Spatial discretization of distributed hydrological response units for SWAT

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ABSTRACT

The Soil and Water Assessment Tool (SWAT) is a well established eco-hydrologic model. For the semi-distributed hydrological model, Hydrological Response Units (HRUs) are the basic modeling units, which are defined by land use, soil and slope. Land surface patches within one Hydrological Response Units (HRUs) should bear identical hydrological properties (including land use, soil, slope and management) and thus have similar hydrological responses. However, it is difficult to determinate the spatial locations and to describe the interactions between different HRUs. This study proposed one schema to discretize HRUs for SWAT on the basis of generalized data input. Within a small watershed of Taihu Basin, the data of land use and soil were generalized for discretizing SWAT HRUs. The SWAT model was modified with the discretized HRUs. The resulted showed that the SWAT improved by discretization schema could be more sensitive the runoff lag process and thus achieved better simulation accuracy.

Keywords: SWAT; HRU Spatial Discretization; Runoff lag; Taihu Lake basin

1 INTRODUCTION

The world is experiencing increasingly more serious situation of water resources. The distributed hydrological model (DHM) has become the indispensable means for exploring the influences of climate change and human on hydrological cycles and water resources. With strict mathematical and physical description of hydrological processes, DHM could account the spatial variations of watershed parameters and horizontally relate different HRUs. Therefore, the Digital Terrain Model (DEM) based DHM is one major trend of hydrological modeling [1]. Theoretically, the absolutely physical DHM is built on the strict hydrological processes [2]. However, none of current DHMs can absolutely describe the strict hydrological processes, and most are based on some hypotheses.

The spatial heterogeneities of watershed hydrology promote the ever increasing important role of DHM [3]. There are mainly two ways to construct DHM. One is to relate spatial watershed units by numerical analyses, and this is so-called physical DHM. Another calculates the net precipitation of each watershed unit or grid, based on which the conflux and the runoff are further estimated. SWAT falls in the latter category. DHMs of this category are simple in model structure and calculation, and thus are strength in the hydrological modeling of large watershed.

As one of semi-physics based DHM[4-5], SWAT generalizes the interior spatial difference of HRUs for the sake of modeling conveniences. In addition, the so-called physics DHMs essentially make generalization in define minimum spatial unit, i.e. the grid, the spatial resolution of which determines the degree of spatial simplification. Therefore, the absolute physical DHM is impossible and unnecessary, because of the limitation of watershed parameters collection and modeling efficiency. The spatial generalization of spatial model unit can greatly promote the simulation efficiency. The definition of sub-watershed and model grid has different influences on the simulation accuracy. Without the specific spatial properties as sub-watershed, the HRUs of

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SWAT only bear detailed non-spatial properties, such as area, slope, land cover and soil type. This fact is one of most serious weakness of SWAT [6]. Without the description schema of interior sub-watershed, the interaction and transmission routes of water and mass between HRUs are thus neglected [7].

This study is to explore the issue of locating HRUs within sub-watershed for SWAT, through analyzing spatial HRU characteristic of land cover, soil type and slope. The discretization schema of HRU locating will be examined with one watershed in Taihu Basin, China.

2 STUDY AREA AND DATA

The Xizao River watershed of Taihu Basin (Zhejiang Province, China) was taken to validate the proposed schema of HRU spatial discretization. Xizao River originates from Yonghe, Anji County and flows southwest into Taihu. This watershed is under the control of typical subtropical monsoon climate, with annual air temperature of 15.5℃ and annual precipitation of 1465.8 mm. The seasonal variation in runoff agrees with that of precipitation peaking at May-June and September. The runoff during May-June accounts for 45-54% of whole year. The upper and middle watershed (upper to Gangkou Gauge, 1,885.36 km2) was simulated for the runoff and pollution with the improved SWAT.

The product of ASTER GDEM in 30m resolution provided the terrain of the study watershed ranging from 1574 m northeast to 5 m. The land cover information was combined by China LUCC collection and the interpretation results of ALOS image, while soil type data were derived from China Soil Database (1:1,000,000). The inputs of precipitation were prepared by interpolating ground climate records with Kriging method[8].

3. METHDOLOGY

SWAT can provide the continuous temporal series of runoff simulation based on the water cycle and balance of land surface. The modeling hydrological processes of SWAT include those on land surface (runoff production on slopes) and those in riverways. The former controls the input of water, sand, organic mass and chemical content into rivers, while the latter determine the transmission routes and times of water and masses.

Generally, SWAT defines sub-watersheds in a watershed according to hydrological connections, and further divided sub-watershed into HRUs according to both the type and fraction of land cover and soil type. This SWAT definition of hydrological unit hypothesizes that the land surface patches of same type HRU have same hydrological response. Therefore, SWAT simulates the hydrological process of each HRU individually, and the runoff and carried masses are summed at the watershed output. For modeling convenience, SWAT completes the whole hydrological simulation through eight sub-models, i.e. hydrological, meteorological, sand, soil temperature, crop growth, organic mass, pesticide and agricultural management ones. The river way process models the transmission of water, sand, organic matter, and pesticide. This sub-model estimates the confluxes of river way and reservoirs separately. SWAT simulates the flow velocity and runoff with Manning's equation, while river way process of water is modeled with Musking routing schema.

3.1 Lag of SWAT HRUs response

The HRU of SWAT is defined with thresholds of land cover, soil type and slope. If the thresholds of land cover and soil type are 50 and 20 ha respectively, SWAT will firstly divide watershed patches into two primary types which be further divided. In this way of HRU definition, the watershed patches within one HRU are probably spatially separate though identical in type of land cover. Then among above primary two types of HRU defined by land cover, the patches which bear one soil type over 20 ha will be defined as new HRU type.

A HRU often consists of more than one grid, which can be spatially adjoining or separate. SWAT treats HRU as the primary modeling unit, and the mean slope and total area of HRUs are calculated as the model inputs. Generally, averaging slope among the distant grids may smooth watershed terrain. This smoothing effect on surface terrain indispensable in a degree biases the hydrological modeling.

Though an HRU is the primary modeling unit of SWAT, the surface patches of the HRU may be spatially disordered. The smoothing of spatial heterogeneous patches in constructing HRU may impair the model accuracy. Without the locations of HRU patches, SWAT can not support HRU-based spatial analyses. As the patches of land cover and soil type are complicate in spatial distribution, the accurate description of each HRU is nearly impossible. In this sense, the improvements over original HRU definition with specific location, continuous distribution and necessary surface properties are the preconditions for SWAT to achieve more accurate hydrological modeling.

The production and conflux process of runoff spans certain period, which is positively determined by watershed scale. SWAT models this fact of surface runoff lag by temporarily reserving fraction of land surface water to postpone it flow into riverway. The fraction of land surface runoff estimated by Green-Ampt (CN) method can be determined by

$$Q_{surf}=(Q_{surf}'+Q_{stor,i-1})*[1-\exp(-surflag/t_{conc})] \quad (1)$$

Where Q_{surf} is the runoff fraction of certain day flow into river way, Q_{surf}' is the runoff of certain day produced by the land surface of a whole HRU, $Q_{stor,i-1}$ is the runoff fraction of previous day that has not flowed into river ways, *surflag* is the runoff lag coefficient, t_{conc} is the time of concentration in sub-watersheds. The equation of $[1-\exp(-surflag/t_{conc})]$ estimates the runoff fraction that flows into river way. Figure 1 shows the influences of *surflag* and t_{conc} on runoff. For certain t_{conc}, the increase in *surflag* causes larger fraction of runoff to be reserved temporarily.

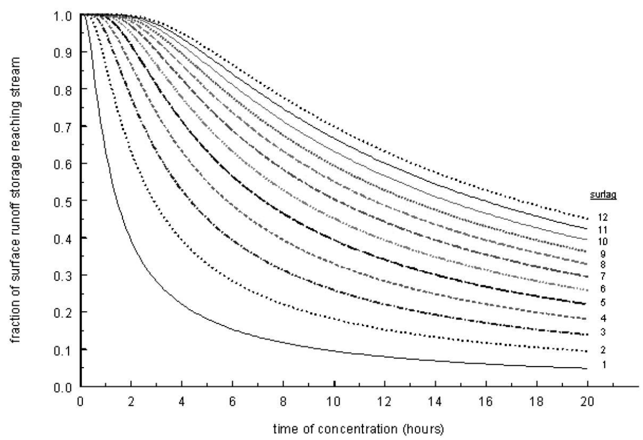

Figure.1 Influence of surlag and t_{conc} on fraction of surface runoff released

The concentration time of a sub-watershed is the duration of from precipitation to the time when the whole runoff of this sub-watershed reached its outlet. This time can be estimated by adding the periods of surface runoff production and riverway transmission. Similarly, the runoff carried sand, organic mater and pesticide experience transmission lag.

For a watershed, SWAT models the processes of runoff, sand and organic mater for each HRU, and sums the estimations of all HRU for a sub-watershed, which then flows into riverway. Since SWAT can not locate HRU patches, the hydrological modeling of HRU process fails to catch the possible location-induced hydrological differences. The routes of HRUs to sub-watershed outlet are probably quite different in distance, which mainly controls the conflux time, sand carrying capacity and decomposition degree of organic mater. Therefore, this study is to estimate the difference of HRUs in conflux time by constructing the distance of HRU barycenter to sub-watershed outlet.

3.2 Spatial discretization of HRU

SWAT introduces runoff lag to express the time difference between surface runoff production and riverway conflux, and thus temporarily postpones part of HRU runoff of current day to flow into riverway. However, SWAT assigns identical runoff lag to all HRUs within a sub-watershed. This simplification can not project the fact of sub-watershed, because the HRU which is farther away from outlet bears the longer runoff lag. The larger a sub-watershed is, the more distinct the difference in runoff lags between HRUs within is. This study proposed one method to estimate the distance between HRU and corresponding sub-waterway outlet, which promises to be sensitive to the HRUs' difference in runoff lag.

3.2.1 Spatial discretization schema

In the proposed spatial discretization schema, the land cover and soil type data are analyzed to achieve the spatial locations and topologies for HRUs patches.

Firstly, the generalized patches (i.e. the HRUs) are defined according to the thresholds of land cover, soil type and slope. Attention should be paid to avoid the small patches of different sub-watersheds to be merged.

The HRUs now have unique spatial identifications and thus can be coded. Such HRU bears both the specific non-spatial properties (land cover, soil type and slope) and the spatial attributes, such as shape, area and barycenter.

Secondly, the property tables of each generalized HRU are constructed according to its surface attributes (land cover, soil type and slope). Correspondingly, the original SWAT input files are updated by the property tables. In the modified file of soil type, each patch has one soil type code which corresponds with different soil types. New field of patch soil code should be appended to the database soil type fore SWAT so that the modification of soil input file can take effect.

Thirdly, the discretized data of land cover, soil type and sloe are input ArcSWAT to produce HRU, whose threshods are same as the ones used in spatial generalization step. Definitive in soil type and specific in space, HRU is spatially discretized. Correspondingly, the HRU attributes are automatically updated into input files of SWAT. Figure 2 compared the HRUs produced by original SWAT schema and the improved one. Figure 2b indicated that the HRU of improved schema is a continuous patch and bears explicit hydrological properties (land cover, soil type and slope) and specific location.

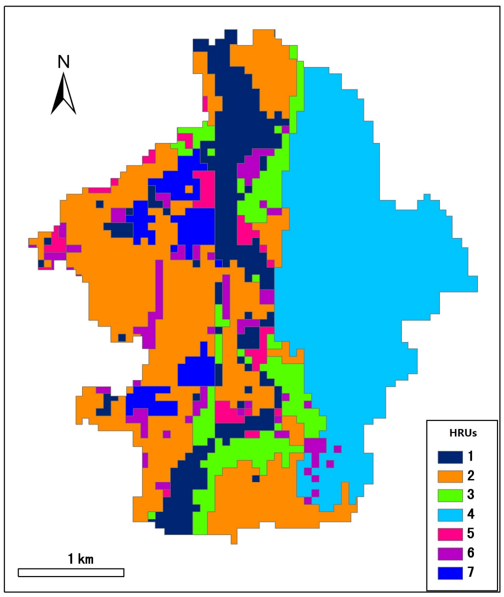

Figure.2a Possible distribution of HRUs using traditional method

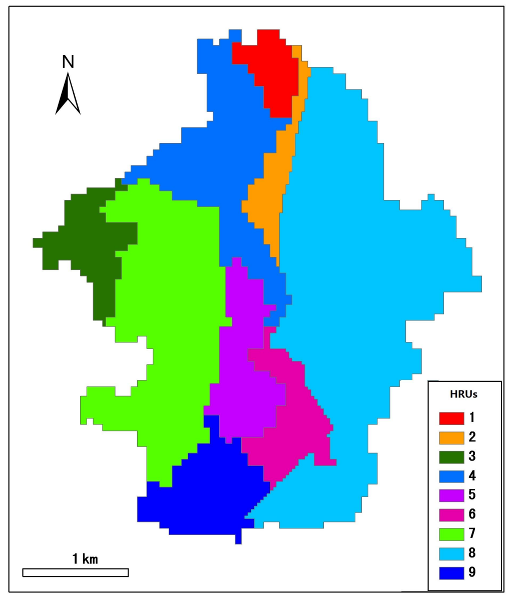

Figure.2b Spatial distribution of HRUs using by modified method

However, the new coding of soil type in spatial discretization does not completely correspond with that of original one. Therefore, the corresponding relation between the code of discretized surface patch and soil type should be constructed and recorded into input file of SWAT. In this way, the code of surface patch is uniquely linked with one soil type, which helps to input the land surface properties into SWAT. This schema also can output the results of HRUs (runoff, sand and pollution) for spatial analyses.

The improved schema of HRU definition realizes the spatial discretization of HRUs, and thus promises the spatial analyses of hydrological processes at more detailed scale. This schema estimates the runoff lags of different HRUs according to the distances of their barycenters to corresponding sub-watersheds outlets, which more agrees with the fact of runoff process.

3.2.2 Schema improvement of SWAT HRU

As HRUs have specific locations after spatial discretization, the distances of their barycentes to corresponding sub-watershed outlets can be calculated to indicate HRU runoff lag, which then is added into HRU database. The estimation of HRU runoff is improved as

$$Q_{surf} = d_i * (Q'_{surf} + Q_{stor,i-1}) * [1 - \exp(^{-surflag}/_{t_{conc}})] \quad (2)$$

where, d_i is the modification coefficient of runoff lag for HRU *i*.

$$d_i = \frac{1}{n} \cdot \frac{n \cdot MaxDis - (n-1) \cdot dis\_stream_i - MinDis}{MaxDis - MinDis} \quad (3)$$

where, *dis stream*$_i$ is the distance from the barycenter of HRU *i* to its sub-watershed outlet, *MaxDis* and *MinDis*, are respectively the maximum and minimum barycenter distances of all HRUs within the sub-watershed under calculation, m and n are two constants (>1) used to regulate the runoff to outlet from the HRU with the longest barycenter distance of the sub-watershed. The dis streami decreases to *1/n* with the increase of di. The di equals 1 if *dis stream*$_i$ equals to *MinDis*, while the di is *1/n* if *dis stream*$_i$ equals to *MaxDis*. The schema simulates the fact of runoff lag that is negatively proportional to the barycenter distance. The coefficient n should be manually modified during SWAT simulation according to the specific characteristics of watershed surface.

Similar improvements over the transmission lag over sand, organic mass and pesticide are also made in SWAT.

4 ANALYSIS

4.1 Results of calibration

The SWAT was calibrated with the method of Generalized Likelihood Uncertainty Estimation (GLUE), and the sensitivity of SWAT to input was examined. The model was calibrated with runoff observation of Gangkou Gauge and Hengtang Gauge on Xizao River. The runoff simulated by improved SWAT was compared with that by non-improved. In the calibration of runoff, the sensitivities of 17 parameters were explored to determine the parameter maximums and adjust the parameter ranges. This step was iterated to attain satisfactory calibration result.

In the Xizao River watershed, the base flow accounts for quite a fraction of the total runoff, which should be carefully considered in calibration. The historical runoff records showed the base flow coefficient of 0.112. Figure 3 and Figure 4 were the calibrated simulation of runoff process at Gangkou Gauge, which indicated the good agreement of simulated daily runoff with observation. The NSE attained 0.67 (R2 = 0.67) at Gangkou. In the calibration period (2001-2005), the NSE of monthly runoff was even high as 0.79 (R2 = 0.81). The calibration results at Hengtang were better during this period, with the NSE of daily and monthly runoffs respectively as 0.71 (R2 = 0.72) and 0.83 (R2 = 0.84). The difference in simulation between gauges can be attributed to surface diversities. Gangkou Gauge locates in the plain region, where the canals and ditches have indispensable influences on the natural hydrological processes of surface and main riverway. However, in the upper Xizao River the regulation of two reservoirs may weaken the effects of the HRU schema improvement in simulating the runoff of Hengtang Gauge.

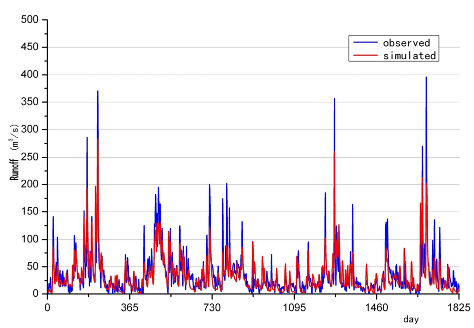

Figure.3 Daily flow hydrograph of Gangkou Station in calibration period using modified model

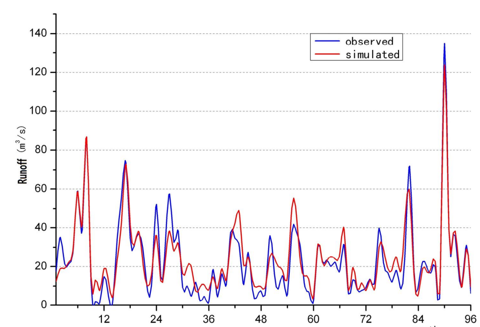

Figure.4 Monthly flow hydrograph of Hengtang Station in calibration period using modified model

4.2 Results of validation

The runoff during 2006-2008 was modeled with SWAT to validate the improvements. The results showed the NSE of 0.76 (R2 = 0.77) and 0.81 (R2 = 0.83) respectively at Gangkou Gauge and Hengtang Gauge.

The runoff simulation during validation period was better than that during calibration period. This suggested that the calibrated parameters promoted the capability of SWAT to model the surface hydrological process. In a degree, the behavior of SWAT showed association with the amount and temporal distribution of precipitation.

It indicated the better simulation (higher NSE) in the years with abundant precipitation. The NSE were 0.78, 0.73 and 0.80 respectively in rainy years (2001, 2002 and 2008). In 2003, the year with less rainfall, the NSW was only 0.49. In general, the validation suggested that the improvements of SWAT over HRU schema can well describe the lags of surface runoff and promotes the response of SWAT to the hydrological process of watershed.

5 CONCLUSION

The study proposed a method of spatial discretization for HRU based on spatial data analyses. The HRU polygons were generalized to produce new HRUs, which were associated with the surface properties of land use, soil type and terrain slope. Therefore, adjusted HRUs bore both the spatial and non-spatial attributes, which can improve the response of SWAT to runoff lags of HRUs. This new HRU schema was validated in upper Xizao River, Taihu Basin, China. The results showed that the NSEs of runoff simulation increased from 0.70 to 0.76 and 0.70 to 0.71 respectively at Gangkou Gauge and Hengtang Gauge by improve HRU schema. The study suggested that the location of HRU is important to well model the runoff lags of different surface patches, and related improvements can promote the response SWAT to watershed hydrological process.

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