hydrographs are derived at three hydrological stations. They are compared with the observed ones. It is shown that the flood volume and timing of peak discharge are well represented. This evidence suggests that the GAME re-analysis data is fully applicable. And this also implies the possibility to apply re-analysis data to hydrological forecasting on the continental scale river basins.

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REFERENCES


Figure 4. The simulated and observed hydrographs at three hydrological stations: (a) Fulaerji, (b) Dalai and (c) Harbin. The solid lines show simulated hydrographs. The dashed lines show observed hydrographs.


