Flood control measures in the Red River basin and numerical simulation of their operation

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Abstract The main objective of flood control measures in the Red River basin is to keep the water level at Hanoi, the capital of Vietnam, below a permitted level. At present, dykes and dams are the main measures for flood control in the basin. Detention ponds or other hydraulic structures are considered as secondary measures. However, it is estimated that despite the effects of dams, Hanoi will be threatened by flooding when possible defined floods occur in the upstream region. In this paper, the current situation of flood diversion and slowing system in the Red River basin is investigated using dynamic hydraulic flood routing simulation.

Key words flood control; flood diversion system; flood routing; numerical simulation; Red River basin, Vietnam

INTRODUCTION

The total catchment area of the Red River is 169 000 km$^2$ of which 82 400 km$^2$ lies within China and a much smaller area, about 15 000 km$^2$, in Laos. It is the largest basin in Vietnam and contains the capital Hanoi. Unfortunately, floods are the frequent natural disasters that threaten the development of the basin, especially Hanoi. They cause dyke breaches and overtopping as well as serious inundation in the delta region. The Red River network is shown in Fig. 1.

The total length of river dykes is about 3000 km (Binnie et al., 1995). Another measure for flood control in the basin is use of the storages of two major dams, Hoa Binh and Thac Ba (Fig. 1), with a total flood-relieving capacity of about 6.8 billion m$^3$. Despite the effects of the dyke system and dams, it is estimated that Hanoi will be threatened by flood if an unfavourable combination of floods from three main tributaries occurs. So, to guard the basin against flood disaster, secondary flood control measures will be used. Those are areas (like large ponds) for flood detention and structures for flood diversion.

To simulate the development of flood flow in natural rivers, the flood flow should be treated as unsteady flow. In this paper, a dynamic flow routing model using the complete Saint-Venant equations is employed. The implicit, finite difference Preissmann scheme (Cunge et al., 1980; Fread & Lewis, 1998) is chosen to apply to flood routing in the case of flood diversion. The Day River flood diversion and slowing system, a flood control system in the basin, is taken into consideration. Results from the study can be used in integrated water resource management for the Red River basin.
GOVERNING EQUATIONS

Channel flow

Varied unsteady flows in an open channel are described by the Saint-Venant equations for one-dimensional free-surface flow. The governing equations are the continuity and momentum equations:

\[ \frac{\partial y}{\partial t} + \frac{1}{b_x} \frac{\partial Q}{\partial x} = 0 \]  

(1)

\[ \frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left( \frac{\alpha Q^2}{A} \right) + gA \frac{\partial y}{\partial x} + gAS_f = 0 \]  

(2)

where \( t \) is time, \( x \) is distance along the longitudinal axis of the watercourse, \( A \) is cross-sectional area, \( y \) is water surface elevation, \( \alpha \) is the momentum correction coefficient, \( b_x \) is storage width, \( g \) is the gravitational acceleration, and \( S_f \) is friction slope and can be evaluated using Manning’s formula:

\[ S_f = \frac{n^2 Q |Q|}{A^2 R^{4/3}} - \frac{Q |Q|}{K^2} \]  

(3)
in which \( n \) is the Manning coefficient of frictional resistance, \( R \) is hydraulic radius and \( K \) is the conveyance factor. Equations (1) and (2) are solved numerically using an implicit, finite difference scheme.

For a river network, a compatibility condition must be satisfied at a junction:

\[
\sum_{k=1}^{m} Q_k = 0 \quad (4)
\]
\[
y_1 = y_2 = \ldots = y_k = \ldots = y_m \quad (5)
\]

where \( m \) is the total of the links, which emanate from the junction, and \( Q_k \) is the discharge of the \( k \)th link.

**Flow in flood-slowing areas and detention ponds**

Flood can inundate the flood plain or fields. In the case of flood diversion and slowing, flood flow may fill up the detention ponds, overtop a dyke at some pre-defined locations, and run over into cells inside dykes. The continuity equation for cell \( j \) is used in the form of quasi two-dimensional flow (Cunge et al., 1980):

\[
A_j(y_j) \frac{dy_j}{dt} = \sum_k Q_{j,k}(y_j, y_k) \quad (6)
\]

The finite-difference approximation can be written as:

\[
A_j \frac{y_j^{i+1} - y_j^i}{\Delta t} = \theta \sum_k Q(y_j^{i+1}, y_k^{i+1}) + (1 - \theta) \sum_k Q(y_j^i, y_k^i) \quad (7)
\]

where \( A_j \) is horizontal water surface area of cell \( j \), \( y_j \) is water stage in the cell \( j \), and \( k \) is the index of the cells adjacent to the cell \( j \).

**Internal boundaries**

Hydraulic structures along or adjacent to the watercourse such as dams, weirs, bridges or waterfalls are considered as internal boundaries. In this case, the reach is considered as the one between two cross sections \( j, j+1 \) just upstream and downstream of the structure. Two equations equivalent to the Saint-Venant equations are required:

\[
Q_j^{i+1} - Q_{j+1}^{i+1} = 0 \quad (8)
\]
\[
Q_j^{i+1} = \Phi(y_j^{i+1}, y_{j+1}^{i+1}) \quad (9)
\]

Equation (9) is usually an empirical relation for computing discharge values through the structures. It may be rewritten by supposing that all functions \( \Phi \) are differentiable so that:

\[
\Phi = \Phi^0 + \frac{d\Phi}{dy} \Delta y + \frac{d\Phi}{dQ} \Delta Q + H.O.T. \quad (10)
\]

This is the Taylor series expansion of the function \( \Phi \) at the time \( (i + 1)\Delta t \) with \( H.O.T. \) denoting higher order terms.
EMERGENCY FLOOD CONTROL MEASURES IN THE RED RIVER BASIN

Flood-slowing areas and the Day River flood diversion system are shown in Figs 1 and 2 respectively. Hanoi is a key location for flood control in the Red River basin. The mean annual maximum water level at Hanoi is about 11 m. According to the Central Committee for Flood and Storm Control of Vietnam, a very dangerous flood condition occurs if the water level at Hanoi is over 11.5 m. If the Hoa Binh and Thac Ba reservoirs operate with their full flood-relieving capacity, the water level at Hanoi reaches 13.40 m, and the General Department of Meteorology and Hydrology of Vietnam predicts that the flood water level continues to rise quickly, the flood must be diverted into the Day River (Institute of Meteorology and Hydrology, 2000).

The Day River flood diversion system includes three main parts: the Van Coc gate (including Hat Mon spillways), the Van Coc reservoir and the Day dam. The system's function is to reduce the peak flood discharge in the Red River by flood diversion for the safety of Hanoi and other provinces with the maximum discharge through Day dam of $5000 \text{ m}^3 \text{s}^{-1}$. The flood is diverted from the Red River to the Day River by the Van Coc gate and Hat Mon spillways initially. It can fill the Van Coc reservoir and then
flow into the Day River through the Day dam, which has six gates made from steel and operated electrically. The opening process includes eight periods with alternate open and rest periods. The gates are opened by lowering them from 13.9 m to 9.0 m. The Day River and its flood plain are important parts in the system with the function of transporting the water from the flood diversion to the sea. The flood plain as well as ponds or lower cells in the fields (inside dykes) may be inundated when diverting the flood because there are some pre-defined locations on dykes for flood spill over.

**NUMERICAL SIMULATION OF FLOOD FLOW IN THE NETWORK WHEN DIVERTING FLOOD**

The flow equations (1–7) are used to simulate the flood flow development when diverting flood from the Red River into the Day River. Flows through Van Coc gate, Hat Mon spillways and Day dam are simulated by using equations (8) and (9). Flood
Fig. 4 Results from calibration (flood of 9–31 August 1996).

Fig. 5 (a) Water level at Son Tay and Ha Noi in supposed flood. (b) Discharge hydrograph at Ha Noi in supposed flood.

control decisions are based on the water level at Hanoi and the development of the predicted flood. The operation schedules of the Van Coc gate and Day dam are supposed to be known functions of time. The time step is 20 min for normal routing without flood diversion but reduces to 5 min during flood diversion. A program written in C++ has been developed. The network investigated is shown in Figs 2 and 3. The distance between dykes along the Day River varies from 180 m to over 4000 m. The typical shape of cross sections in the Day River is a compound section with the maximum width of water surface in the main channel varying from 100 m to 900 m. The flood plain is the cultivated area.
The flood of 9 to 31 August 1996 was used for the calibration process. This was a large flood in the Red River with the water level at Hanoi at 12.43 m. Upstream boundaries used in calibration are discharge hydrographs at Hoa Binh, Yen Bai, Vu Quang, Hung Thi and Ba Tha. The downstream boundaries are water level hydrographs at Nhu Tan, Phu Le, Ba Lat, Dinh Cu, Tien Tien and Pha Lai. The investigated and measured topographical data from 1992–1999 are used in the simulation. As the dynamic unsteady flow model is often sensitive to the value of the Manning coefficient of frictional resistance \( n \), the calibration process adjusts the value of \( n \) to produce the minimum differences between the observed and simulated hydrographs of discharge and water level. The value \( n \) is selected via a trial-and-error calibration methodology. Initial values and adjustments of \( n \) are based on field investigations and other guidelines (Yen, 1992).

Results of the calibration are shown in Fig. 4. The error in discharge is 4–15%. The maximum error in maximum water level (at peak) is 42 cm and the maximum error in time of the peak is 10 h. The Manning coefficients for the reach from Ba Tha to Tan Lang (about 50 km in the Day River, see Fig. 2) are selected as 0.040–0.055 for the flood plain and 0.030–0.035 for the main channel.

These results are acceptable and the model was used in the next process: simulating the flood in the case of flood diversion. When the system takes part in “flood prevention and combat”, a question will arise: how will the system work? Thus, the development of flood flow in the system as well as in the network will be investigated. In this study, the real flood occurred in the Red River basin in August 1971, the largest flood on record. Without flood diversion and dyke breaches, the maximum water level at Hanoi would be about 14 m, and it would also cause a water level at Hanoi of over 13.4 m for a period of 90 h. In this situation, the flood must be diverted into the Day River. By using a one-dimensional unsteady flow model, the flood is routed dynamically in the network. Some results are shown in Fig. 5(a and b). Within about 23 km downstream of the Day dam, flood flow reduces gradually because of the expansion of cross sections and the greater resistance effects of the flood plain. The Manning coefficients in this reach were set at 0.065–0.070. The flood flow in the next river reach with a length of 100 km is influenced by floods from other rivers as well as backwater from the Dao River (Fig. 2). The tide at Day mouth affects strongly the flood flow in the last 40 km reach. This flood causes inundation in the flood plain of Day River as well as in cells of the flood-slowing area with average depth of 3.5 m and average time of 5 days. The discharge at Hanoi is reduced from 24 090 to 21 870 m³ s⁻¹ (Fig. 5(b)) while the water level is reduced from 14.75 m to 14.10 m. At this stage, the dyke around Hanoi will not overtop but may be breached because of its poor quality (Binnie et al., 1995). Thus, the safety of Hanoi will still be threatened by floods.

**CONCLUSIONS**

The problem of flood diversion into the Day River has been considered with a one-dimensional unsteady flow model. The Day River flood diversion system can reduce the water level at Hanoi by 0.65 m but this water level is still high and can threaten the dyke around the city. The water level at Hanoi cannot be reduced to the required level
of 13.4 m by only using the system. The structures of the system seem to be working as designed. The flood diverted from the Red River by the system can cause the inundation of the flood plain of the Day River as well as in the flood-slowing area. The average depth and average time of inundation in the flood-slowing area are 3.5 m and 5 days, respectively. The results of this study show that a one-dimensional, dynamic, unsteady flow model with quasi two-dimensional treatment for flows in ponds and the flood plain can be a robust solution for flood routing in a river network where there are many hydraulic structures as well as flood control structures.

From the flood flow development in the network, it can be said that the flood diversion has to be considered in the context of the flood regime in other tributaries of the Day River as well as flood tides from the sea. When a very large flood occurs, the system cannot ensure the safety of Hanoi. Finally, it is necessary to emphasize that environmental and social issues should be considered in the analysis.

REFERENCES