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Influences of topographic index distribution on hydrologically sensitive areas in agricultural watershed

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Abstract A hydrologically sensitive area (HSA) is an area with a very quick response to runoff and higher surface runoff probability since all watersheds are prone to generate runoff in one way or the other. The accurate description of runoff generation in time and space has important practical significance for land use and watershed management. The aim of this article was to establish HSAs identification method based on topographic index, and to estimate the spatio-temporal variability of surface runoff probability in different periods. The sensitive month was defined using critical monthly surface runoff probability combined with topographic index. Then the corresponding spatial and temporal boundary of HSA was estimated by the relation of average annual runoff and topographic index. The presented approach was applied in Meishan watershed, which is humid in the summer and has a monsoon climate. The analysis results indicated the probably sensitive months are from February to October with spatial topographic index distribution ranging from 13.02 to 17.13. April–October was estimated as seasonal HSAs with topographic index ranging from 9.21 to 14.05. In addition, the inter-annual variability of seasonal HSAs is much greater and the critical topographic index is 9.21 in July.

Keywords Topographic index · Hydrologically sensitive areas · Identification · Watershed

1 Introduction

In humid, well-vegetated areas, the spatial variability of topography, land use, soil types, hydro-meteorological conditions affect the process of surface runoff probability. The runoff source areas vary in size and ranges from a single storm to seasonal fluctuations even during individual storm events. These source areas are referred to as variable source areas (VSAs) or as hydrological active areas (Walter et al. 2000; Agnew et al. 2006). The current water quality protection strategies usually lack a sound hydrological underpinning for pollutant transport processes. And it is difficult to implement real-time monitoring in the whole watershed. The term hydrologically sensitive area (HSA) was used to refer to areas in a watershed especially prone to generating runoff that are, therefore, potentially susceptible to transporting contaminants to perennial surface water bodies (Walter et al. 2000). HSAs have a high propensity for surface runoff and make significant contributions to overall runoff volume. So a quantifiable description of HSAs will provide a basis for restricting pollutant transfer in runoff and is beneficial to watershed regulation.

In regards to runoff response to topographic index, considerable effort has been devoted to identifying the spatial distribution and variation rules of HSAs in recent years. As

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early as in 1967, Hewlett and Hibbert put forward the concept of VSAs to describe the dynamics of the surface runoff with a multiple factors including topography, climate, soil type and vegetation. Later in a study of runoff generation in a small New England watershed, Dunne and Black (1970) suggested that most storm runoff was produced as overland flow from a small proportion of the watershed. Boughton (1990) adopted surface soil water storage capacity to assess major runoff events and core areas in watershed through two experimental basins under two different climatic conditions. They revealed that the runoff location and area were different corresponding to different rainfall events, even during the same rainfall event but in different periods, based on the rainfall-evaporation-soil water -runoff balance model in a small watershed of 16.8 ha in Australia. Zhang and Huang (2002) applied soil moisture routing (SMR) model to examine the monthly extreme runoff probability to define the scope and location of HSA. They preferred that about 10 % of a watershed could be regarded as HAS which produced over 20 % runoff. Their study considered the spatial soil water distribution and different land use type responses, but overlooked the topography influence. There were somebody identified topography, soils and rainfall characteristics combining to create the specific VSAs in their study watershed (Chuang et al. 2008; Brooks et al. 2007; Sarah Dean et al. 2009). Studies of VSAs have continued with several directions emphasized in the literature. Agnew et al. (2006) used SMR model to calculate the saturated runoff probability. And then they combined the distance from the river and relation of saturated runoff and topographic index to define the border of HSAs and key areas of watershed management. Chuang et al. (2008) and (Zhang et al. 2013) introduced a standard soil volume water to analyze runoff generation probability in different seasons in Lianhua watershed, and under different runoff generation probability levels a variable hydrology sensitive scope in different seasons was presented in their study (Schneiderman et al. 2007).

This study attempts to establish HSAs identification approach based on topographic index. The rest of the paper is the following. In Sect. 2 a brief description of improved topographic index and relevant information about the study region is given. In Sect. 3 an identification method on hydrology sensitive boundary and area is presented. The correlation of topographic index and spatial variability of the surface runoff in different periods is set up. Section 4 presents the application in Meishan watershed in China. The paper ends with some conclusions.

2 Topographic index description

TOPMODEL (topography based hydrological model) is a semi-distributed hydrological model that suggests that all
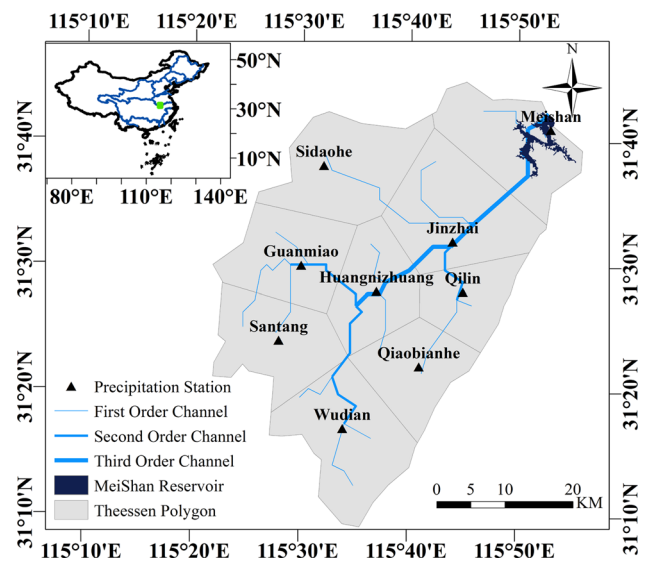
Fig. 1 Location of precipitation stations and drainage system in Meishan watershed

topographic units of a watershed with an identical or comparable index value develop, in principle, similar hydrologic responses. The detailed explanation about the TOPMODEL and how the model parameters are calibrated are given by Wolock and McCabe (1995), thus is not provided here. The topography in a watershed is parameterized in TOPMODEL as the statistical distribution of the topographic index by Beven and Kirkby in Beven and Kirkby (1979) (Kong and Rui 2003):

$$TI_i = \ln(\alpha_i / \tan \beta_i) \tag{1}$$

where TI_i is the topographic index of a point i within a watershed, α_i is the upslope area per unit contour length that drains through the point i, and β_i is the local topographic slope angle acting at the same point. The topographic index represents the propensity of a point within the watershed to generate saturation excess overland flow. It can also be used as an indicator of the average annual soil water content over a long period of time (Boughton 1990; Agnew et al. 2006; Yong et al. 2007).

3 Study region and spatial distribution of topographic index

The Meishan watershed is located in the upstream region of Huai River basin (115°21′–115°56′E, 31°9′–31°45′N), with a drainage area of 1,970 km^2 and the largest water storage area of 9,229 km^2. It has a typical monsoon climate characterized by high humidity and abundant rainfall. The elevation (yellow sea height datum) ranges from 80 to 1,445 m. Affected by the monsoon climate, 60–70 % annual precipitation in this watershed concentrated in the period from May

Fig. 2 Spatial distribution of the topographic index in Meishan watershed

(a) The MFD algorithm   **(b)** The modified MFD algorithm
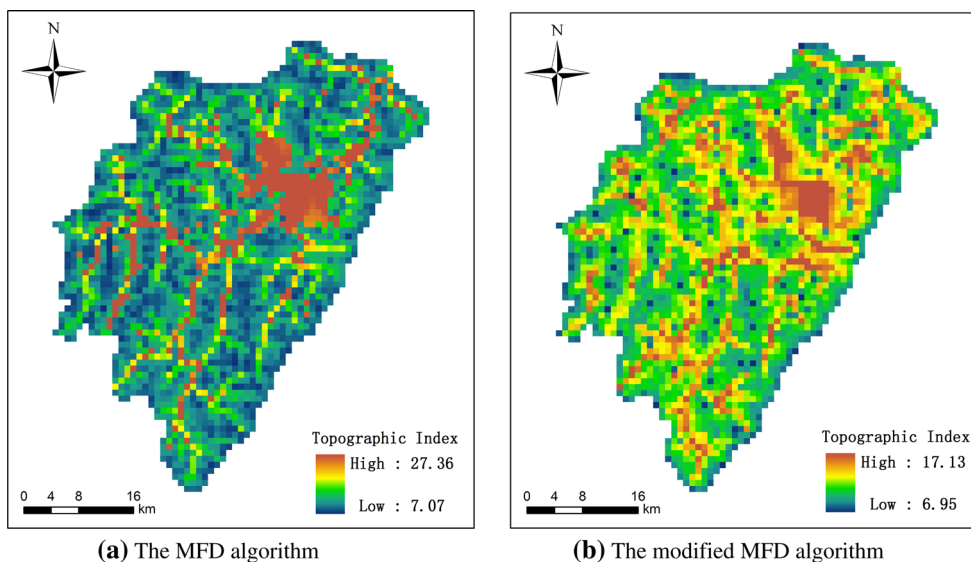
Table 1 Statistical results of the topographic index in Meishan watershed

Algorithm	Minimum	Maximum	Mean	Variance	Std. deviation
MFD algorithm	7.07	27.36	11.92	21.85	4.67
Modified MFD algorithm	6.95	17.13	10.73	2.93	1.71
Difference	0.12	10.23	1.19	18.92	2.96

to September. Therefore flood occurred from late June to mid-July as a typical season flood. There are 9 rainfall stations distributing across the catchment shown in Fig. 1.

In this study, the spatial distribution of the topographic index in Meishan watershed was calculated using the MFD algorithm and the modified MFD algorithm respectively (Wolock and McCabe 1995; Lyon et al. 2004; Schneiderman et al. 2007). The results are shown in Fig. 2.

The statistical results of the calculated topographic index using the MFD algorithm and the modified MFD algorithm are shown in Table 1, the latter is more reliable than the former in calculating the topographic index (Yong et al. 2007).

4 Methodology of the HSAs Identification

4.1 Calculating the average monthly surface runoff probability

Based on its topographic characteristics, the watershed can be divided into a number of small grids, and each grid has a probability of generating surface runoff that varies from

month to month as a result of the variability of precipitation and evapo-transpiration. To reflect the correlation between the average annual surface runoff and spatial distribution of topographic index, we proposed to use an average hydrological sensitive boundary concept to analyze the changing situation of HSAs at time and space scale in a watershed (Zhang and Huang 2002). Then the average situation of HSAs at space scale without changing with month during a year can be expressed clearly. The main steps of this method are the follow.

Firstly, monthly saturation probability, P_{sat}, for the areas with the maximum topographic index value, is obtained and defined as the ratio of the number of saturation days to the number of rainy days within the month.

$$P_{sat} = \frac{D_{sat}}{D_{rain}} \tag{2}$$

where, P_{sat} is the monthly saturation probability, D_{sat} is the number of saturation days and D_{rain} is the number of rainy days within the month.

Then let $P_{sat_i}{}^j$ be the probability of generating surface runoff in the month i of the year j, where $i = 1, 2, \ldots, 12$ and $j = 1, 2, \ldots, m$. So according to the region with the maximum, the average saturation probability $\overline{P_{sat_i}}$ for a specific month i over m years can be expressed as the following:

$$\overline{P_{sat_i}} = \frac{1}{m} \sum_{j=1}^{m} P_{sat_i}{}^j \tag{3}$$

Owing to the uneven precipitation in 1 year, the precipitation in winter only occupies 10 % in total yearly precipitation. The uneven precipitation distribution directly leads to the regulated changing trend of surface runoff at time and space scale. In order to quantitatively measure the

surface runoff generation probability and the changing trend of the HSAs location and range during the year, in this study, the month with $\overline{P_{sat_i}}$ <10 % (the proportion 10 % can be adjusted by the climatic condition of watershed) is considered as the hydrological insensitive months and those with $\overline{P_{sat_i}}$ equal to or >10 % as the hydrological sensitive months (Chuang et al. 2008).

According to the calculated hydrological sensitive months, we can assume a boundary between the sensitive months and non-sensitive months, and the boundary can be termed as the critical hydrological sensitive month at time scale aiming at the same topographic index. Therefore, HSAs are unlikely to occur in the whole watershed in a hydrological insensitive month.

4.2 Calculating an average hydrological sensitive value

Another concept, average hydrological sensitive boundary is proposed to describe the relationship between the average surface runoff of any points with spatial distribution of the topographic index in watershed over a specific period. As stated previously, topographic units of a watershed with an identical or comparable index value are assumed to have similar hydrologic responses. Let the topographic index values be sorted in descending order and divided into L units expressed as TI_i ($i = 1, 2, \ldots L$, and usually L is 25, 50 or 100). Suppose that Rv_i^j is the surface runoff over a specific period of time j in the areas with topographic index TI_i, where $i = 1, 2, \ldots L$ and $j = 1, 2, \ldots, D$. Then the total surface runoff Rv_i accumulated over D for areas with topographic index TI_i can be obtained as:

$$Rv_i = \sum_{j=1}^{D} Rv_i^j \qquad (4)$$

Then Rv_i is plotted against TI_i in Fig. 3 and topographic index TI_i is taken as horizontal ordinate. The total surface
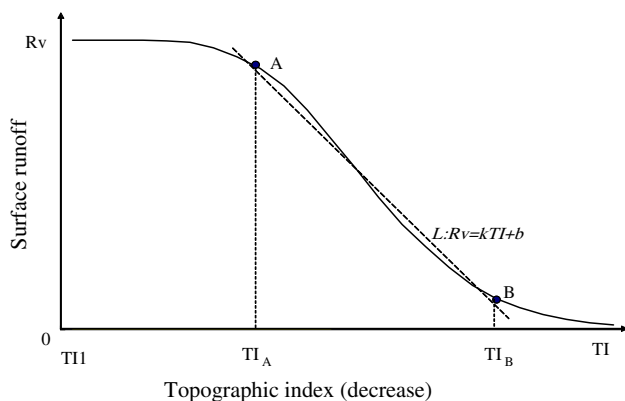
runoff Rv_i accumulated over D for areas with topographic index TI_i as the vertical ordinate. As shown in Fig. 3, Rv_i is a monotonic function of TI_i with two inflection points at TI_A and TI_B, respectively. The general trend is that the larger the topographic index value, the larger the total surface runoff amount. More specifically, when $TI_i > TI_A$, Rv_i increases slowly with the increase of TI_i and then stabilizes at a high level; when $TI_i < TI_B$, Rv_i gradually approaches to zero with the decrease of TI_i; and when $TI_B \leq TI_i \leq TI_A$, Rv_i is approximately linearly related to TI_i with the best-fitting line of $Rv = kTI + b$, where k is the slope of the equation. In this study, TI_A and TI_B are used to separate the HSAs from the non-HSAs. Thus, areas with topographic index values above the threshold TI_A are considered to be hydrological sensitive, whereas areas with topographic index values below the threshold TI_B to be hydrological insensitive. As Rv_i is the average value over years, so TI_A and TI_B are referred as average hydrological sensitive and insensitive values in this paper respectively.

5 Results and discussion

5.1 Parameter calibration

In this study, the spatial distribution of the topographic index of Meishan watershed is calculated using a modified MFD algorithm. The calibration period is from 1998 to 2003 and the verification period is from 2004 to 2007. The statistical results of main parameters and modeling errors are shown in Tables 2 and 3 respectively. It shows that the deterministic coefficient is >0.75 in the calibration period and 0.6 in the verification period, and runoff depth error is <0.1 in the calibration period and verification period, which are acceptable.

The spatial distribution of surface runoff for Meishan watershed is shown in Fig. 4. Surface runoff mainly occurs in the areas with higher topographic index values, which are in consistent with the spatial distribution of the topographic index.

The spatial distribution of the monthly probability of surface runoff in April and August is shown in Fig. 5. It shows that surface runoff is unlikely to occur in November,

Fig. 3 The relationship between topographic index and surface runoff

Table 2 Parameter calibration of the runoff model in Meishan watershed

Maximum storage capacity of the root zone (SRMAX)	Initial value of root zone deficit (SR0)	Exponential decay rate (SZM)	Effective infiltration rate\T0	Effective slope routing velocity RV
0.0549	0.0112	0.0155	3.02	2081.2

Table 3 Simulation errors of the runoff model in Meishan watershed

Calibration period (1998–2003)		Verification period (2004–2007)	
Runoff depth error (%)	Deterministic coefficient (%)	Runoff depth error (%)	Deterministic coefficient (%)
−2.66	89.2	3.75	88.1

December and January as the probability is almost zero in these months. As expected, there is a high probability of generating surface runoff in summer months, when the topographic index value is below a given threshold, the probability would decrease gradually. As shown in Fig. 5, the spatial distribution of the monthly probability agrees well with that of the topographic index. A regular transition

from high-probability areas to low-probability areas is observed.

The monthly variation of the surface runoff probability with topographic index shows that surface runoff is most likely to occur during March to August, followed by February, September and October, and then by January, November and December (Fig. 6). When the topographic index is >13, the monthly probabilities of surface runoff tend to stabilize at a high level for any point in the watershed, but they gradually approach zero when the topographic index is <9.5. It is in good agreement with theoretical results. The areas that generate surface runoff are the largest in July, followed by June and August. The spatial distribution and probability of surface runoff are

Fig. 4 Spatial distribution of the surface runoff in Meishan watershed
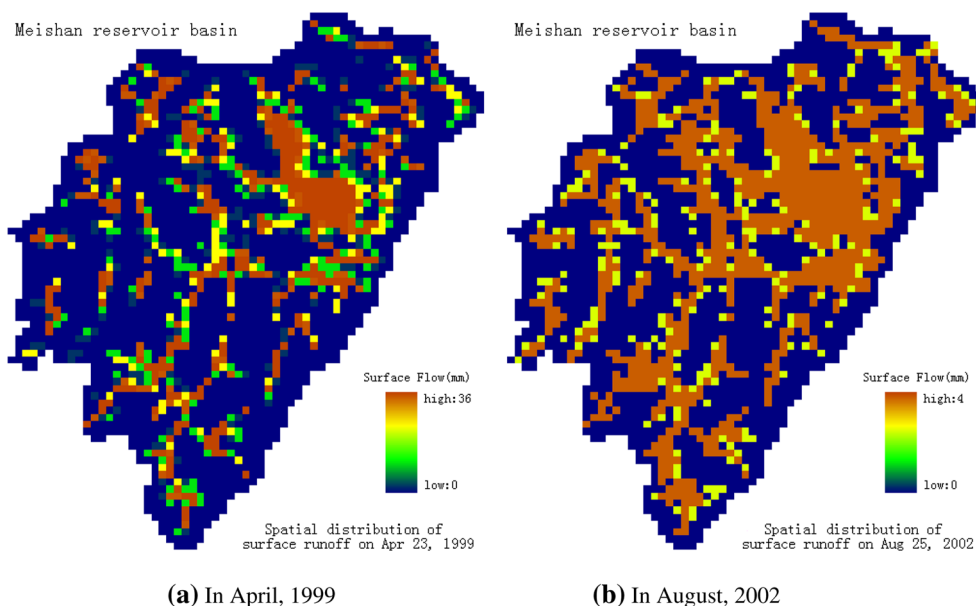
(a) In April, 1999   **(b)** In August, 2002

Fig. 5 Spatial distribution of the monthly probability of surface runoff in Meishan watershed

**(a)** In April, 1999   **(b)** InAugust, 2002
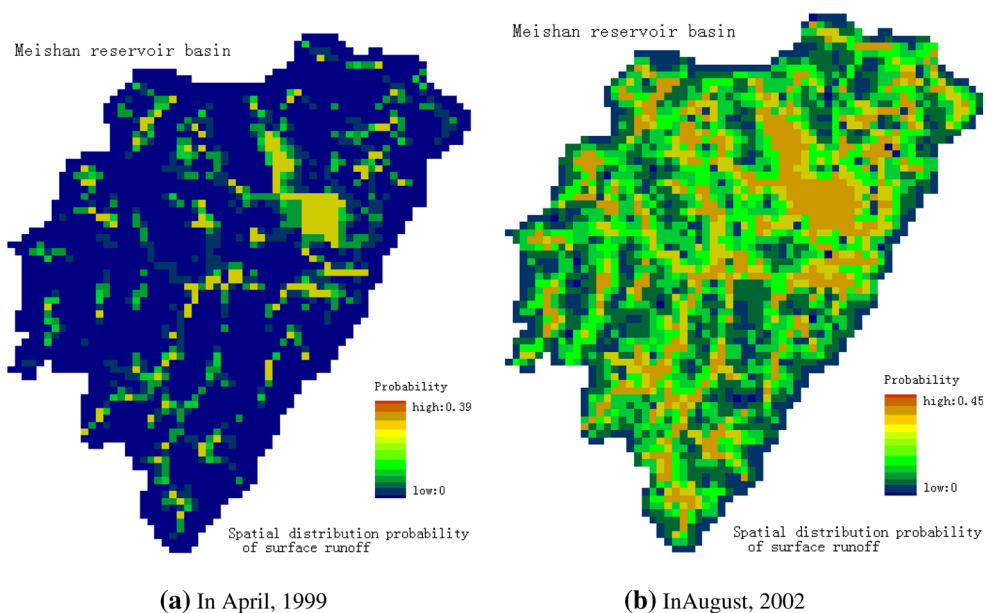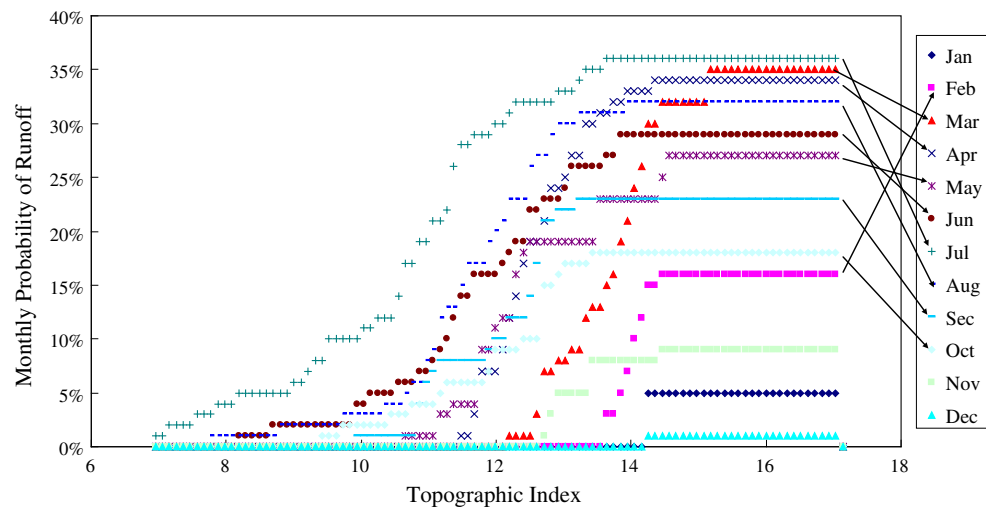
Fig. 6 Runoff probability and its relationship with topographic index from Feb to Oct

highly sensitive to the topographic index in February and March, the monthly probabilities in February and March stabilize at a low level when the topographic index is less than the critical value, but increase rapidly and then stabilize at a high level. In accordance with the definition of the monthly hydrological sensitive boundary, January, November and December are the hydrological insensitive months, while months from February to October are the hydrological sensitive months.

5.2 Identification of HSAs

A temporal-spatial coordinate system is developed to identify the HSAs and seasonal HSAs in Meishan watershed, with month as the horizontal ordinate and topographic index as the vertical coordinates. As shown in Fig. 7, the sensitive months are from February to October for the HSAs and from April to October for the seasonal HSAs, and topographic indices range from 13.02 to 17.13 for the HSAs and from 9.21 to 14.05 for the seasonal HSAs, respectively. Seasonal HSA is highly sensitive to season, as it is large in June to August. The spatial distribution of the HSAs in March and June is shown in Fig. 8, and the percentage of the HSAs in Meishan watershed is shown in Table 4.

The results show that: according to the spatial distribution of surface runoff, the runoff volume and its generating location coincide with the distribution of river location and topography index in Meishan watershed. At time scale the sensitive hydrology months are the period of February–October. For the most months, non-HSAs accounts for the largest portion at space scale in the watershed. In July, the HSAs accounts for over 80 %. The hydrological sensitive boundary fluctuates much greater with season. The main surface runoff generation
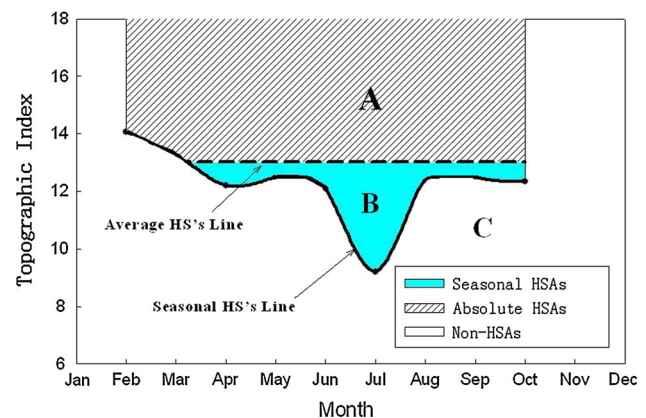

Fig. 7 Identification of the HSAs in Meishan watershed

probability in 1 year occurs in July with the critical topographic index 9.21. Meanwhile at the spatial scale, the average hydrological sensitive boundary in Meishan watershed is located in the area with topographic index 13.02. The average HSAs occupies a smaller proportion of HSAs and the area ratio keeps relatively steady over a whole year. However the seasonal hydrological sensitive area varies much greater.

In comparison to the identification method (Chuang et al. 2008), which used rainfall-runoff probability as assessment index of HSA, an improved topography index is combined with the TOPMODEL in this paper for identifying HSAs' location in main runoff generation region. The presented method is a fully quantitative assessment method. This study overcomes the runoff calculation defects of single flow direction algorithm and traditional multiple-flow direction algorithm by combined the Geometric cone inscribed circle algorithm with TOPMODEL. And the new algorithm of the topographic index combined with hydrological model can cope with abnormal raster

Fig. 8 The spatial distribution of the HSAs in Meishan watershed
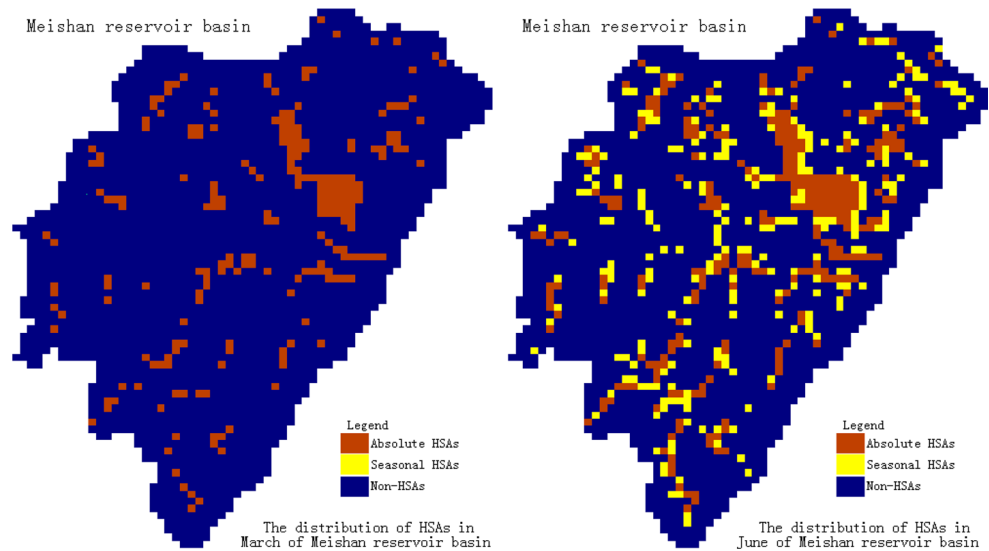
Table 4 Hydrologically sensitive units and the percentage of the HSAs in Meishan watershed

Month	Non-HSAs units/ percentage	Absolute HSAs units/ percentage	Seasonal HSAs units/ percentage	Total units of the watershed
2	2,474/94.93	132/5.07	0/0.00	2,606
3	2,380/91.33	226/8.67	0/0.00	2,606
4	2,092/80.28	297/11.40	217/8.33	2,606
5	2,182/83.73	297/11.40	127/4.87	2,606
6	2,062/79.13	297/11.40	247/9.48	2,606
7	459/17.61	297/11.40	1,850/70.99	2,606
8	2,182/83.73	297/11.40	127/4.87	2,606
9	2,182/83.73	297/11.40	127/4.87	2,606

data in DEM. It can reflect an influence coming from hydrological similarity and topographic features on surface runoff. As an important parameter, Topographic index reflects the characteristics of watershed topography. To a great extent, it determines the flow direction, flow path and the cumulative trend in watershed. However the spatial distribution of actual soil water and runoff trend is also affected by some other factors such as rainfall distribution variability at time and space scale, so using a single topographic index to simply reflect hydrological processes of watershed is not in line with the actuality (Kong and Rui 2003; Lyon et al. 2004; He et al. 2012). The generating location of surface runoff takes dynamic changing status affected by many factors such as topography, climate, soil water and so on. Besides, there is a close relationship between topography and the saturated zone in hydrological sensitive areas (Agnew et al. 2006). The present researches on HSAs identification all focused on the surface runoff probability in watershed (Chuang et al. 2008). Based on the above research, this paper proposed a new calculation method on surface runoff probability, which was monthly saturation probability. And based on soil water and topographic index and distribution, monthly saturation probability is used to analyze the occurrence trend of surface runoff during rainfall period. In accordance with the priority of the monthly, the average and the seasonal hydrological sensitive boundary, the hydrology sensitive area can be identified at two-dimensional coordinate system with time scale and spatial scale for any watersheds. The method better considers the topographic features distribution at space scale and monthly saturation probability at time scale. The modeling and analysis results in Meishan watershed in China reflect the reasonability and applicability on HSA identification.

6 Conclusions

The key problem on hydrological sensitive areas identification lies in the determination on the surface runoff size and spatial distribution. Thereby the monthly runoff probability combined with topography is determined to further set up hydrological sensitive boundary and range. The proposed method for calculating the probability of surface runoff in this paper reflects occurrence trends of surface runoff during rainfall period. Based on this a topographic index based method in this study is proposed to identify the HSAs in agricultural watershed, Meishan, and the relationship between the total surface runoff and topographic index is investigated. And the average hydrological sensitive boundary, critical monthly sensitive boundary and seasonal hydrological sensitive boundary are described quantitatively. The HSAs of watershed and their variation can be indicated at time and space scale. It could be concluded that the temporal-spatial distribution of the

HSAs is featured by: (1) the average and seasonal HSAs are concentrated, the average HSA shows less temporal variation throughout the year; (2) In most months the non-HSAs accounts for the largest portion of the Meishan watershed, followed by the average HSAs and the smallest is the seasonal HSAs.

This study provides a good reference to understand the variation of water quantity process and the variation of runoff in highly regulated river basin, and is expected to support the watershed management. The study might provide an insight into the temporal and spatial variation of the runoff contributing areas and has important practical significance in agricultural best management practice.

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