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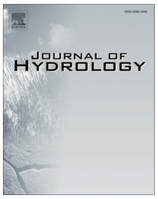

Xinanjiang model combined with Curve Number to simulate the effect of land use change on environmental flow

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SUMMARY

Land use change has been identified as an important contributor of runoff changes. In this study, a new model, XAJ-CN, was developed by integrating the Xinanjiang model and Curve Number of SCS-CN (Soil Conservation Service) model to assess runoff changes in the Dongjiang River basin. Three sub-basins, located in the middle and lower Dongjiang River basin, were selected as case studies, which constitute the most important water source system for Guangdong province and Hong Kong. Based on the land use and soil properties, the proposed XAJ-CN model was calibrated and validated using 10 years of data. It was observed that the simulated runoff series matched the observed one well, indicating that the performance of the XAJ-CN model was satisfactory. The proposed model was then applied to simulate the effect of land use changes on runoff variations under six specific scenarios. In the end, the impact of urbanization on environmental flow was analyzed using the IHA (indicators of hydrologic alteration) and HMA (histogram matching approach) methods. Results showed that the impact of land use change on runoff was more obvious in the flood season when compared to the dry season, and the effect of change in the CN value on surface runoff was the greatest in the flood season, while the change in the CN value mainly affected groundwater runoff in the dry season. Results also showed that the magnitude of monthly river flow all increased, and the maximum flow magnitudes of 1-day, 3-day, 7-day, 30-day and 90-day periods were larger under the urbanization scenario than those in the baseline period. In addition, there was a great variation in the frequency and duration of high and low pulses.

1. Introduction

The impact of environmental changes on the hydrological cycle has received significant attention in recent years. Land use/land cover (LULC) change is one of the important components of environmental changes. Generally, geology, topology and soil types of watersheds remain the same. On the contrary, human activities, such as urban sprawl, road construction, housing and dwellings, schools, hospitals, silvicultural and agricultural activities cause changes in land use/land cover in watersheds (Isik et al., 2013). Land use change directly reflects the degree of influence of human activity, which can affect the water cycle and directly lead to changes in water resources supply and demand.

Many studies have discussed the influence of land use changes on hydrology (e.g. Jennings and Jarnagin, 2002; Beighley et al., 2003; Zhang and Schilling, 2006; Zheng et al., 2009; Öztürka et al., 2013). Wagener (2007) pointed out that hydrological impacts of land use and land cover changes were still controversial and further research was necessary. But most of the studies have mainly been on quantitative analyses of the influence of land use change on hydrology. There is a great need to study the effect of this change on future environmental flows.

Hydrological models have been widely used to investigate many issues arising during planning, design, operation, and management of water resources systems (Lin et al., 2010, 2014a), and also to quantify the impacts of land use and climate changes on the hydrological cycle (Jiang et al., 2012; He et al., 2013). The Soil Conservation Service Curve Number (SCS-CN) model was first developed by the Soil Conservation Service of the United States Department of Agriculture (USDA) in 1954 to transform rainfall

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to direct surface runoff. The advantage of the SCS-CN model is that it objectively reflects the influence of soil type, land use and antecedent soil moisture content on the rainfall-runoff process. Though the model has its own limitations (Mishra et al., 2005; Suresh and Mishra, 2012), it has been widely used in many countries all over the world (Yuan et al., 2001; Mishra and Singh 2003; Geetha et al., 2008).

The Xinanjiang model is a conceptual rainfall–runoff model, which has been successfully and widely used in humid areas of China since its initial development in the 1970s and publication in 1980 (Zhao et al. 1980). The main feature of the Xinanjiang model is the concept of runoff formation on the repletion of storage, which denotes that runoff is not produced until the soil moisture content of the aeration zone reaches field capacity (Zhao, 1992). The Xinanjiang model has not only been used for flood forecasting (Hu et al., 2005; Li et al., 2009) but also for analyzing the impacts of climate change (Jiang et al., 2007). Liu et al. (2009) coupled the Xinanjiang model to a kinematic flow model based on digital drainage networks for flood forecasting. Yang et al. (2011) coupled the Xinanjiang and SWAT models to simulate agricultural non-point source pollution in Songtao watershed of Hainan, China. However, applications of the Xinanjiang model in land use impact studies are scarce so far, and Hapuarachchi et al. (2003) found that the Xinanjiang model performs better than the SCS-CN model for river flow predictions in tropical areas. Therefore, another issue addressed in this study is to improve the Xinanjiang model so as to assess land use impact for humid and semi-humid areas of China.

The Dongjiang River basin, is a typical humid area in south China, which is also a key fresh water source for the Pearl River Delta (one of the most developed areas in China), and supplies 80% of fresh water for Hong Kong (Chen, 2001). Climate changes, hydrological processes and even environmental streamflow changes have been attracting increasing concerns in recent decades (Zhang et al., 2013, 2014). However, due to fast and persistent economic development and urbanization, the quantity and quality of available water resources in the Dongjiang River basin have become serious issues This region has experienced rapid land use changes since the 1980s, which has resulted in altered hydrological response (He et al., 2013).

The objectives of this study are: (1) to use the Xinanjiang model and Curve Number of the SCS-CN model to form a new model for hydrological modeling and forecasting in the humid area; (2) the performance of the proposed model is evaluated by comparing observed and simulated surface runoff values for three sub-basins in the Dongjiang River basin, South China; and (3) the calibrated model was applied for watershed simulation and scenario analysis, and the effect of land use change on environmental flow was assessed using IHA (Indicators of Hydrologic Alteration) method.

2. Methodologies

2.1. XAJ-CN model

In the Xinanjiang model, the total runoff of the basin is calculated using a soil moisture storage capacity distribution curve, based on the concept of runoff formation on repletion of storage. After that, the total runoff is divided into three components, i.e. surface runoff, interflow, and ground water runoff using a free water capacity distribution curve. Then the surface runoff is routed by the instantaneous unit hydrograph, while interflow and groundwater are routed through linear reservoirs representing interflow and groundwater storage respectively (Zhao and Liu, 1995).

To consider land features such as soil, slope, vegetation and land use in a basin, a Curve Number (CN) is used in the SCS-CN model, which is a key and comprehensive parameter within the SCS-CN model. There is an empirical relation between CN and S (potential retention in the basin) as

$$S = \frac{25400}{\mathrm{CN}} - 254 \tag{1}$$

CN describes the watershed features before rain and is affected by AMC (Antecedent Moisture Condition), slope, vegetation, soil type and land use condition with a value ranging from 0 to 100. AMC can be divided into 3 conditions: -arid condition, -normal condition and -moist condition. Detailed information about the classification and estimation of the CN values can be found in Mishra and Singh (2003) and Durbude et al. (2011).

The value of S mainly depends on three factors, i.e., land use condition, hydrological soil type and antecedent moisture condition. Suresh and Mishra (2012) argued that parameter S was a constant for a storm and varied from storm to storm in a watershed, and these are absolutely two contradicting statements for the same S, which leads to misconceptions of the model structure. So they proposed another new parameter "S_{abs}" as potential maximum retention, which is assumed as the summation of potential retention (S) and moisture content (M) for a watershed and defined as (Suresh and Mishra, 2012)

$$S_{abs} = S + M \tag{2}$$

Parameter S_{abs} is a constant quantity for a watershed irrespective of storms, which may be equivalent to parameter WM (areal soil moisture storage capacity) in the Xinanjiang model. But moisture content M also varies from storm to storm in a watershed. To avoid this problem, the areal soil moisture storage capacity WM and the value of S only in -arid condition (S_I) are adopted in this study. A relationship between S_I and WM is developed as follows:

$$WM = \alpha \cdot S_I \tag{3}$$

where α is a coefficient.

A schematic diagram for combination model of the Xinanjiang model and Curve Number (XAJ-CN) is shown in Fig. 1. The model consists of four sections (shown in Fig. 1), including evapotranspiration, runoff production, runoff separation and flow routing. The inputs to the model are precipitation, P, pan evaporation, EM, land use, and soil type. The output is the discharge at the outlet, TQ. E is the actual evaporation, which includes three components EU, EL, and ED in the upper, lower and deep layers respectively. W is the areal mean tension water storage, which also has three parts WU, WL, and WD in the upper, lower and deep layers respectively. FR is the runoff contributing area factor which is related to W. RB is the runoff directly from the impervious area. R is the runoff from the pervious area, which is divided into three components, surface runoff (RS), Interflow (RI), and groundwater runoff (RG). Then these three runoff components are further transferred into QS, QI and QG, and form the total flow. There are 15 parameters for flow routing, which could be grouped as follows. KE, X, Y and C are the evapotranspiration parameters; α, B and IMP are runoff production parameters; SM, EX, KI and KG are runoff separation parameters; and CI, CG, N and NK are runoff concentration parameters. The concepts of these parameters are displayed in Table 1.

2.2. Model calibration

The SCE-UA method, proposed by Duan et al. (1992), was selected to calibrate the parameters of the model, which is based on a synthesis of the best features from several existing methods, such as the genetic algorithm. This method also introduces a new concept of complex shuffling, which has been proved as an effective and efficient optimization technique for calibrating watershed models (Duan et al., 1994).