Real time flood forecasting and management for the Han River in China

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ABSTRACT The paper describes a major study that was carried out to achieve accurate flood forecasting using the mathematical models for the Han River in China. The optimal management of a large dam in the basin is of great economic interest, and calls for an accurate flood forecasting system, which consists of a rainfall-runoff model combined with a telemetering system. The runoff model contains a series of CLS (constraint linear system) models. The nonlinear effect between rainfall and runoff was modelled by using both the API (antecedent precipitation index), combined with a threshold (the classic CLS approach), and by using explicit soil moisture accounting (developed at the East China College of Hydraulic Engineering, Nanjing), combined with a threshold based on rainfall intensity. The optimal parameter values were obtained by minimizing the error variance subject to a set of linear constraints. The results of the forecasting models were used in the linear programming management model.

Prévision et régularisation en temps réel des crues de la rivière Han, Chine

RESUME L'article décrit une importante étude qui a été conduite en vue de prévoir les crues avec la plus grande précision possible à l'aide de modèles mathématiques pour la rivière Han, en Chine. La gestion optimale d'un grand barrage dans ce bassin présente un grand intérêt économique et requiert une méthode de prévision des crues de haute précision, en l'occurrence un modèle de précipitations-ruissellement combiné avec un système de télémesure. Le modèle de ruissellement comprend une série de modèles de type CLS (constraint linear system). L'effet non-linéaire entre précipitation et ruissellement a été décrit mathématiquement en recourant, d'une part, au concept API (antecedent precipitation index), combiné avec un seuil (l'approche CLS classique) et, d'autre part, à un concept explicite de prise en compte de la rétention en eau du sol (mis au point au Collège d'Ingénierie Hydraulique de la Chine Orientale, Nanjing), combiné avec un seuil basé sur l'intensité des précipitations. Les valeurs paramétriques optimales ont été obtenues en minimalisant la variance.
THE STUDY AREA AND ITS PROBLEMS

The Hanjiang is one of the main tributaries of the middle reach of the Changjiang (Yangtze River). It rises at the foot of the Qiling Mountains and after 1750 km joins the Changjiang at the city of Wuhan (Fig. 1). The basin area is 159 000 km², covering part of five provinces with a population of about 27.5 million.

The climate is characterized by monsoons. Mean annual rainfall ranges from 700 to 1000 mm. Rainfall is not evenly distributed over the year: 70-80% of the entire annual rainfall occurs between May and October. The rainy season begins later in the upper reaches than in the lower reaches. Rainfall is fairly rare in winter.

The heaviest storms occur in July, lasting 3 to 5 days. In September, rainfall in the upper reaches lasts for longer periods, 5 to 10 days, with large flood volumes as a result. In the middle-lower reaches this rainfall is less dangerous than that causing the July floods, because it is not so heavy and because it does not arrive at the same time in the upper reaches and downstream of the Danjiangkou Dam.

Characteristic data for the basin are given in Table 1.

<table>
<thead>
<tr>
<th>TABLE 1</th>
<th>Data for Hanjiang</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean annual runoff</td>
<td>502 YM³*</td>
</tr>
<tr>
<td>Maximum annual runoff (1964)</td>
<td>1 040 YM³</td>
</tr>
<tr>
<td>Minimum annual runoff (1941)</td>
<td>180 YM³</td>
</tr>
<tr>
<td>Maximum recorded discharge (October 1964)</td>
<td>29 000 m³s⁻¹</td>
</tr>
<tr>
<td>Maximum reconstructed discharge (July 1935)</td>
<td>54 000 m³s⁻¹</td>
</tr>
<tr>
<td>Annual runoff coefficient</td>
<td>0.39-0.54</td>
</tr>
</tbody>
</table>

*YM³ stands for 10⁸ m³. It is customary in China to express large numbers in power 4 series: 10⁴ (wan), 10⁸ (yi).

The flood hazard is very serious in the lower part of the river. In the 134 years from 1822 to 1955, the embankments were overtopped 103 times; even after the embankments had been raised and reinforced, they were flooded 4 times between 1949 and 1955.

The flood of 1935 was especially serious. According to available data, the embankments were damaged in 14 places with flooding of 430 000 ha; nearly 4 million people were left homeless, and 80 000 people lost their lives. The catastrophic scale of this event and the fact that the repair and maintenance of the embankment require an outlay of enormous financial resources and labour each year make measures for flood protection, and hence for flood control, an absolute priority, quite apart from any economic arguments to justify these.
Other problems are connected with the possibility of using the water volumes for irrigation, hydropower and navigation. As already stated, a large part of the discharges in the river occurs during the rainy season, whereas in the dry season the discharges are insufficient. Many studies and works have been carried out in an attempt to resolve the problems of the Hanjiang basin and to exploit the water resources.

To meet the above requirements a reservoir with an enormous storage capacity was needed. Three dams were designed and the effects that each dam would have independently were studied, as well as the effects of all three working in combination.

The Danjiangkou Dam was chosen: it controls 60% of the Hanjiang basin and is able to provide complete flood control in the middle and lower reaches of the river. At the same time its position makes it ideal for energy production requirements and gravity irrigation. The reservoir was created by damming the Hanjiang 800 m downstream of the confluence with the Danjiang. The reservoir has a catchment area of 95 200 km$^2$.

The dam is 97 m high from the foundation with a central part that is a concrete gravity dam 1140 m long and two earth wings with a clay core, making a total length of 2500 m. The total useful volume is 104 YM3, reduced to 53 YM3 during the rainy season. The spillway composed of eight outlets, can release a total of 11 800 m$^3$s$^{-1}$. There are also 12 deep outlets. The total normal capacity is, therefore 22 000 m$^3$s$^{-1}$. Furthermore, in case of emergency (return period 100 years), another 12 outlets can be opened, making an overall total capacity of 50 000 m$^3$s$^{-1}$. The hydropower station has six 150 000 kW units and the maximum discharge through the turbines is 1620 m$^3$s$^{-1}$. Two irrigation intakes exist with capacities of 100 and 500 m$^3$s$^{-1}$.

Besides flood control, the reservoir serves two purposes: to guarantee a constant flow over the whole year and to create a sufficient level for hydropower and gravity irrigation.

**FLOOD FORECASTING AND MANAGEMENT PROJECT**

The management of this major work is of great concern. Within the framework of the Technical Cooperation programme between Italy and China, a study was carried out for the improvement of flood forecasting and the preparation of a real time management model. The project included setting up and calibrating the models, as well as the installation of a computer centre and a pilot telemetering network.

The flood management model needs a reasonably accurate forecast of the inflow to the dam from the upstream basin and of the runoff at the control station from the lower basin (see Fig.1). Considering the size of the basin, elementary periods of 6 h are used. Precipitation data for an elementary period are represented by the total rainfall over 6 h and discharge data by the mean discharge. The order of magnitude of the flood wave is one week. This means that a forecast should be made for 28 periods in advance. To take the best advantage of the available discharge data, the hydrological model was calibrated separately for every sub-basin delimited by a discharge station. The upper basin is divided into 12 sub-basins,
the lower basin into eight. Six years of measurements were used for the calibration. After the calibration, the single sub-basins were assembled in a cascade type scheme. Forecasting consists in starting upstream and using the forecast outflow of the upstream section as the future inflow of the downstream section.

The forecast of future precipitation is a difficult task. Statistical analysis precludes any autoregressive scheme. However, meteorological estimates are often available. These estimates are becoming more reliable as a result of satellites and the worldwide exchange of information. The forecasting model can be run under different assumptions for the coming rainfall.

The structure of the hydrological model is linear and uses a CLS approach. This is described in the next section.

FLOOD FORECASTING MODEL

The classic CLS approach computes the outflow hydrograph as the sum of the linear response of a series of hydrological inputs. These inputs are the tributary inflows of the upstream basin and the rainfall of the basin itself. Part of the variation of the outflow can be explained by the autoregressive response.

The response function of an instantaneous unit hydrograph connects the input to the output:

\[ q(t) = \sum h(i) u(t - i) \]

where \( q \) is the outflow series; \( h \) is the response function; and \( u \) is the hydrological input. As mentioned above, the hydrological input can be the tributary inflow from upstream basins (I), precipitation (P) or the outflow itself (Q) in the case of an autoregressive response.

We can write in a general form:

\[ Q = \sum h_I I + \sum h_P P + \sum h_A Q \]

To take care of the nonlinear response of the rainfall, the CLS method divides the rain into two or three different classes and computes a separate hydrograph for each class. The separation of the rainfall is based on the API index. The API index is defined as:

\[ \text{API}_t = K(\text{API}_{t-1} + P_{t-1}) \]

where \( K \) is a recession factor given by the user and \( P \) is the rainfall of the previous period.

The threshold(s) can be given by the user or computed automatically. In the latter case, the first threshold is computed as the average value between the highest and lowest API value and the eventual second threshold as the average between the first threshold and highest API value. These values are, in many cases, satisfactory. Otherwise, the user can adjust the threshold values during the calibration runs.

The lowest class of rainfall represents the ordinary rain condition, the second class intense events, and the third class (if this exists) extreme cases. It is obvious that the runoff coefficient, given by
the sum of the hydrograph ordinates, must be the lowest for the first class, and higher for the second and third. This is because, in the case of ordinary rainfall, a large part of the precipitation is lost owing to infiltration, but in the case of heavy rainfall, when the ground is saturated, infiltration is less and a larger proportion of the precipitation becomes runoff. Therefore, during calibration, the threshold values should be adjusted in such a way that the resulting runoff coefficients of the classes are in an increasing order.

The new version, CLSN, can also handle a different type of threshold. This computation is based on a method developed by the Nanjing Technical Institute. The Nanjing model is based on the assumption that rain falls uniformly over the basin, but infiltration capacity varies from 0 to a maximum value, WMP. It follows that the part of the precipitation lost due to infiltration varies as a function of the precipitation itself. When the ground is fully saturated, no further infiltration can occur. Furthermore, the remaining infiltration capacity varies as a function of the previous precipitation.

The variation of the infiltration capacity follows the law

\[ W = W_{MP} \times \left[ 1 - (1 - f/F)^{1/B} \right] \]

where \( W_{MP} \) is the maximum capacity; \( f/F \) is the ratio of the area to the total catchment area (obviously, this ratio varies between 0 and 1); and \( B \) is a parameter.

The total infiltration capacity is computed by integrating \( W \) over the whole area:

\[ W_M = \int_0^1 W \, d(f/F) = W_{MP} / (1 + B) \]

When \( W_O \) is the infiltration volume already absorbed by the previous rainfall and \( A \) the equivalent precipitation, the net runoff can be computed in the two cases (Fig. 2).

\[ (a) \text{ A + P > WMP: } R = P - W_M + W_O \]

\[ (b) \text{ A + P < WMP: } R = P - W_M + W_O + W_M \times \left( 1 - \frac{A + P}{W_{MP}} \right) B + 1 \]

After each period, the new value of the infiltration capacity is computed using the antecedent precipitation index formula:

\[ W_O = K \times (W_O + P - R) \]
where $K$ is a recession factor (accounting for losses due to deep infiltration and evaportranspiration); and $P - R$ represents the increase of water content.

The CLSN program can divide the runoff using one or two thresholds. When these are used, a separate hydrograph is computed for the various classes of runoff. There are two different ways of using thresholds. When the PP1 type threshold is used, the entire net runoff of the period is associated with one or the other hydrograph. Where the PP2 type threshold is used, the entire net runoff is associated with the first hydrograph until the runoff does not exceed the threshold. When the runoff is larger than the threshold, the runoff equal to the threshold is associated with the first hydrograph and the excess with the second.

The threshold values should be given in such a way that each hydrograph will receive some runoff. Otherwise, an error message appears. Furthermore, the total net runoff cannot be less than the discharge of the downstream section, since the sum of the hydrographs is less than one.

The CLS approach takes a complex nonlinear system of the continuous rainfall-runoff process and models it as a set of simple contemporaneously occurring linear systems. A minimum number of linear systems is used to obtain the desired accuracy of fit between the observed and computed flow output. By using quadratic programming, it is possible to make individual estimates of the impulse response functions (instantaneous unit hydrographs) that have minimum variance and no bias.

This concept was further developed in CLSN. The number of constraints was increased. Each upstream tributary inflow response function is set equal to the unit. This means that there is no loss or gain of water from the tributary inflows. The response of the precipitation zones is limited to unity. In this way the model cannot attribute to any zone a higher contribution than the precipitation of that zone. The sum of the product of each response function and the relative inflow or precipitation is equal to the total outflow. This guarantees that the response has no bias.

This constraint reduces the autoregressive response, which is then limited to that part of the variation of the net outflow (total outflow less the sum of the tributary inflows) that cannot be explained by the precipitation.

**REAL TIME MANAGEMENT MODEL**

The flood management can be classified in the following five classes of action that can be taken in increasing order:

(a) **Normal operation**: the release corresponds to the amount given by the established management policy.

(b) **First safety level is reached at Huangzhuan (5000 m$^3$s$^{-1}$)**: it would be necessary to open the flood diversion channel; but before doing this, the flood can be retained in the Danjiangkou reservoir.

(c) **Reservoir level of 157.0 m reached**: a further increase in reservoir level would cause upstream damage; flood diversion channel is opened.

(d) **Second safety level is reached at Huangzhuan**: the second
safety level is reached when the discharge is equal to the sum of
the Dujiatai diversion flood capacity and the Dujiatai safe capacity.
The latter varies as a function of the water level in the Yangtze
River. When the second safety level at Huangzhuan is reached, it
becomes necessary to increase the flood detention in the Danjiang
kou reservoir.

(e) Danjiangkou Reservoir maximum level is reached: further
storage in the reservoir is not possible. It is necessary to use the
downstream flood detention areas.

The problem is solved by linear programming optimization. A
special linkage programme was prepared to insert the freshly forecast
hydrological data into the linear programming (LP) model. The cycle
at each forecasting consists of the run in sequence of the following
programs (after the real time data entry, check and assembly have
been completed):

(a) real time forecasting at the Danjiangkou dam and at the
Huangzhuan control section;
(b) linkage of the forecast;
(c) LP optimization;
(d) eventual graphical representation of the results.

The LP model is built in such a way that the aforesaid management
criteria are ensured. This is achieved by the use of penalty
coefficients in the objective function of the LP model. The weights
used refer to the maximum reservoir volume during the forecast period,
the discharge at the Huangzhuan control station, above the first
safety level, and the reservoir capacity. Other weights, smoothing
weights, are used to ensure an even release, without sudden changes.

The flood reduction at the Huangzhuan control station is expressed
by the auxiliary variable which is equal to the differences between a
fictitious upper discharge level and the largest discharge occurring
during the forecast period. A limit is imposed on the variable $F$, so
that it cannot exceed the difference between the fictitious upper
level and first safety discharge level. It follows that the model
will try to increase the variable $F$, thus reducing the flood peak
until the first safety discharge level is reached. But no benefit is
associated with any further increase, i.e. any reduction of the flood
peak below the first safety level. The reason that a fictitious
upper level is used instead of the second safety level is that, in
the case of an exceptional flood, the diversion area must be flooded.
This means that the computed discharge at the control section exceeds
the second safety level and would make the variable $F$ negative, which
is not possible in a linear programming model. On the other hand,
when any constant amount is added, this does not alter the solution
and allows the variable $F$ to remain positive in all cases.

The excess water is accumulated in the detention area. The
penalty coefficient associated with the total volume of flood detention
is higher than the penalty coefficient associated with the flood
detention in the Danjiangkou Reservoir. This implies that flood
detention in the reservoir is preferable to flood diversion into the
downstream detention area. Figure 3 illustrates the model's action
for the various classes of floods at the Huangzhuan control section.

Another penalty coefficient is associated with the maximum volume
reached during the forecast period in the Danjiangkou Reservoir. A
lower penalty coefficient is used for normal flood detention (under
Real time flood forecasting for the Han River

Fig. 3 Classes of floods.

level 157.0 and a higher one for exceptional flood detention (from level 157.0 to 160.0).

An additional penalty coefficient is associated with the last value for the storage. This coefficient forces the storage down towards the minimum volume suggested by the management rules at the end of the forecast period. The emptying of the flood storage, after the flood wave has passed, leaves room for eventual future floods.

Finally, two more penalty coefficients are used in the model as smoothing coefficients. These coefficients ensure a smooth release pattern. They are associated with the highest value and the sum of the absolute value of the second derivative of the release sequence. The second derivative expresses the change in the differences of the release series:

$$XX_J = \left| (X_J - X_{J+1}) - (X_{J+1} - X_{J+2}) \right| = \left| X_J - 2X_{J+1} + X_{J+2} \right|$$

The model was calibrated using several recorded events.

In real time operation, the first value of the release vector is used and the optimization repeated at the next period.

CONCLUSION

A flood forecasting and management model was set up for a large basin in China. The forecasting model uses the CLS approach. The basin was divided into 20 sub-basins, and a separate model was set up for each sub-basin. The forecasting consists in starting upstream and using the forecast outflow of the upper sub-basin as the inflow of the lower sub-basin.

Figures 4 and 5 display typical results. Figure 4 shows the 0 period forecast: i.e. the computation of the present discharge is a function of the past precipitation and tributary inflows. This hydrograph provides an important indication of the goodness of the model. The hydrograph in Fig. 5 shows the forecasting of six periods (36 h in advance). It is to be noted that the future precipitation is assumed to be zero. This accounts for the deficit of the flood peaks.

Table 2 shows the statistics for the simulation of the intense events (5000 m$^3$s$^{-1}$) in terms of peak and flood volume. The years
FIG. 4  Computed hydrograph.
FIG. 5 Six period forecast.
1973-1978 were used for the calibration and the years 1979-1980 as a check. The simulation was made with and without updating. In the computation with updating, the measured discharges are used; without updating the computed discharges are used.

Table 2 shows the number of events with a computation error of more than 20% either for the peak value or the volume, and the total of the events.

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