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Assessing the effects of different cropping patterns on drainage capability of the southern riverine basin

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Abstract Compared with natural watersheds, only a few studies have been conducted to take the specific characteristics of farmed watersheds into account in hydrological modelling. The purpose of this paper is to develop a conceptual rainfall–runoff model with which both the impact of human activities on flood events and the effects of different cropping patterns on drainage capability of the southern riverine basin could be assessed, especially the existence of drainage practices and ditch networks. Applications of the model are demonstrated for Luoshan drainage basin, which is located in Hubei Province. To analyse the role of cropping patterns, six hypothetical scenarios are discussed. Results show that the drainage system of Luoshan drainage basin can dispose of the excess water from 3-day rainfall totals, with return periods of 6.9 years in five days and with the area of paddy fields being increased, the drainage capability would be strengthened.

Key words cropping patterns; drainage capability; rainfall–runoff model; Luoshan

INTRODUCTION

Most runoff simulation models have been developed at the global-catchment scale or at the local-soil column scale. Few models have been specifically designed for agricultural fields. Compared with natural catchments, farmed catchments, such as irrigation areas and drainage areas, have very different hydrological processes. On farmed catchments, human activities such as agricultural land use, management practices, and crop stages can be significant factors in controlling flood generation. In addition, other factors, including the operating regulations of drainage sluices and pumps and the ditch network, also influence flood routing. These factors must be taken into account in hydrological modelling.

The existing models for simulating hydrological processes in agricultural catchments can be classified into three groups: physically based models (Dunn & Mackay, 1996; Moussa *et al.*, 2002; Jia *et al.*, 2005), conceptual models (Xia & Liu, 1995; Castro *et al.*, 1999), and empirical relations (Chahinian *et al.*, 2005). These models provide a good platform for this study. In this paper, a conceptual hydrological model is designed which takes the effects of crop growth, management practices, and internal drainage systems on hydrological processes into account. It is therefore suitable for evaluating the effects of cropping pattern changes on drainage capability of a large-scale drainage basin.

Model description

A large-scale drainage basin generally consists of a field drainage system and a main drainage system. Internal drainage pumping stations, field ditches and diversion ditches are the part of the field drainage system that first picks up water from the low-lying regions and then removes it to sub-ditches. The main drainage system consists of lakes, main ditches, sub-ditches, exterior drainage pumping stations, and drainage sluices, etc. The function of it is to route water through the basin to the outlet.

Drainage basins can be subdivided into several sub-basins according to the geographical information and the characteristics of the drainage system. The modelling starts with simulating and routing the runoff through the sub-basin, and then simulates the discharge of internal drainage pumping stations according to need. The results are input into the hydrodynamic model, which is adopted to transport flow through the main drainage system as upstream boundary conditions or lateral inflow. A general description of each procedure is given.

Simulation of runoff generation

Since different land uses correspond to different hydrological characteristics, different methods are therefore used. Due to the actual land uses in the study area, four different methods are adopted here.

The water budget on paddy fields is simulated by the monolayer soil-structure Tank model with a surface water layer (Fig. 1). The paddy vertical structure is divided into two layers: the surface water layer and the soil layer. In the surface water layer, the paddy storage depth *HW* in surface water layer rises with rainfall *P* and diminishes with actual evaporation *E*, surface drainage *DW* and infiltration to the soil layer *FW*. *DW* is a function of *HW* and drainage threshold *OH*, which is equal to the highest permissible depth, a function of breeds and stage of growth. *FW* is considered as a constant. A conceptual TANK model is employed to simulate the runoff in the soil layer. The model has two lateral holes and one bottom hole, which represent the outlet of surface runoff, interflow and groundwater runoff, respectively. The storage depth of soil layer *HS* rises with *FW* and diminishes with evapotranspiration *ET*, surface runoff *RS*, interflow *RI*, and groundwater flow *FS*. The maximum tensional storage of soil layer *WM*, controlling coefficient of surface runoff H_1 and controlling coefficient of interflow H_2 are parameters that represent the volume of groundwater, surface runoff and interflow, respectively. The outflow coefficient of surface runoff *KS*, interflow *KI*, and groundwater runoff *KG* are parameters that greatly influence the shape of the stream line.

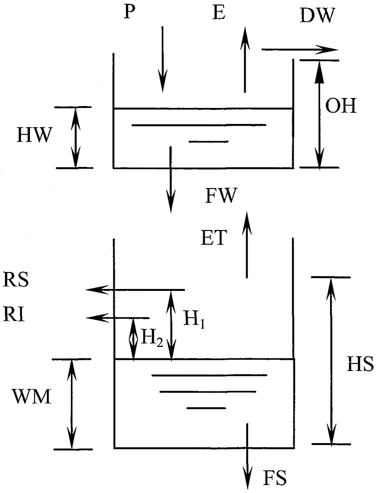

Fig. 1 Vertical water budget of paddy fields.

In this study, QualHYMO modelling is used to simulate the runoff of dry lands and grass lands. QualHYMO (1985) is a continuous hydrological model developed from HYMO by Williams & Hahn (1973), and is especially suitable for rural basins undergoing urbanization or agricultural areas. A detailed discussion of the model can be found in Caterina *et al.* (2001). The model has four calibration parameters, i.e. $S_{\min}$, $S_{\max}$, S_k and API_k. $S_{\min}$ and $S_{\max}$ represent the range of the maximum catchment retention. S_k is a calibration parameter in the API method. API_k is the antecedent precipitation index constant.

Special land uses such as lakes, polders or retention areas are simulated by a single reservoir. Once the water level of the reservoir exceeds the maximum level, all the rainfall is transformed into surface runoff, otherwise no runoff is generated. Evaporation is taken out from the water volume of that reservoir at the beginning. For other impermeable areas such as urban areas, runoff is generated immediately, as long as rainfall rate is greater than evaporation rate. Finally, the total runoff from the sub-basin is the weighted sum, as a function of their respective areas.

The Williams unit hydrograph is used as the transfer function to route surface runoff and interflow to sub-ditches or internal drainage pumping stations in this study. The time to peak t_p and the recession constant x_k are the two parameters to be calibrated. As for the groundwater runoff, a linear reservoir model is adopted to calculate its flow, and the recession coefficient kgg is a calibration parameter.

Discharge simulation of internal drainage pumping stations

The spatial distribution of internal drainage pumping stations is dotted casually, each of them operating independently of the other. For the convenience of the study, based on practice the following assumptions are adopted: (a) all the internal drainage pumping stations in one sub-basin are generalized as one internal drainage pumping station; (b) the discharge of the generalized internal drainage pumping station is the bilinear function of volume of waterlogging. Based on the hypothesis above, at time t, the discharge of the internal drainage pumping station QO_t can be described as:

$$QO_t = QI_t - dV_t/dt = \begin{cases} \sigma V_{\max} & V_t < V_{\max} \\ Q_{\max} & V_t \geq V_{\max} \end{cases} \tag{1}$$

where QI_t represents the inflow output from the runoff generation models. V_t is the volume of waterlogging; σ is the discharge constant, a parameter to be calibrated; $V_{\max}$ is the threshold of the volume of waterlogging, when the actual volume of waterlogging is greater than the threshold, the drainage capability of the internal drainage pumping station reaches its maximum.

Numerical simulation of flow-routing

The flow conditions in a drainage system vary with time, which can be determined by proper hydrodynamic models. In this study, St Venant equations are employed for numerical simulation of one-dimensional (1-D) unsteady open channel flow. The 4-point operators Preissmann implicit finite difference scheme is used here. While St Venant equations are inapplicable to flow conditions since as flow through sluices and pumping stations, special hydraulic equations replaced by the corresponding Taylor's expansions when doing numerical simulation are used; they are called initial boundary conditions. The discharge of a sluice is a function of the number of opened gates, the gate opening, and the upstream and downstream water level. Pumping stations play an important role in reducing the water levels of the main ditch. The discharge of an exterior drainage pumping station is a function of the operating units and lift head. For an intricate network of drainage ditches, there must be many junctions. At each junction, the continuity equation and the dynamic equation should be met.

St Venant equations and junction equations with proper initial and boundary conditions constitute the mathematical model for unsteady flow in the unsteady open-channel network.

APPLICATION

Description of the study area

Luoshan drainage basin is located in Sihu region of Hubei province. The 935-km^2 drainage basin is the lowest region in Jianli County. There are three precipitation stations: Luoshan Station, Chiba Station and Zhuhe Station. The drainage system is formed by man-made sub-ditches, one main ditch named Luoshan Ditch, two exterior drainage pumping stations, two generally closed drainage sluices, and lots of internal drainage pumping stations (Fig. 2). The total design discharges of the two exterior drainage pumping stations are 210 m^3 s^{-1}. The total design discharges of internal drainage pumping stations are 126.6 $m^3 s^{-1}$ and the total installed capacities are 13 495 kW, serving a total area of about 378.8 km^2.

Along with the development of the economy and the change of policy, the area of paddy fields increased at the expense of dry lands. The planting area of medium rice also increased at the expense of early and late-season rice. In order to answer how cropping patterns affect the drainage capability of the Luoshan drainage basin, six scenarios were designed, based on data in hand, which can be divided into two sets (Table 1). In Set A, how the drainage capability changes with the change of proportion of the area of paddy fields to the area of dry lands is analysed when all the other factors remain unchanged. In Set B, how the drainage capability changes with the change of the planting area of the medium rice is studied, still supposing all the other factors remain unchanged. At present, the area of paddy fields accounts for 58.7%, and the area of dry lands accounts for 41.3% of the total arable area. The planting area of early-season rice, medium rice and late-season rice is 16.3%, 71.6% and 28.4%, respectively. Therefore, Scenario A2 and B2 correspond to the present.

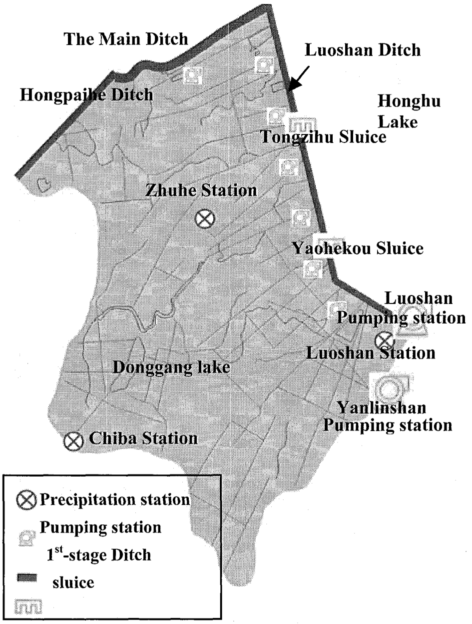

Fig. 2 Diagram of Luoshan drainage basin system.

Table 1 Six Scenarios of cropping patterns (%).

Scenario	Set A paddy fields	dry lands	Scenario	Set B Medium rice	Early-season rice	Late-season rice
A1	20.0	80.0	B1	30.0	59.0	70.0
A2	58.7	41.3	B2	71.6	16.3	28.4
A3	80.0	20.0	B3	100.0	0.0	0.0

Model parameterization and calibration

The model contains many parameters, which reflect geometrical and soil characteristics, land use, etc. Some of them can be obtained by field observations, and the others need to be calibrated. In this study, 14 parameters are calibrated. The adaptive genetic algorithm developed by Zhang (Zhang & Hu, 2002) is used for optimization algorithms. In the algorithms, genetic parameters are regulated adaptively based on population diversity, which is determined according to the similarity of chromosomes. The RMSE between observed and simulated upstream water levels of the Luoshan pumping station and the Yanlinshan pumping station is used as the objective function. The input data is daily hydrological and meteorological data extracted from 1979 to 2004, the water budget model for runoff generation runs with a daily time interval, and the flow routing model runs with a 3-hour time interval.

Due to the absence of detailed measurements of the drainage basin, there is no consistent way to verify the values of the parameters, but the ranges of parameter values can be obtained by analysing the spatial properties and data gathered. The parameter WM represents the maximum tensional storage, and its value is <100 mm and >40 mm. Through the observation in paddy fields, H_1 and H_2 are generally less than 20 mm. The ranges of the parameters $S_{\min}$ and $S_{\max}$ can be estimated from the SCS curve number. The parameters t_p and x_k define the shape of the Williams unit hydrograph, therefore their ranges can be analysed from typical flood events. Parameter σ represents the relationship between water levels and the discharges of the internal drainage pumping station. By analysing this relationship, the range of its value can be determined. Based on related literature, the other ranges of parameter values are set. Only the value within the range is accepted. The results are listed in Table 2. The Nash-Sutcliffe coefficient used to evaluate model efficiency is generally superior to 0.75, reflecting a relatively good agreement between observed and calculated hydrographs.

Table 2 Calibrated values of parameters.

name	WM (mm)	KS	KI	KG	H_1 (mm)	H_2 (mm)	$S_{\min}$ (mm)
value	50	0.32	0.24	0.09	12	8	10
name	$S_{\max}$ (mm)	S_k	API_k	t_p	x_k	kgg	σ
value	70	0.02	0.9	28	20	0.96	0.35

RESULTS AND DISCUSSION

Effects of cropping patterns on runoff generation

Criteria for waterlogging control are adopted to reflect the drainage capability of a drainage basin in China. For most Chinese large-scale drainage basins it is a common practice to express the criterion for waterlogging control in draining off all the excess water from 3-day rainfall totals with return periods of certain years in five days for dry lands, or reducing water levels of paddy fields to the depth of submergence tolerance of crops in five days. Therefore, return periods of 3-day rainfall totals were used in this study.

Most of the water in the surface drainage system originates from surface runoff and interflow, therefore the sum of the two kinds of runoff from 3-day rainfall totals with different return periods is analysed in detail. The sum of the two kinds of runoff of 14 3-day rainfall events for the six scenarios are shown in Fig. 3. For the same rainfall event, Scenario A1 produces the highest runoff values and Scenario A3 produces the lowest values. Compared with the present, if the area of paddy fields is decreased by 65.9%, the runoff increases between 2.5% and 26.6% (average 10.5%); if the area of paddy fields is increased by 36.3%, the runoff can be reduced by 5.6% on average. The results indicate that the increase of the area of paddy fields can decrease the runoff. This is due to the flood-retarding affect of the paddy fields. The comparison of the results of Scenario B1 with Scenario B3 in Fig. 3(b) shows that the increase of the planting area of medium rice does not always result in the decrease of the runoff, although for most events this is true. The reason is that the paddy retarding capacity not only relates to the breed, but is also subject to the stages of growth.

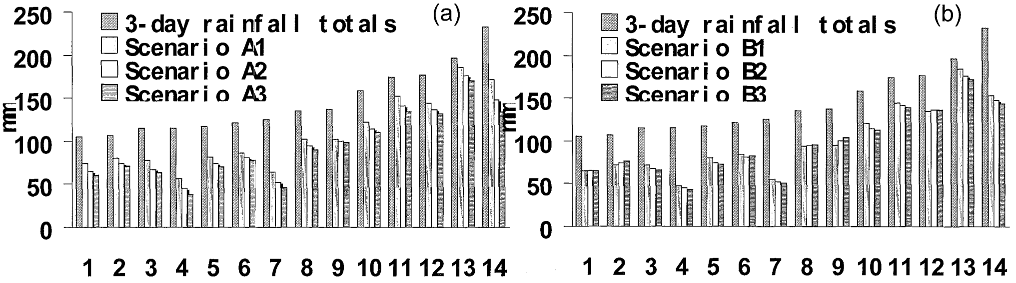

Fig. 3 Comparison of simulated runoffs for the two scenario sets: (a) Scenario Set A and (b) Scenario Set B.

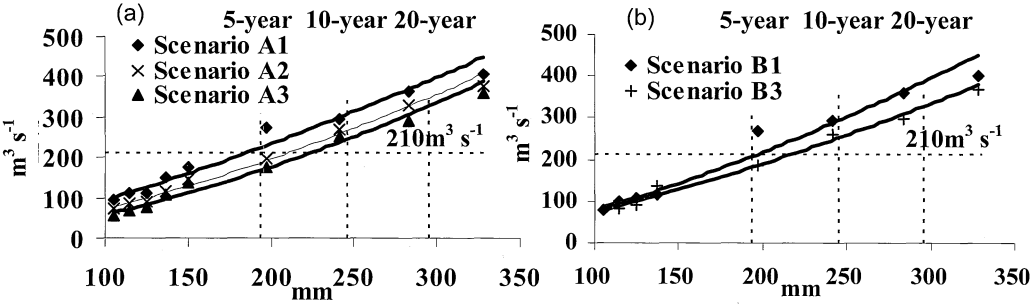

Fig. 4 Relationship between 3-day rainfall totals and required design discharge: (a) Scenario Set A and (b) Scenario Set B.

Effects of cropping patterns on drainage capability

The relationship between 3-day rainfall totals and the required design discharge to control the excess water under the depth of submergence tolerance of crops, or drain off all the excess water in five days for Scenario Set A, is shown in Fig. 4(a). The corresponding results for Scenario Set B are shown in Fig. 4(b).

As shown in Fig. 4(a), in the present conditions, the design discharge of 210 $m^3 s^{-1}$ can only make the volume of waterlogging from 3-day rainfall totals with return periods of 6.9 years under control. Since the result is in accordance with the real situation, it further verifies that the simulation model is effective. For a 10-year return period, the required design discharge should be increased to 259 $m^3 s^{-1}$ and for a 20-year return period, the required design discharge should be 337 $m^3 s^{-1}$. For the same storm event, the required design discharge of Scenario A1 is the highest and the required design discharge of Scenario A3 is the lowest. It indicates that with the increase of the area of paddy fields, the drainage capability of Luoshan drainage basin is enhanced. Increasing the area of paddy fields from 20% to 80%, the drainage capability can be improved from return periods of 4.3 years to return periods of 7.7 years. This is mainly because of the expanding of paddy retarding capacity with the increase of the area of paddy fields.

From Fig. 4(b) it can be seen that for the same storm event, the required design discharge of Scenario B3 is always lower than Scenario B1. The results show that the increase of planting area of medium rice can also improve the drainage capability. The conclusion is inconsistent with the results in Fig. 3(b). This is because the results in Fig. 4(b) are results under the most unfavorable conditions, and the storm event generally occurs in July when the paddy retarding capacity of Scenario B3 is larger than that of the Scenario B1.

CONCLUSIONS

In this paper, a conceptual hydrological model is developed to simulate the hydrological processes of large-scale drainage basins. The model features a simple structure, an explicit concept, and unambiguous parameters, and it can be applied to a wide range of watersheds. Aiming at different land uses, the model adopts different simulating methods, and takes the influence of factors such as the growth, sowing and harvesting on runoff generation into account when modelling paddy fields. As a result, the model is capable of accessing the effects of different cropping patterns on runoff. When conducting the simulation of flow-routing through the network, many human activities, such as the operating regulation of sluices and pumping stations, are taken into account; therefore the effects of cropping pattern changes on drainage capability can be evaluated effectively.

The results demonstrate that the drainage system of Luoshan drainage basin can dispose of the volume of waterlogging from 3-day rainfall totals with return periods of 6.9 years in five days. Increasing the area of paddy fields by 36.6% can improve the drainage capability to return periods of 7.7 years. Increasing the planting area of medium rice can also improve the drainage capability according to the simulation results.

The drainage capability is subject to many factors, but only one factor is analysed in this study, and the other factors remain unchanged. Our future research will extend to cover more factors.

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