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Coupling Green-Ampt infiltration method and two-dimensional kinematic wave theory for flood forecast in semi-arid catchment

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Abstract

Due to the specific characteristics of semi-arid catchments, this paper aims to establish a grid-and-Green-Ampt-and-two-dimensional-kinematic-wave-based distributed hydrological physical model (Grid-GA-2D model) coupling Green-Ampt infiltration method and two dimensional overland flow routing model based on kinematic wave theory for flood simulation and forecasting with using GIS technology and digital elevation model (DEM). Taking into consideration the soil moisture redistribution at hillslope, Green-Ampt infiltration physical method is applied for grid-based runoff generation and two-dimensional implicit finite difference kinematic wave model is introduced to solve depressions water storing for grid-based overland flow concentration routing in the Grid-GA-2D model. The Grid-GA-2D model, the Grid-GA model with coupling Green-Ampt infiltration method and one-dimension kinematic wave theory, and Shanbei model were employed to the upper Kongjiapo catchment in Qin River, a tributary of the Yellow River, with an area of 1454 km^2 for flood simulation. Results show that two grid-based distributed hydrological models perform better in flood simulation and can be used for flood forecasting in semi-arid catchments. Comparing with the Grid-GA model, the flood peak simulation accuracy of the newly developed model is higher.

1 Introduction

From the last part of the 20th century, a large number of distributed hydrological models or semi-distributed hydrologic models (Beven and Kirkby 1979; Abbott, 1986; Singh, 1995; Todini and Ciarapica, 2001; Yu et al., 2000; Yang et al., 2002; Ao et al., 2003; Xiong and Guo, 2004; Jia et al., 2005; Li et al., 2006; Xu and Cheng, 2010; Bao et al., 2010) have been developed for flood simulation and flood forecast with the rapid development of spatial survey technology such as GIS, RS and DEM. Grid-based distributed hydrological models, which consider the spatial variability, have become one of the most important tools for the present hydrological investigations (Abbott and Refsgaard,

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1996; Vieux, 2001). Large number of distributed hydrological models such as SHE model (Abbott et al., 1986), DHSVM model (Wigmosta et al., 1994), TOPKAPI model (Liu et al., 2002), TOPMODEL (Beven and Kirkby, 1979) have been developed and applied in practical use. The runoff generation in the models TOPKAPI, TOPMODEL, BTOPMC (Ao et al., 2003) and Grid-Xin'anjiang model (Bao, 2006; Li et al., 2006; Wang et al., 2007; Yao et al., 2009; Bao et al., 2011) is based on saturation excess mechanism. Though this models work well in humid regions, they perform poorly in semi-arid catchments and arid catchments as the runoff generation mechanism is different in such regions (Wang, 2010). The hydrological regime in semi-arid catchments and arid catchments is extreme and highly variable, where flash floods from a single large storm can exceed the total runoff from a sequence of years (Wheater et al., 2008). The Grid-GA distributed hydrological model (Wang, 2010; Wang et al., 2010a, b), based on topographical information of each grid d cell extracted from DEM and Green-Ampt infiltration method (Green and Ampt, 1911), was developed for flood simulation and flood forecast. Catchment characteristic information such as topography, soils, vegetation cover, climate and other spatially distributed features affect surface and subsurface water distribution at hillslope to river catchment scales was extracted based D8 method (Wang et al., 2007) used in most distributed hydrological modeling and Muskingum-Cunge method (Cunge, 1969) was applied for flow concentration in the Grid-GA model. Depressions storing water is usually ignored because of using D8 method in sinks filled module of hydrological process modeling. Consequently, runoff hydrographs are overestimated and flood peak time advances in several time due to removing the depressions.

In the last twenties years, kinematic wave model has been applied for overland flow routing (Cundy and Tento, 1985; Govindaraju et al., 1992; Tayfur et al., 1993; Giráldez and Woolhiser, 1996; Woolhiser, 1996; Tayfur and Kavvas, 1998; Tayfur, 2001; Singh, 1996, 2001; Liu et al., 2004; Mohammadian et al., 2004; Tayfur and Singh, 2006, 2007). One-dimensional kinematic wave model is used to simulate overland flow process with assuming one-dimensional slope with smooth and uniform surface.

However, the process of runoff generation on a hillslope with a complex topography should be calculated such that the process of flow concentration is adequately represented (Liu et al., 2004). Obviously, one-dimensional kinematic wave model is inadequate to properly simulate the direction of overland flow routing, and two-dimensional kinematic wave model is needed. Singh presented that routing overland flow with explicit finite difference kinematic wave model tends to instable (Singh et al., 2002).

In this paper, two-dimensional implicit finite difference kinematic wave model is introduced to solve catchment sinks storing water for grid-based concentration of overland flow routing. A grid-and-Green-Ampt-and-two-dimensional-kinematic-wave-based distributed hydrological physical model (Grid-GA-2D model) coupling Green-Ampt infiltration physical method and two dimensional overland flow routing model based on kinematic wave theory was developed for flood simulation and forecast with using GIS technology and digital elevation model (DEM). Taking into consideration the soil moisture redistribution at hillslope, Green-Ampt infiltration physical method is applied for grid-based runoff generation in the Grid-GA-2D model. In the Grid-GA model, one-dimensional kinematic wave model is instead of Muskingum-Cunge method for flow concentration in this paper. In the end, the Grid-GA-2D model, the Grid-GA model and Shanbei model (Zhao, 1983) were applied in the upper reaches of the Qin River above Kongjiapo station, a tributary of the Yellow River, to investigate the reliability and improvement of the developed model.

2 Study catchment

In order to investigate the applicability of the Grid-GA-2D model, it was applied to the upper reaches of the Qin River above Kongjiapo station, a tributary of the Yellow River. The Grid-GA model and the Shanbei model were also applied for comparison. The control area of Kongjiapo station is 1454 km^2 and is located between latitudes 36.18° N and 37.00° N and longitudes 111.95° E and 112.56° E. The Qin River is located in the subtropical monsoon zone, which is the continental monsoon significant, with four distinct seasons. The studied catchment average annual precipitation is 544 mm, 67.8 % of which is within the period of the flood season (June–September). Three rainfall stations and one hydrological station are available in the Kongjiapo catchment. Figure 1 shows the sketch of the upper reaches of the Qin River above Kongjiapo station.

3 The Grid-GA-2D model

3.1 Grid-GA model

The Grid-GA model adopts grids for the DEM as computational elements for distributed rainfall-runoff modeling with each element consisting of a runoff generation component and a grid-based flow routing component. Evaporation, runoff yield, and flow concentration in every pixel are calculated based on the related modules (Wang et al., 2010b). Outlet flow of each grid to the outlet of the whole catchment is routed from cell to cell using Muskingum-Cunge method based on the calculated order with the DEM grid cells elevation. During the calculated modules of runoff yield and runoff concentration in every computational element, reinfiltration at hillslope is taken into consideration (Wang, 2010).

Taking into consideration the soil moisture redistribution at hillslope, Green-Ampt infiltration physical method was applied for grid-based runoff generation and Muskingum-Cunge method was used for flow concentration from cell to cell. In this paper, one-dimensional kinematic wave model is applied to substitute Muskingum-Cunge method.

3.2 Grid-GA-2D model

The influence of microtopography on the hydrological response of natural catchments is significant (Singh and Frevert, 2002). Some depressions in the overland storing water for some time during rainfall after ponding occur. This water is retained on the surface and is ultimately evaporated or infiltrated (Cappelaere et al., 2003).

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In most of distributed hydrological models, sinks are considered as spurious features with single direction methods in the filled sinks module and, as a result, these models do not deal with the sinks that represent real depressions. Consequently, the runoff hydrographs are overestimated due to removing the depressions (Wang et al., 2009). Therefore, watershed retention of surface runoff cannot be ignored.

To solve this problem, this paper introduced two-dimensional implicit finite difference kinematic wave model in the Grid-GA-2D model in the concentration of overland flow routing. The Grid-GA-2D model is developed with coupling Green-Ampt infiltration method and two dimensional overland flow routing model based on kinematic wave theory. The errors contained in the DEM data is corrected with ANUDEM method (Hutchinson, 2004; Zhang et al., 2005). As the runoff generation module is the same as that of the Grid-GA model (Wang, 2010; Wang et al., 2010a, b), here two-dimensional overland flow routing based on kinematic wave theory was just described.

3.3 Two-dimensional overland flow routing based on kinematic wave theory

Once the retention storage in a grid cell is filled by excess rainfall, overland flow occurs. As shown in Fig. 2, only a few grids have single flow direction.

Figure 3a is the partly original DEM data of the upper reaches of the Qin River above Kongjiapo station. From the figure, the elevation of the central grid is the lowest in that of all grids. The elevation of the central one ought to be added with D8 method in sinks filled module of most distributed hydrological modeling including the Grid-GA model, which results in grid flow can be out of the central grid with single direction (shown in Fig. 3b and c). However, for the contribution for the hydrograph of the catchment outlet, depressions water storing capability is neglected in this hydrological modeling process. In this paper, two-directional model (Singh and Frevert, 2002) was introduced for taking into consideration sinks water storing. The sinks in DEMs were calculated as a reservoir, so the flow can routing out of the central grid while the water stage being above that of the other grid (shown in Fig. 3d).

3.3.1 Overland flow governing equations

The Saint-Venant equations with the continuity equation and momentum equation were used to describe the governing equation of overland flow. In the last ten years, some researcher applied explicit finite difference diffusion wave theory to route overland flow and proved the results tend to instable (Singh et al., 2002). Overland flow model based on kinematic wave theory can perform enough precision in flood simulation and forecasting (Rui et al., 2008; Rui and Jiang, 2010). In the Grid-GA-2D model, two-dimensional implicit finite difference kinematic wave model was applied to describe the governing equation of overland flow. Expressed as the two partial differential equations in the form of Eqs. (1), (2) and (3) (Taky et al., 2009).

The governing equation for the overland flow is a two-dimensional continuity equation:

$$\frac{\partial h}{\partial t}+\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}=r_{\mathrm{e}} \tag{1}$$

where h is the depth of overland flow, q_x is the unit discharge in the x-direction, q_y is the unit discharge in the y-direction, $r_{\mathrm{e}} = P_e - f$, is excess rainfall rate , P_e is the net rainfall rate and f is the infiltration rate. The net rainfall is the total of infiltrated rainfall and excess rainfall for overland flow with net rainfall rate being above on infiltration rate.

Momentum equation:

$$x\text{ direction}: \frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=g\left(S_{\mathrm{o}x}-S_{\mathrm{f}x}-\frac{\partial h}{\partial x}\right) \tag{2}$$

$$y\text{ direction}: \frac{\partial u}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=g\left(S_{\mathrm{o}y}-S_{\mathrm{f}y}-\frac{\partial h}{\partial y}\right) \tag{3}$$

where $S_{\mathrm{o}(x,y)}$ is the land surface slopes in the x-and-y-directions, $S_{\mathrm{f}(x,y)}$ is the friction slopes in the x- and-y-directions, u, v are respectively the average velocity in the x-and-y-directions, in units $\mathrm{m\,s^{-1}}$, g is the acceleration of gravity, in units $\mathrm{m\,s^{-2}}$.

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Eqs. (2) and (3) reveal the force of unit quality water suffered and the relationship between the specified direction of flow and its acceleration. For a given x or y direction, equation by the right is the force of per unit quality flow suffered, and in the left side of equation there is the acceleration produced by Flow velocity in time and space. In accordance with the kinematic wave theory, ignoring the inertia term and the pressure term in the Saint-Venant equation, Eqs. (2) and (3) can be simplified to obtain kinematic wave equation, as following:

$$S_{fx} = S_{ox} \tag{4}$$

$$S_{fy} = S_{oy} \tag{5}$$

Where S_{ox} and S_{oy} are the land surface slopes in the x- and y- direction, respectively, and are calculated from DEM data. S_{fx} and S_{fy} are the friction slopes in the x- and y-direction, respectively.

The unit discharge in the x-direction q_x is defined using a general resistance form:

$$q_x = \alpha_x h^{\beta} \tag{6}$$

Similarly, in the y-direction q_y:

$$q_y = \alpha_y h^{\beta} \tag{7}$$

For the Manning equation β is a constant (Maidment, 1993), and the terms α_x, α_y are defined as:

$$\alpha_x = \frac{1}{n}|S_{0x}|^{1/2}\frac{S_{0x}}{|S_{0x}|} \tag{8}$$

$$\alpha_y = \frac{1}{n}|S_{0y}|^{1/2}\frac{S_{0y}}{|S_{0y}|} \tag{9}$$

$$\beta = 5/3 \tag{10}$$

where n is the Manning roughness coefficient. The terms $(S_{fy}/|S_{fy}|)$ and $(S_{fx}/|S_{fx}|)$ in Eqs. (8) and (9) are used to determine the direction of the flow.

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3.3.2 Calculation of two dimensional kinematic wave model

The Grid-GA-2D model used a grid where each grid cell ia sssumed a homogenous unit with one representative value for any hydraulic or hydrological parameter (e.g., roughness coefficient, infiltration parameter, land use parameter, etc.). Figure 4 is the sketch of DEM grid in two-dimension kinematic wave model.

For a grid unit, its principle of mass conservation can be described that the variation of the grid cell water volume is the difference between inflow and outflow in the dt time. Overland grid-based flow is calculated for the whole catchment with the principle of mass conservation in the Grid-GA-2D model.

Calculation of h in the Eqs. (6) and (7) is following.

For x or y direction, the continuity equation of the Saint-Venant equations can be simplified based on kinematic wave theory.

$$B\frac{\partial h}{\partial t}+\frac{\partial}{\partial x}\left(\frac{Bh}{n}R^{2/3}\sqrt{S_0}\right)=P_e(x,t) \quad (11)$$

where B is water width, L is channel length, $P_e(x,t)$ is the net rainfall rate. Overland flow can be simplified as the flow of wide and shallow channel, thus the hydraulic radius (R) is approximately equal to the water depth (h). Therefore, Eq. (11) can be written as

$$B\frac{\partial h}{\partial t}+\frac{B\sqrt{S_0}}{n}\frac{\partial}{\partial x}\left(h^{5/3}\right)=P_e(x,t) \quad (12)$$

Through to discretize Eq. (12) with the four-point implicit finite-difference scheme, the following equation can be shown.

$$\left(h^{5/3}\right)_{i+1}^{j+1}-\left(h^{5/3}\right)_{i}^{j+1}+D_1\left(h_{i+1}^{j+1}+h_i^{j+1}\right)=D_2 \quad (13)$$

Where

$$\left.\begin{array}{l} D_1=\frac{n}{\sqrt{S_0}}\cdot\frac{\Delta x}{2\Delta t\theta} \\ D_2=\frac{n\Delta x}{2\theta B\sqrt{S_0}}\left((P_e)_{i+1}^j+(P_e)_i^j\right)-\frac{1-\theta}{\theta}\left((h_{i+1}^j)^{5/3}-(h_i^j)^{5/3}\right)+\frac{n\Delta x}{2\theta\Delta t\sqrt{S_0}}\left(h_{i+1}^j+h_i^j\right) \end{array}\right\} \quad (14)$$

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Assuming when the tth time $t=0$, $h_i^0=0$ is the initial condition.
Meanwhile, $h_0^j=\text{known}$ is the upstream boundary condition.
So for $j=0$, the following equations can be shown.

$$\begin{cases} \left(h_1^1\right)^{5/3}-\left(h_0^1\right)^{5/3}+D_1\left(h_1^1+h_0^1\right)=D_2|_0^0 \\ \left(h_2^1\right)^{5/3}-\left(h_1^1\right)^{5/3}+D_1\left(h_2^1+h_1^1\right)=D_2|_1^0 \\ \ldots\ldots \\ \left(h_N^1\right)^{5/3}-\left(h_{N-1}^1\right)^{5/3}+D_1\left(h_N^1+h_{N-1}^1\right)=D_2|_{N-1}^0 \end{cases} \quad (15)$$

where $N=L/\Delta x$ is iteration number. According to Eqs. (13) and (14), D_1 and D_2 can be calculated. Substituting the upstream boundary condition into Eq. (15), we get the following equation.

$$\left(h_1^1\right)^{5/3}+D_1 h_1^1=\beta_1 \quad (16)$$

where

$$\beta_1=D_2|_0^0+\left(h_0^1\right)^{5/3}-D_1 h_0^1 \quad (17)$$

Assuming the calculated runoff depth is z, so the following equation can be shown.

$$f(x)=D_1 x-\beta_1+(z)^{5/3} \quad (18)$$

h_1^1 can be calculated by bifurcated approach (Wang, 2010). In a similar way, according to Eq. (15), runoff depth of every grid unit can be obtained and every grid discharge can be calculated by Manning formula in the studied catchment.

Flow direction is based on friction slopes in the kinematic wave model.

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$$x \text{ direction}: S_{fx}^{t}(k-1 \to k) = S_{0x}(k-1 \to k) \tag{19}$$

$$y \text{ direction}: S_{fy}^{t}(j-1 \to j) = S_{0y}(j-1 \to k) \tag{20}$$

where S_{0x} and S_{0y} can be calculated by DEM data.

$$S_{ox}(k-1,k) = \frac{E(j,k-1) - E(j,k)}{B} \tag{21}$$

$$S_{oy}(j-1,j) = \frac{E(j-1,k) - E(j,k)}{B} \tag{22}$$

where $E(j,k)$, $E(j,k-1)$ and $E(j-1,k)$ is the elevation of grid units. The unit discharge in the x-direction between grid cell $(j\ ,k-1)$ and (j,k).

If $S_{ox}^{t}(k-1 \to k) \geq 0,$ then

$$q_x^t(k-1 \to k) = \frac{1}{n(j,k-1)}\left[h^t(j,k-1)\right]^{5/3}\left[S_{ox}^t(k-1 \to k)\right]^{1/2} \tag{23}$$

If $S_{fx}^{t}(k-1 \to k) < 0,$ then

$$q_x^t(k-1 \to k) = \frac{-1}{n(j,k-1)}\left[h^t(j,k-1)\right]^{5/3}\left[-S_{ox}^t(k-1 \to k)\right]^{1/2} \tag{24}$$

Similarly, $q_x^t(k \to k+1), q_y^t(j \to j+1), q_y^t(j-1 \to j)$ can be calculated.

In the Grid-GA-2D model, flow concentration parameter is roughness coefficient. According to the global DEM data resolution of $3'' \times 3''$ provided by CIAT (2004) and the land use data reolution of of $30'' \times 30''$ provided by UMD (1998), the Kongjiapo catchment was extracted. The types of land use are reclassified into four main types: forest, grassland, cropland, and water for getting roughness coefficient value (Yao et al., 2009) (Fig. 5 Land use map of the upper reaches of the Qin River above Kongjiapo station).

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4 Application of models

4.1 Application and comparison with Shanbei model

In order to verify the applicability of the Grid-GA-2D model, it was applied to the upper reaches of the Qin River above Kongjiapo station for flood simulation. The Grid-GA model and Shanbei model were used for comparison. Ten representative flood events from 1958 to 2001 are selected. Flood events from 1958 to 1988 were applied for models calibration and the other three events were used to verify the models in the studied catchment. As flood occurs usually flash with short-time in semi-arid, the time step is one of the most important factors in flood simulation and forecasting (Singh and Frevert, 2002; Wang et al., 2010b). In this paper, the time step is 1 h due to the data constraints in Kongjiapo catchment. Table 2 is simulated results of ten representative flood events in Kongjiapo catchment. The statistic values of models results consist of the relative error of flood volume, the relative error of flood peak discharge, the peak time error and the Nash coefficient, i.e., the coefficient if determination. The parameters of the Shanbei model and the Grid-GA model were calibrated by the SCE-UA method (Duan et al., 1992, 1993, 1994; Bao et al., 2010). More details about parameter estimation of the two models can be referred to Wang (2010). For runoff generation parameters, the Grid-GA-2D model agrees with the Grid-GA model.

For the Grid-GA-2D model and the Grid-GA model, most peak flows of simulated flood events were overestimated, probably because of the theory of runoff generation mechanism, since the two grid-based distributed hydrological models assumes the generation of overland flow as precipitation is over the infiltration rate. The mean value of peak discharge simulated by the Grid-GA-2D model and the Grid-GA model is better obviously than that of the Shanbei model. From Table 2, for the relative error of flood volume, the peak time error and the Nash coefficient, the two grid-based distributed hydrological models performed is as well as the Shanbei model. This proves the advantage of excess infiltration mechanism in simulating flood hydrograph, especially peak flows simulation in semi-arid catchment.

4.2 Comparison of the Grid-GA-2D model and the Grid-GA model

For the advantages of GIS technology, DEM and excess infiltration mechanism, the Grid-GA-2D model and the Grid-GA model performed well in simulating observed flood thin hydrograph in Kongjiapo catchment. The two distributed hydrological models obtained the closed accuracy in the relative error of flood volume and the Nash coefficient of all flood events, but the Grid-GA-2D model performed significantly better in flood peak discharge and peak time simulation than that of the Grid-GA model (Fig. 6 is the two grid-based hydrological models simulated discharge hydrograph of FloodNo. 19930803). The reason is depressions storing water in the catchment overland is neglected because of using single direction with D8 method in sinks filled module of hydrological process modeling, which results in flood peak discharge overestimating and peak time advances from zero to three hours. It is serious for flood simulation and forecasting in semi-arid catchment. In the Grid-GA-2D model, two-dimensional implicit finite difference kinematic wave model was introduced to solve catchment depressions storing water for grid-based concentration of overland flow routing, so the relative error of flood peak discharge and the peak time error is 7.6 %, 0.4 h, respectively. Wherever, the relative error of flood peak discharge and the peak time error simulated by the Grid-GA model is 12.9 %, 1 h, respectively. It proves the reliability and improvement of the developed Grid-GA-2D model. The modeled hydrographs drop too quickly for the flood recession period. The reason is that interflow is present in Kongjiapo catchment and interflow routing module is missed in the Grid-GA model and the Grid-GA-2D model. In the further study, a interflow routing model would be introduced into the Grid-GA-2D model. As kinematic wave models were applied for flow concentration in the two grid-based distributed hydrological models, water stage hydrograph of the studied catchment outlet can be obtained. For lack of water stage observed data, only the simulated water stage hydrograph of FloodNo. 19820801 was described (Fig. 7 is the water stage hydrograph of FloodNo. 19820801 simulated by the Grid-GA-2D model and the Grid-GA model).

5 Conclusions

In this paper, the grid-and-Green-Ampt-and-two-dimensional-kinematic-wave-based distributed hydrological physical model (Grid-GA-2D model) coupling Green-Ampt infiltration physical method and two dimensional overland flow routing model based on kinematic wave theory for flood simulation and forecast with using GIS technology and DEM. Two-dimensional implicit finite difference kinematic wave model was introduced to solve depressions storing water of catchments overland for grid-based concentration of overland flow routing. In order to investigate the reliability and improvement of the Grid-GA-2D model, the Grid-GA model and the Shanbei model were also employed for comparison in the upper reaches of the Qin River above Kongjiapo station.

Depressions storing water of overland flow routing was taken into consider, so the Grid-GA-2D model perform higher accuracy, especially in flood peak discharge and peak time simulation than that of the Grid-GA model in semi-arid catchment. Compared with the conceptual Shanbei model, advantages of the two grid-and-excess-infiltration-mechanism-based distributed hydrological models show obviously flood simulation and forecasting. However, due to the runoff generation mechanisms include saturation excess in semi-arid catchment, possibilities for introducing a saturation excess mechanism package in order to improve the simulation precision of the Grid-GA-2D model and the Grid-GA model should be addressed in a further study.

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Table 1. Calibrated parameter values of flow concentration.

Land Use	Index of land Use	Roughness coefficient (n)
Forest	1	0.1
Water	2	0
Cropland	3	0.035
Grassland	4	0.17

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Table 2. Simulated results of flood events in Kongjiapo station.

	Flood No.	Precipitation (mm)	Peak flow ($m^3 s^{-1}$)	Relative error of flood volume (%)			Relative error of flood peak (%)			Peak time error (h)			Nash coefficient		
				GGA2	GGA	Shanb	GGA2	GGA	Shanb	GGA2	GGA	Shanb	GGA2	GGA	Shanb
Calibration	19580802	28.9	280	−12.1	−11.5	−9.7	7.2	18.1	−20.3	0	1	−1	0.82	0.79	0.83
	19640713	28.5	264	−17.2	−17.7	6.7	−5.2	12.6	−14.9	1	2	−2	0.79	0.74	0.81
	19750725	68.6	205	15.1	21.3	15.7	10.2	25.2	−20.3	0	1	−1	0.72	0.62	0.71
	19810815	82.7	380	−13.0	−11.2	11.3	−11.2	−10.6	−13.1	−1	0	1	0.81	0.83	0.81
	19820801	72.1	214	16.4	23.1	20.8	8.5	15.7	−12.7	0	1	−1	0.71	0.62	0.71
	19850913	116.3	1026	−13.2	−9.9	−17.2	2.0	11.2	−13.2	0	0	−1	0.94	0.92	0.86
	19880813	79.9	613	−12.1	−6.2	−13.3	−11.5	−7.8	17	1	1	1	0.76	0.78	0.72
Validation	19930803	147.5	2070	−8.6	−8.9	−8.9	0.3	10.1	18.2	0	0	1	0.92	0.88	0.87
	19960804	59.3	269	−2.2	6.7	9.5	−14.1	−8.5	11.1	1	3	−2	0.86	0.87	0.83
	20010726	50.1	390	−34.6	−27.5	33.1	5.4	8.9	12.9	0	1	−1	0.82	0.86	0.78
	Mean value			14.5	14.5	14.6	7.6	12.9	15.4	0.4	1	1.2	0.82	0.79	0.79

Notes: GGA2 – the Grid-GA-2D model, GGGA – the Grid-GA model, Shanb – Shanbei model.

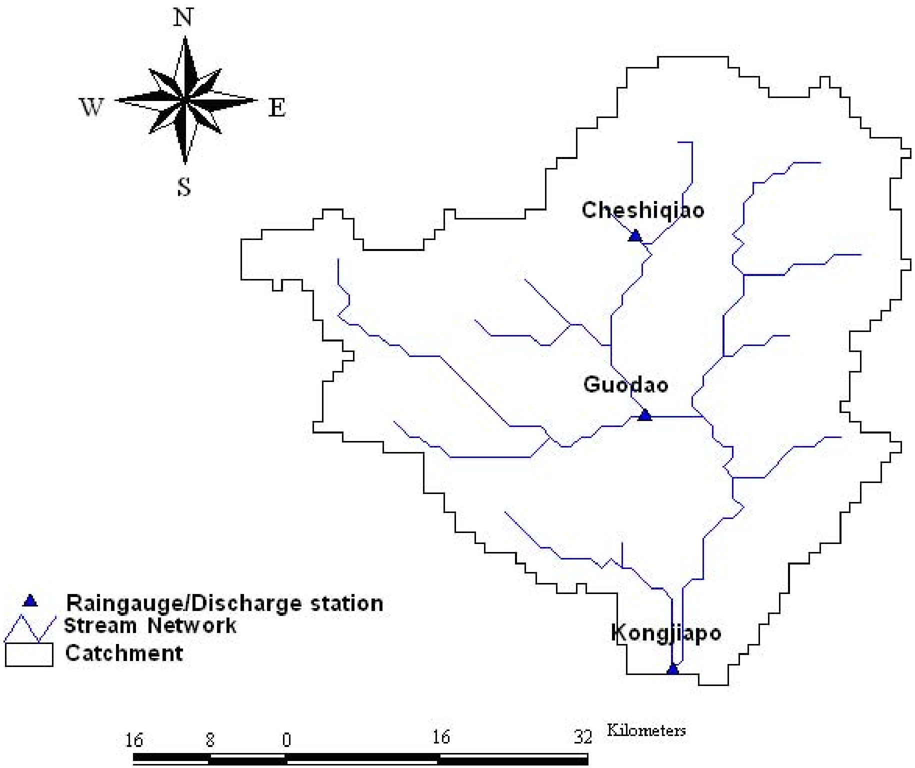

Fig. 1. Sketch of the upper reaches of the Qin River above Kongjiapo station.

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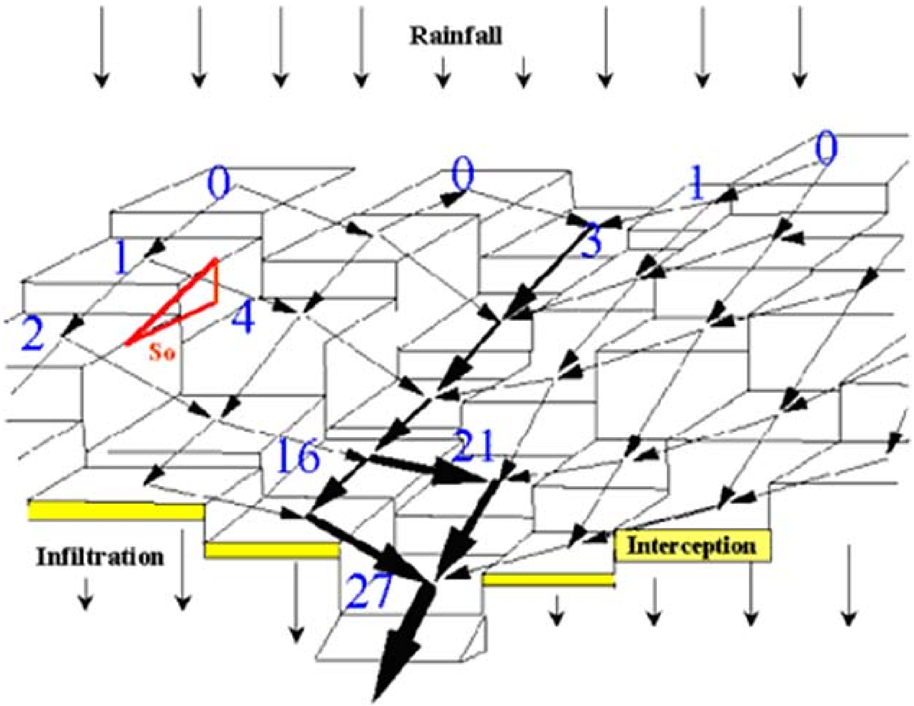

Fig. 2. Schematic representation of overland flow routiong. Note: the surface shown is the water surface.

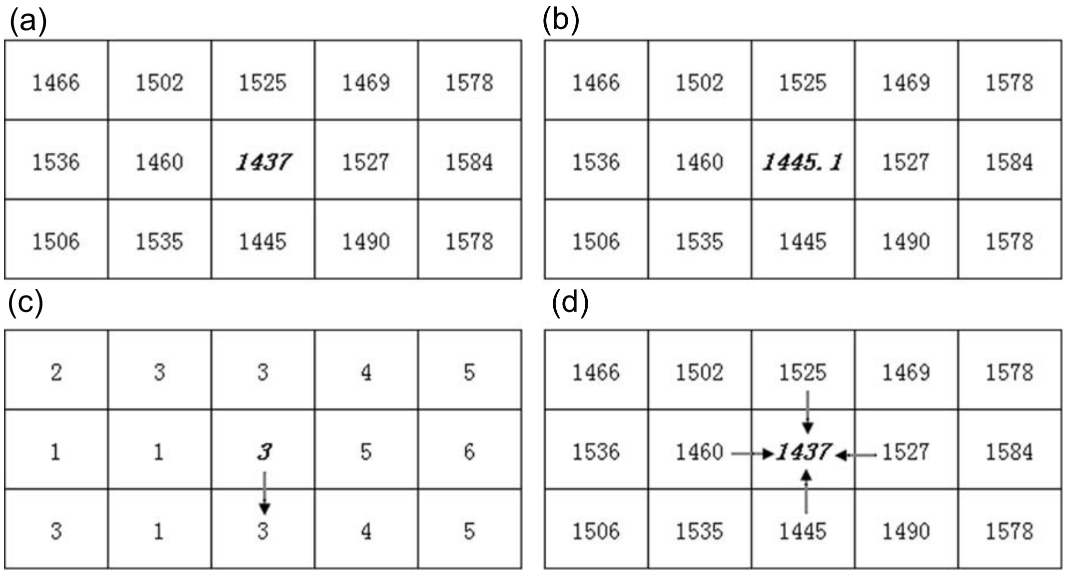

Fig. 3. (a) The original DEM data, **(b)** filled DEM data with D8 method, **(c)** flow direction with D8 method, **(d)** two dimension flow direction with the original DEM data.

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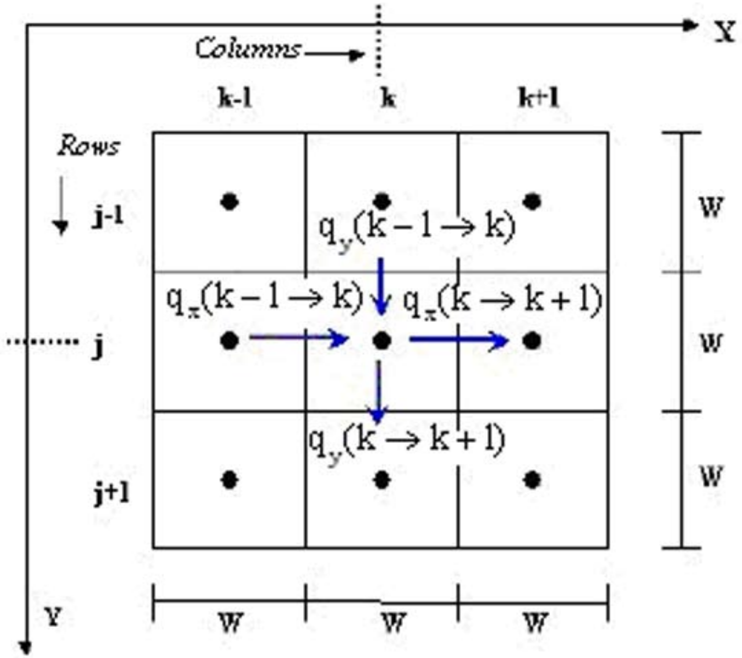

Fig. 4. Sketch of DEM grid in two-dimension kinematic wave model.

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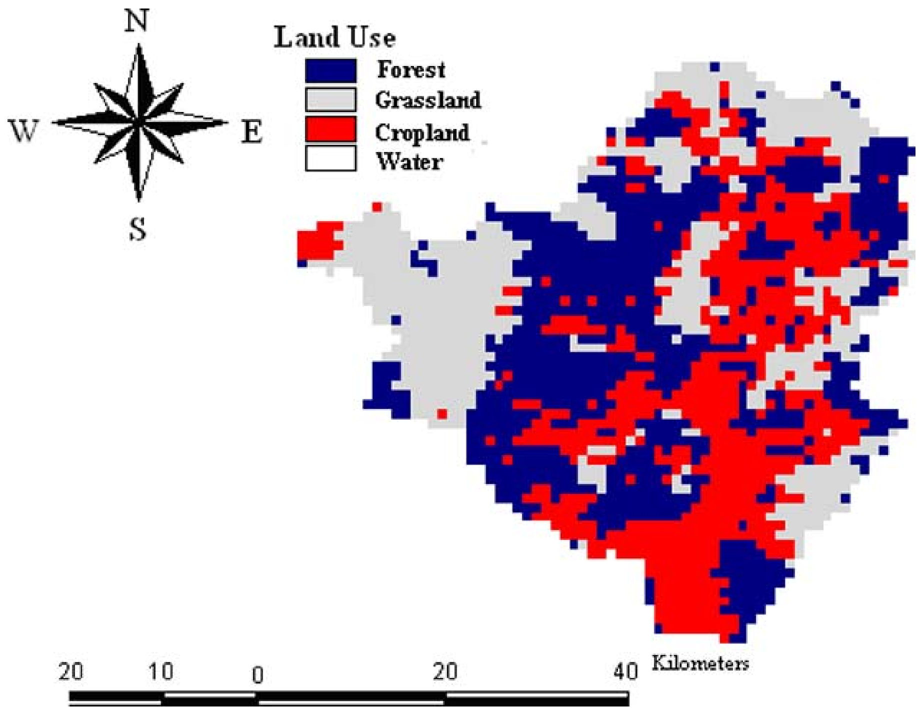

Fig. 5. Land use map of the upper reaches of the Qin River above Kongjiapo station.

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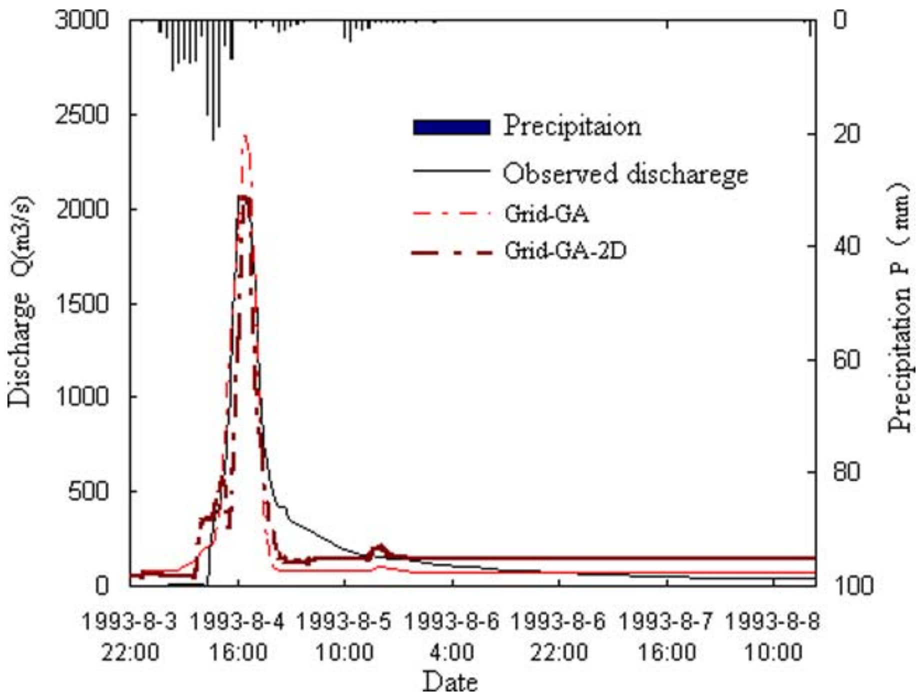

Fig. 6. Model results of FloodNo. 19930803.

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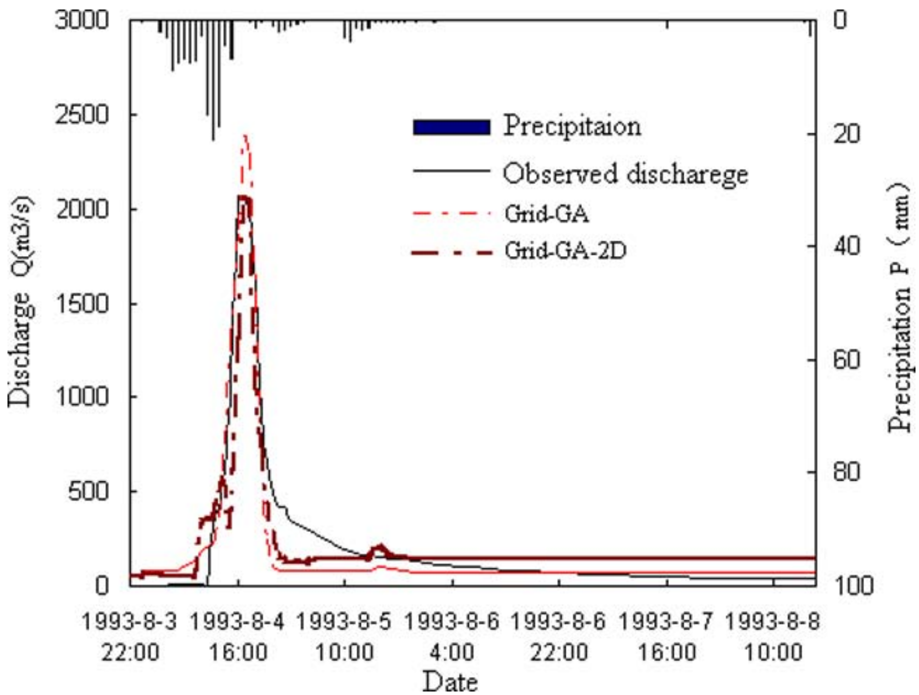

Fig. 7. Model results of FloodNo. 19820801.

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