2-D hybrid approach to storm flood modelling in the Shalan catchment

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Abstract A hybrid approach to storm flood modelling has been introduced and applied to a flood simulation in the Shalan catchment in Heilongjiang Province, northeast China, by combining a simplified hydrological rainfall model with a 2-D hydraulic runoff model. When combining, the scale matching and numerical instability should be taken into account and solved. In the application a rainfall process has been constructed based on field surveys and quantified flooding facts. One of the parameters in its expression should be inversely determined. Digital Elevation Models (DEM) and their extracted river network provide a strong geological base to enhance rainfall and runoff simulation. The practical simulation results agree well with collected flood data in Shalan. It turns out to be one of the most useful tools to simulate storm floods in flat plains or uneven mountain areas.

Key words DEM; hybrid approach; rainfall; runoff; Shalan catchment

INTRODUCTION

A heavy storm occurred in Shalan valley, a very small mountainous area in Heilongjiang Province, northeast China, on 10 June 2005, causing the most severe disaster in 100 years of this area's history, often referred to as a "6.10" storm. A significant flood suddenly formed and surged into a local village and a primary school. A total of 109 people lost their lives in the tragedy, including 105 children. They had no chance to escape from the violent current because the school was located in a lower part of the valley terrain and maximum water depth at the school reached up to 2 m. The administration was shocked and made a series of field investigations to find out the main reason for this tragedy and how to avoid it in the future (IWHR Survey, 2005).

In the provincial primary investigation report, "6.10" storm is identified as a local severe storm, occurring once every 100 years. The area-averaged rainfall was 123 mm in 3 hours and the maximum rainfall was over 200 mm in some places. Since it is an ungauged mountain area, the hydrological rainfall approach was based on surface runoff analyses during the flood investigation.

In general, the latter can be done if sufficient runoff data are available, and a proper hydrological model is adopted to simulate local storm floods (Singh, 2000b).

In this paper a hybrid approach to that problem has been studied, i.e. for rainfall, hydrological analysis based on meteorological observed data, and quantified narrative facts. For runoff, a hydraulic analysis was applied to simulate surface flow along the valley. In the study, a completed 2-D unsteady flow model was applied, instead of using a simplified kinematic wave model or a Muskingum-Cunge model. A hydraulic model needs a numerical description of the valley, so a Digital Elevation Model (DEM) was applied.

Firstly a 2-D hydraulic model is introduced in this paper, which has previously been successfully used to simulate flood evolution in flood plains in China. The advantage is that it is easy to display the velocity field and water depth distribution based on its output results. Subsequently, a simpler rainfall mode was introduced. To couple the rainfall mode with the hydraulic model, some difficulties needed to be overcome such as their scale matching and numerical stability caused by geological unevenness and complex flow pattern. Based on DEM, a river network in the Shalan area was extracted, and rainfall subregions were classified. An explicit expression of the rainfall process based on field surveys and quantified flooding facts have also been introduced, as well as its parameters. One of the parameters should be determined inversely. Finally, based on the simulation results, some facts were revealed, which will be discussed in some detail.

HYBRID APPROACH USING SIMPLIFIED HYDROLOGIC PROCESSES AND THE 2-D HYDRAULIC MODEL

2-D hydraulic model

The applied model is often referred to as a 2-D unsteady model, derived from depth averaged Saint-Venant equations. Under Cartesian coordinates, its continuity and moment equations could be given as follows:

$$\frac{\partial z}{\partial t}+\frac{\partial (uh)}{\partial x}+\frac{\partial (vh)}{\partial y}=q \tag{1}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+g\frac{\partial z}{\partial x}+g\frac{n^2u\sqrt{u^2+v^2}}{h^{4/3}}-k\sqrt{u^2+v^2}\frac{\partial u}{\partial x}=0 \tag{2}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+g\frac{\partial z}{\partial y}+g\frac{n^2v\sqrt{u^2+v^2}}{h^{4/3}}-k\sqrt{u^2+v^2}\frac{\partial v}{\partial y}=0 \tag{3}$$

where Z is water elevation; h is water depth; u and v are depth averaged Cartesian velocity components; q is the external water discharge, such as rainfall or laterally coming flow, etc.; n is the manning coefficient; t is the time(s); $g\frac{n^2v\sqrt{u^2+v^2}}{h^{4/3}}$, $g\frac{n^2v\sqrt{u^2+v^2}}{h^{4/3}}$ is the flow resistance in x or y direction, respectively; $k\sqrt{u^2+v^2}\frac{\partial u}{\partial x}$, $k\sqrt{u^2+v^2}\frac{\partial v}{\partial x}$ is the local flow resistance in x or y direction, respectively; k has a positive value when the oncoming flow velocity is larger than local flow velocity in the calculated cell, otherwise k is zero. In this study, k is set to be 0.4.

Once the above equations were discretized, convection terms neglected and characteristic theory applied, the momentum algorithm forms, were developed by Li *et al.* (2005); they are shown in equation (4). The discretized scheme is shown in Fig. 1, where the flow simulation field is divided into cells and cell C stands for the currently calculated cell with all variables subscripted by C and neighboring cells are, according to their directions, labelled as E, S, W, N, ES, WS, WN, and EN. All variables with superscript n and n + 1 signify their value is taken at nth time and n + 1th time, and stand for the known and unknown, respectively. So V_E^n, V_S^n, V_W^n, V_N^n, V_{ES}^n, V_{WS}^n, V_{WN}^n, V_{EN}^n are velocities at the current time step in the corresponding cells, and $V_{E,b}^{n+1}$, $V_{S,b}^{n+1}$, $V_{W,b}^{n+1}$, $V_{N,b}^{n+1}$ are velocities at the next time step in four borders of cell C.

$$\begin{aligned}
V_{i,b}^{n+1} &= \lambda^+\cdot\{(\frac{V_c^n+V_i^n}{2})+[sign(c,i)\cdot g\frac{Z_i^n-Z_c^n}{\Delta D}\\
&\quad+\mathrm{k}\frac{\sqrt{(V_c^n+V_{i,A}^n)_x^2+(V_c^n+V_{i,A}^n)_y^2}}{4}\cdot\frac{V_{i,A}^n-V_c^n}{\Delta D}\\
&\quad+V_{i,b}^{n+1}\sqrt{(V_{i,b,x}^{n+1})^2+(V_{i,b,y}^{n+1})^2}\,(g\cdot\frac{n^2}{(\frac{h_i+h_i}{2})^{4/3}})]\Delta t\}\\
&+\lambda^-\cdot\{(\frac{V_c^n+V_j^n}{2})+[sign(c,j)\cdot g\frac{Z_j^n-Z_c^n}{\Delta D}\\
&\quad+k\frac{\sqrt{(V_c^n+V_{j,A}^n)_x^2+(V_c^n+V_{j,A}^n)_y^2}}{4}\cdot\frac{V_{j,A}^n-V_c^n}{\Delta D}\\
&\quad+V_{j,b}^{n+1}\sqrt{(V_{j,b,x}^{n+1})^2+(V_{j,b,y}^{n+1})^2}\,(g\cdot\frac{n^2}{(\frac{h_j+h_c}{2})^{4/3}})]\Delta t\}
\end{aligned} \tag{4}$$

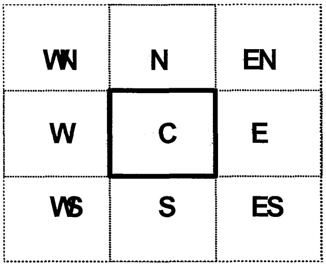

Fig. 1 Discretized scheme in grids.

where $i,j = E,S,W,N$, $\Delta D \begin{cases} = \Delta X, if\ i = E,W \\ = \Delta Y, if\ i = S,N \end{cases}$ and *sign*(*c*,*i*) are sign function, its positive or negative value depends on cell *i*th location compared with cell *C*; a positive value is taken when cell *i* is located on the upper or left side of cell *C*.

For the continuity equation, a central difference discretized scheme is adopted, Z_c^{n+1} is expressed as:

$$Z_c^{n+1} = Z_c^n + [\frac{(V_{W,b}^n + V_{W,b}^{n+1})(h_W^n + h_W^{n+1}) - (V_{E,b}^n + V_{E,b}^{n+1})(h_E^n + h_E^{n+1})}{2\Delta x} + \frac{(V_{N,b}^n + V_{N,b}^{n+1})(h_N^n + h_N^{n+1}) - (V_{S,b}^n + V_{S,b}^{n+1})(h_S^n + h_S^{n+1})}{2\Delta y}]\Delta t \tag{5}$$

Simplified hydrological process

It is often assumed that the hydrological cycle has neither a beginning nor end, and that it processes continuously (Chow *et al.*, 1988). Precipitation might come down into soil, and precipitated water might be intercepted by vegetation, forming surface flow. The infiltrated flow through soil might come out as surface runoff and runoff might infiltrate into the soil again. Evaporated water becomes part of the atmosphere, then falls down as rain. Though the runoff–rainfall expression could be described in Horton's mode or as saturation overland flow mode, its complexity still remains due to a certain amount of spatio-temporal difference in climate and soil. If flood-runoff is caused by a heavy storm, i.e. the rainfall intensity is much stronger than the soil infiltration capacity, some factors in the water cycle, such as evaporation, interception, infiltration, or subsurface flow, might be insignificant. Therefore, hydrological processes influencing flood–runoff can be simplified as net rainfall, which could be embedded into an hydraulic model. If detailed rainfall data is obtained, the land can be subdivided into different rainfall zones. If additional detailed geographic data and the vegetation distribution are acquired, suitable hydrological parameters can be set.

In this paper, for each cell, a saturation overland flow mode is adopted to get q in equation (1), where q is defined as $q = (P - E) - (W_m' - W')$, and P and E stand for precipitation and evaporation, respectively. Here W_m' is the water storage capacity (mm), W' is the actual water storage at the beginning (mm).

Though precipitation can be viewed as an input to a hydraulic model, there are still some challenges met in the hybrid approach. These are discussed as follows:

(a) Scale matching problem. Once a hydrological mode is set to couple with a hydraulic model, scale matching becomes a challenge. It can be classified as either temporal scale matching or spatial scale matching. For the rain process, its time step takes at least several minutes. But for the runoff process, its calculation time step is bound by the model and its mesh size, as well as what flow situation is encountered. In some cases this could be within 60 or 30 s. Another problem is that for the hydraulic model, water depth in a cell should be more than 0.001 m, otherwise the calculation cannot be completed. However, in a single time step, the cell only gets a net rain amount of less then 0.001 m, and this cannot be neglected. To maintain a water quantity balance is therefore very important in the calculation. To solve this issue, the concept of the memory cell is introduced in our study. The calculation cell possesses a memory function; it automatically receives net rainfall, no matter how small it is. And it will not let the program run until its accumulated water amount reaches a limit, e.g. 0.001 m. In the memory function design, it not only remembers how much net rainfall there is into or out of cells, but also takes water exchange between cells into account to maintain the water balance.

Spatial scale in rainfall models is also different from that in runoff models. Their entire simulated areas are different in size; usually the simulated area in rainfall models is much larger than one in runoff models, and the former covers the latter. To simply solve the problem, cells can also be marked with a subregion number of a rainfall region.

(b) Numerical instability caused by topographic unevenness. Topographic unevenness, such as sharp slopes and banks, concave or protruding places, as well as dry-wet joints often makes hydraulic model running numerically unstable. Such a kind of numerical instability occurs especially with flood calculations in mountainous areas.

To overcome such numerical instability, some algorithms techniques have been used in our programming, such as adding a local energy dispersion term, taking characteristic algorithms forms and partly using try-correct techniques.

SIMULATION OF THE "6.10" STORM FLOOD

Spatial information derived from DEM

The objective zone was located at the upper reach of the Shalan River, above Shalan town in An'ning City, Heilongjiang Province. Based on the 2004 (3) Arc Second SRTM elevation, digital elevation data with 90-m resolution, the river network of the Shalan River basin was extracted using an eight-level matrix (D8) approach. The matrix approach is developed as software for extracting drainage networks from raster DEM using the Pfafstetter scheme. The river network could be marked as the main river and its tributaries (Li *et al.*, 2004). The river network and related information of the upper basin of the Shalan River is shown in Fig. 2.

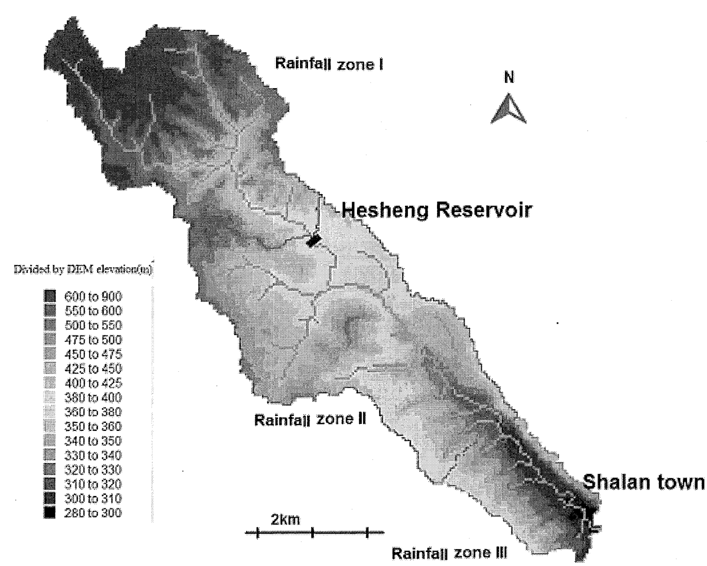

Fig. 2 River network and related information in the upper river basin of the Shalan River.

The extracted drainage area is 114.3 km^2, a narrow strip running from northwest to southeast, with a length of 30 km and width of 3~6 km. The elevation in the northwest mountain area is 500~900 m, whereas in the southeast valley area it is 300~400 m. In a previous study (Cheng, 2005), the real drainage area above Shalan village is 115 km^2, including the Hesheng reservoir catchment of about 45 km^2, which is covered with rich forest vegetation. The riverbed average slope is 6‰, with an elevation difference of 84 m. Based on the above information and DEM, the entire rainfall region is divided into three subregions: (i) Hesheng reservoir catchment with a drainage area of 42.6 km^2, (ii) part of the valley between the reservoir and valley outlet with drainage area of 49.9 km^2, and (iii) the river basin between the valley outlet and Shalan town with a drainage area of 21.8 km^2. The total elevation difference is 82 m. All the data measured in DEM is calibrated, and is very close to that in the previous study (Cheng, 2005).

Rainfall process

After checking the provincial primary investigation report and all available field survey data, it came to mind that the rainfall peak appeared to shift along the valley and become higher and higher. Consequently, the matter of how to express this kind of phenomenon seems to be a key subject in this study. One of the distribution patterns of rainfall processes can be expressed as follows:

$$F(x,t) = (1 + \frac{\alpha x}{X_0}) F_0(x, \beta(t - x/v)) \quad (6)$$

where X_0 is distance from the reservoir to the valley outlet; x is also distance measured from the reservoir to a specific rainfall subregion; α and β are distribution parameters, α has a constant value, β is set to be 1 at the reservoir, otherwise it takes the value from statistically analysed rainfall duration in a specific rainfall subregion; v is shift velocity of the rainfall peak.

Before running the model, some parameters should be determined based on field surveys and statistical analysis. In our case study, peak shift velocity is $V = 1.8$ m s^{-1}, and for all subregions rainfall duration retains the same value of $\beta = 1$. One of the parameters, α, is obtained through a series of calculations, its value continuously reset until the simulation results agree well with the observed flooding facts. The final α value is about 4.8 mm km^{-1}, indicating that the maximum rainfall intensity had increased to 4.8 mm while passing a distance of 1 km downstream.

Initial and boundary conditions

In the study, rectangular grids of 90 m are adopted for the hybrid model. There are a total of 14 110 grids in the simulated area, and the maximum elevation difference in adjacent grids was 45 m. Roughness coefficient is expressed as the Manning coefficient.

The simulated start time is the same as the actual storm, which started at 12:30 h, and ended at 17:00 h. Initially the valley is saturated with earlier rainfall, and its streamflow is set at 20 $m^3 s^{-1}$. The upstream reservoir, the Hesheng Reservoir, is small and during the rainfall no flood had been released from the reservoir (only regular flow out downstream to keep the reservoir water at a fairly constant level). Therefore, for runoff simulation, it is assumed that flow out of the reservoir is at a regular flow, without considering the reservoir regulation. Of course it can also serve as an upstream boundary condition. The downstream condition has been set at the valley outlet, because there is a bridge across the stream and its design flood discharge is known. The flow over the bridge is assumed to be flow over a board weir. The rainfall process at the reservoir is assumed to follow a specific curve of normal distribution; its duration is about 2.5 h as cited from other reports. The accumulated rainfall, which is a definite integral of rain intensity over its duration, is verified to be nearly equal to the measured volume in the reservoir pluviometer.

Simulation results

As a kind of inverse problem, the rainfall shift parameter α, is determined through computation, with a value of 4.8 mm km^{-1}. Therefore, the downstream rainfall process at subregions can be

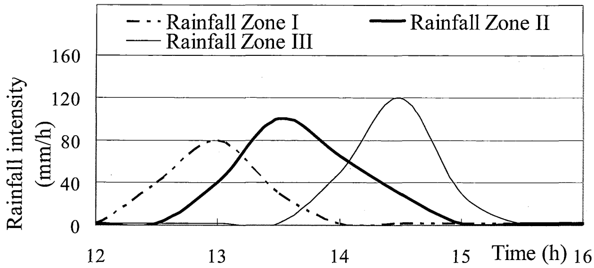

Fig. 3 Rainfall in three rainfall subregions.

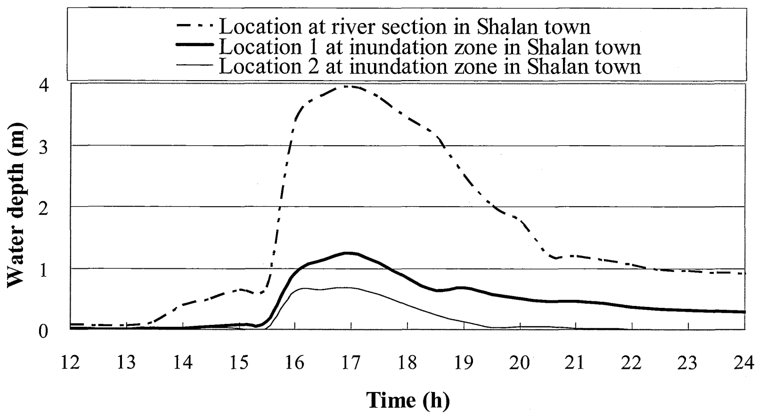

Fig. 4 Flood process in three locations along the Shalan River.

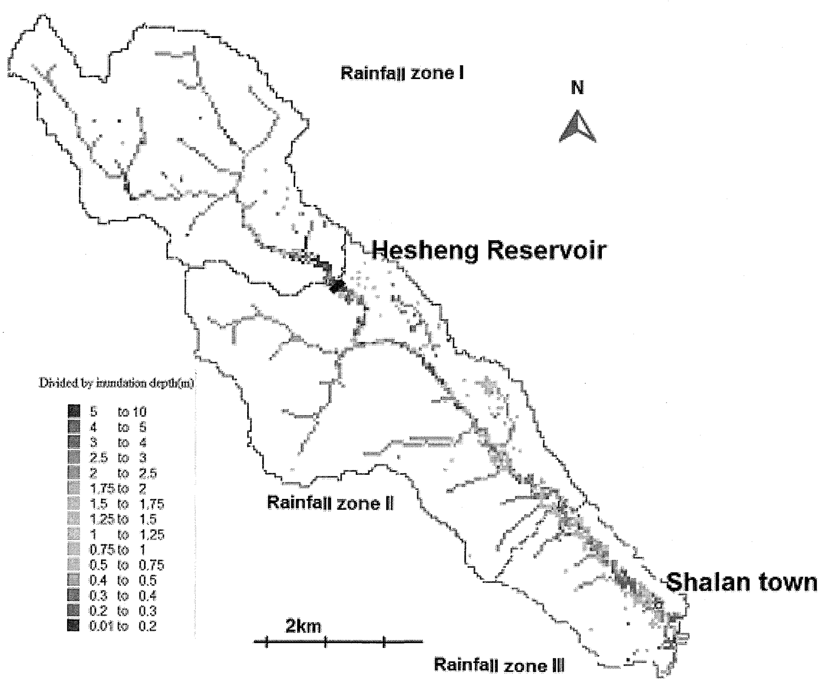

Fig. 5 Inundation fields distribution in Shalan River Basin.

revealed from upstream rainfall processes. The results are shown in Fig. 3. The rainfall intensity in subregion II and subregion III is about 100 mm h^{-1} and 120 mm h^{-1}, respectively, and the rainfall amount in the three subregions is about 75 mm, 94 mm and 112.5 mm, respectively.

The results also show that a total of 9 million m^3 runoff water is yielded over a 5 h period of rainfall. The maximum flood discharge through the valley outlet was 415 $m^3 s^{-1}$, which is beyond the bridge design capacity, and caused some water to overtop the bridge with a water depth of 0.5 m. The maximum water depth nearby the Shalan town was 1.3 m, and at the primary school 2 m and subsided to half these values in 3 h (Fig. 4). Most inundated fields ranged within an extension of 500 m along the river (Fig. 5).

DISCUSSION AND CONCLUSION

A hydraulic runoff model can be coupled to a hydrological rainfall model if their scale matching and numerical stability problems are carefully overcome. Such a hybrid approach can serve as one of the helpful tools to solve rainfall floods in mountainous areas.

DEM and its extracted flow networks offer a strong geological base to build hydraulic runoff models. For some ungauged areas the rainfall process can be expressed based on field surveys and quantified flooding facts.

The rain flood in the Shalan valley resulted in serious loss of life and property. Through our simulation, the following facts are revealed:

(a) The "6.10" storm rain was less strong than that presented in the provincial primary investigation report.
(b) The bridge and some buildings at its two abutments at the valley outlet reduced the discharge capacity and caused more serious inundation in lower lying upstream areas, such as the village and the primary school. To derive rainfall data from runoff data should be carefully carried out; if there is something constructed in the flow passage or outlet, the derived rainfall might be exaggerated.
(c) Another reason for getting more serious floods, is that the rainfall peak was travelling along the valley in the same direction of its forming flow.

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