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Terrain analysis and steady-state hydrological modelling of a small catchment in southern China

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Abstract: Many hydrological characteristics of a catchment can be inferred from its topography. The eco-hydrological model, Topog, uses a sophisticated analysis of topography to describe the hydrological characteristics of a catchment in detail. This paper describes an integrated terrain analysis and steady state hydrological modelling study of a small forest catchment on Leizhou Peninsula, southern China using Topog. The terrain analysis was based on a DEM (digital elevation model) of the central part of the peninsula including the upper valley of the Nandu River. The basic hydrologic characteristics defining the Jijia catchment were catchment boundary, high points and saddles, calculated ridges and streams, and an element network separating the catchment into a large number of relatively uniform units for modelling. The topographic attributes of each element were calculated automatically, including slope, aspect, upslope contributing area and potential incident solar radiation. The slope of the catchment was relatively low: the difference between slopes of most elements was in the range of 2.8~5.7 degree, or less than 2.8 degree. The general description of the Jijia catchment provided by Topog included total catchment area of 0.63 km^2 and average amount of incident radiation of 44, 25, and 34 $MJ \cdot m^{-2} \cdot d^{-1}$ for summer, winter and equinoxes, respectively. The catchment convergence index and steady-state wetness indices (WI) of the elements of the Jijia experimental catchment with and without solar radiation-weighting were also obtained. From steady-state drainage flux modelling, we obtained a distribution of WI across the catchment. By setting different parameter values of uniform drainage flux, the mapped simulations of WI over the catchment indicated that the bigger the uniform drainage flux was, the higher the WI would be.We modelled a radiation-weighted drainage index at different values of uniform transmissivity (*T*), different shaded soil fraction (*Es*), and different uniform rainfall (*R*). The result illustrated that the mapped distribution of WI varies as a consequence of these different data inputs. The distribution of WI was strongly affected by *T* values which indicated that soil wetness within some stream zones might extend more widely, given a bigger *T* value. Conversely, lower values of *T* resulted in more uniform spatial distribution of WI over the catchment. Modelled results also varied with shaded fraction, which indicated that a small increase in solar radiation would result in spatially different distribution of soil moisture content over the catchment. Finally, we made a comparison between a set of uniform rainfall values and found that Topog predicted the expected trend that soil moisture within the catchment increased with increasing uniform rainfall values.

Key words: eucalyptus plantations; Topog modelling; wetness index; Leizhou Peninsula
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Reforestation is important in China, where large areas of eucalyptus plantations have been established in Guangdong and other southern provinces, and selection and breeding have achieved high growth rates. The large scale establishment of eucalyptus plantations in southern India[1], South Africa[2, 3] and other countries have been associated with depletion of water resources[4]. Therefore, it is important to understand the hydrological effects of plantations in China. A four-year study was conducted, beginning in 1999, on the Leizhou Peninsula of western Guangdong, China to measure water use of eucalyptus plantations. Hydrological modelling, in conjunction with field experimentation, can be very useful in understanding catch-

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ment hydrology. Hydrological characteristics including soil moisture and erosion hazard index are readily calculated by the distributed parameter eco-hydrological Topog model[5]. Calculation of the erosion index entails consideration of most of the parameters affecting the erosion processes, including local and source area topography, soil hydraulic and strength properties, vegetation cover and climatic factors[6]. This paper describes the application of the Topog model to some of the project data to make a preliminary analysis of the steady-state hydrological properties of a small typical catchment. Further papers will report the dynamic modelling of streamflow and groundwater recharge in the catchment, in relation to climate and soil conditions and vegetation management.

1 Study site

The plantations are located at Jijia Forest Farm, the soil of which is classified as deep red clay soil, developed form basalt, with high aggregate stability and low fertility within the Jijia demonstration catchment area (20°54′N, 109°52′E). The site is on flat to undulating terrain typical of the peninsula lowlands. Leizhou peninsula, Guangdong Province, has a tropical climate, with long term monthly mean temperatures of around 28 ℃ in July and 16 ℃ in January. Annual precipitation varies from 1 300 mm in the south to 2 500 mm in the north of the peninsula and annual variation is high. Over 80% of the rainfall occurs between April and September, up to half of this in typhoons which occur up to seven times per year. At the study site, the mean daily maximum temperatures were 31º in July and 20º in January, and mean daily minimum temperatures were 22º and 13º in July and January, respectively. The monitored plantations were *Eucalyptus urophylla* planted in mid-1996 (2 m×1.5 m spacing). The investigation of relatively young plantations is appropriate as the usual rotation period for plantations in the area is 4 years. At the experimental plots, the normal land use includes eucalyptus plantations grown on short rotations for woodchip and fuel wood production; sugar cane; and other agriculture including pineapples, bananas, melons and vegetables.

1.1 The Topog hydrological model package

Developed by CSIRO Land and Water, Australia[7–9]and applied in many situations[5, 10–12], Topog describes how water moves through landscapes; over the land surface, into the soil, through the soil and groundwater and back to the atmosphere via evapotranspiration. Conservative solute movement and sediment transport are also simulated. The primary strength of Topog is that it is based on a sophisticated digital terrain analysis model, which accurately describes the topographic attributes of three-dimensional landscapes. It is a versatile and comprehensive hydrological model, intended for application to small catchments (up to 10 km^2, and generally smaller than 1 km^2). Topog is a terrain analysis-based hydrological modelling package which can be used to: describe the topographic attributes of complex three dimensional landscapes; predict the spatial distribution of steady state waterlogging, erosion hazard and landslide risk indices; simulate the transient hydrologic behaviour of catchments, and how it is affected by change of catchment vegetation; imitate the growth of vegetation and how it impacts on the water balance; model solute movement through the soil; model sediment movement over the soil surface. Topog software is available free of charge from the Topog Internet site, http://www.per.clw.csiro.au/topog. The programs are usually compiled in a Unix or Linux operating system.

1.2 Methods

For the development of a DEM, at 1︰10 000 scale, 2.5 m contour interval topographic map (Tangjia Community) was digitized using Didger (Golden Software Inc, USA) software, and the output file was edited using Microsoft Excel to produce Jijia.xyz, a data file in the required format for input to Topog.

Topog was compiled from downloaded source programs in a Gentus Linux 6.2 environment on a Pentium (800 MHz) computer. The Demgen and Element utilities were used to create an element network using a contour interval of 2 m. The-Sumatr, -Params and -Xhistog programs were used to determine and compare the hydrological properties of each element, and the program-Simul was applied to calculate steady-state simulations of wetness index (WI). The wetness index[5, 12] in Topog is calculated as:

$$\mathrm{WI} = 1/MT\int q(x,y)dA \qquad (1)$$

where M is the local slope (m/m, dimensionless), T is the local transmissivity of the soil profile （$m^2 \cdot d^{-1}$）, and the region of integration is the upslope catchment area per unit length of contour. A is element area（m^2）；q is net subsurface drainage flux ($m \cdot d^{-1}$), a spatially varying quantity.

WI depends on local characteristics of soil and terrain, and on integrated drainage characteristics from upslope. All of these can be spatially variable. Changes in any of them due to land use will result in a change in WI. This is the basis for the modelling techniques applied in Topog.

2 Results

As many other researchers have demonstrated, the eco-hydrological model Topog focuses on describing the complex interrelationship between topography, soils, climate and vegetation. Topog is sophisticated in handling of complicated contour topography, which begins with a digital elevation model（DEM）of the area to be modelled.

2.1 Terrain Analysis using Topog

Almost all the analysis of catchment characteristics is based on the topography[13]. Contours of the hillslope, and the network of computational elements are shown in Figure 1. The basic hydrologic characteristics of the Jijia catchment are shown, including catchment boundary, high points and saddles, calculated ridges and streams, and element network. Once the surface discretisation has been completed, a suite of algorithms are used to perform a range of analyses on each element in the

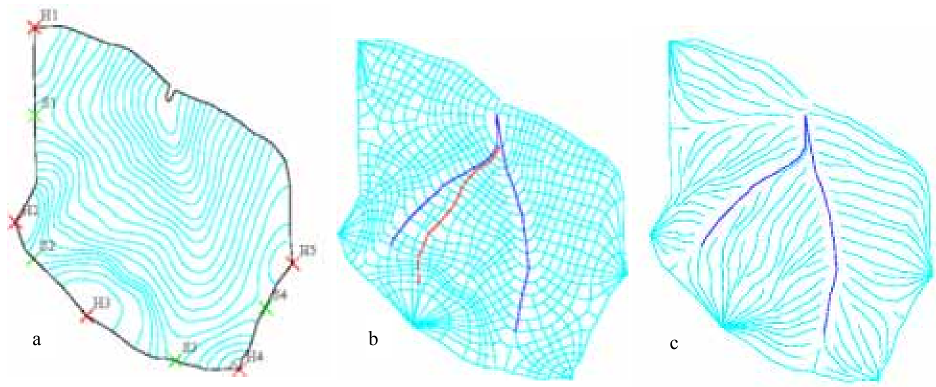

Fig. 1 Full element network for Jijia demonstration catchment, illustrating analysis of complex topography. Results shown for (a) catchment boundary and high points (H) and saddle points (S), and (b) elements derived from Topog-element, plotted at 2 m intervals, showing derived stream channels (blue) and derived dividing ridge (red); and (c) possible contour-based runoff trajectories and streams by Topog modelling

computed network. The topographic attributes automatically calculated include slope, aspect, upslope contributing area and potential solar radiation. All the results are stored in various files for access during later hydrologic simulations. The red line in Figure 1(b) shows a calculated ridge between two valleys（or streams）.

The slope of the catchment is low, which is in accordance with the general topography of Leizhou Peninsula. The slopes of most elements are in a range of 2.8~5.7 degree, or less than 2.8. Figure 2(a) shows variation in aspect across the catchment, which would impose effects on distribution of solar radiation over the catchment.

We now have a general idea of the hydrological characteristics of the Jijia catchment using Topog's analysis of element attributes, such as catchment convergence index, winter and summer radiation. The total area of the catchment is 0.63 km^2 and it has been divided into 751 elements in all. The largest element has an area of 3 378 m^2 while the smallest element is 139 m^2 with average area of 844 m^2 (Figure 1(b)). As shown in Figure 2(b), the slope is gentle and the maximum slope is 6.3 degree with average slope of 3.1. The maximum, the minimum and the average hill slope length are 141 m, 9 m and 31 m, respectively. The maximum, average, and minimum

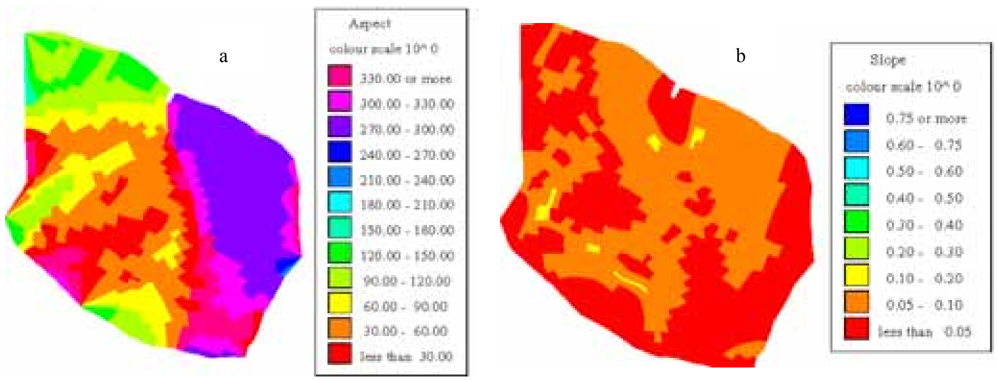

Fig. 2 Distribution of aspect and slope over Jijia catchment deduced by Topog from the DEM, shown (a) for aspect and (b) for slope

amount of summer radiation are 44 $MJ \cdot m^{-2} \cdot d^{-1}$, 44 $MJ \cdot m^{-2} \cdot d^{-1}$, and 42 $MJ \cdot m^{-2} \cdot d^{-1}$, respectively. Those of winter radiation are 27 $MJ \cdot m^{-2} \cdot d^{-1}$, 25 $MJ \cdot m^{-2} \cdot d^{-1}$, and 22 $MJ \cdot m^{-2} \cdot d^{-1}$, respectively; while those of equinox radiation are 35 $MJ \cdot m^{-2} \cdot d^{-1}$, 34 $MJ \cdot m^{-2} \cdot d^{-1}$, 33 $MJ \cdot m^{-2} \cdot d^{-1}$, respectively (Figure 3).

2.2 Steady-state modelling of Wetness Index for the Jijia Catchment

Topog requires the values of environmental state vari-

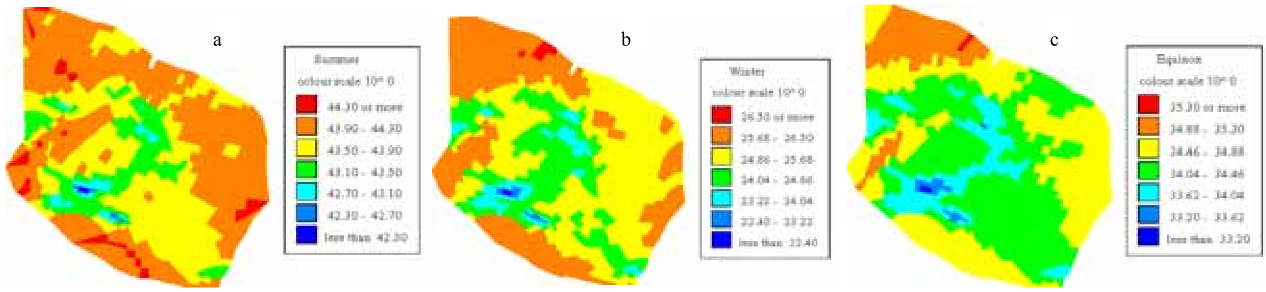

Fig. 3　The distribution of solar radiation over the catchment shown (a) for the winter, (b) for summer, and (c) for equinox

ables such as soil depth, hydraulic conductivity and vegetation cover, all of which are likely to be spatially distributed in the catchment.

With the results from Topog modelling, we obtained a distribution of WI of the catchment. By setting different parameter values of uniform drainage flux (the steady downslope movement of water through the soil of the catchment), the simulations shown in Figure 4 were derived under steady-state conditions, but transient simulations can also be modelled. The mapped distribution of WI over the Jijia Catchment is shown in Figure 4a and 4b, indicating that the bigger the uniform drainage flux is, the larger scale the WI will be. Such maps are useful in deciding whether localized planted sites are similar to each other for comparison of tree growth potential.

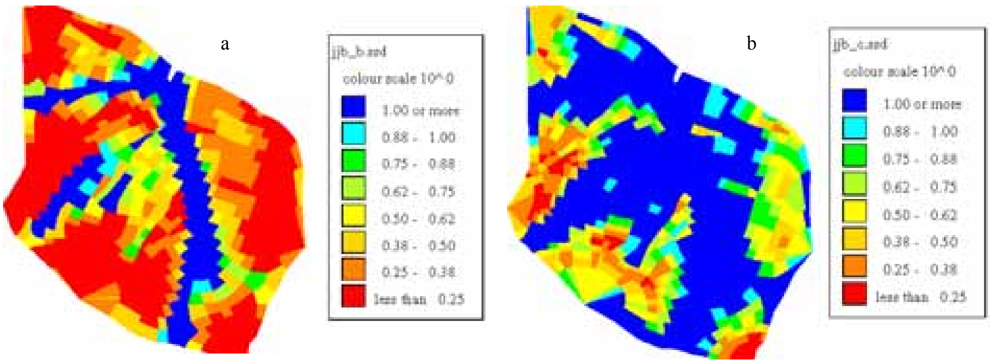

Fig. 4　Distribution of WI in the Jijia catchment (a) for uniform drainage flux at the rate of 0.3 mm·d^{-1} and (b) for uniform drainage flux at the rate of 1.0 mm·d^{-1}

2.3　Radiation-weighted drainage index

If the amount of solar radiation is taken into account in the modelling, there should be another pattern of distribution of WI over the catchment, because differences in radiation among elements affect the loss of water by evapotranspiration. We modelled radiation-weighted drainage index at different values of uniform transmissivity (*T*). The results illustrate that at different values of shaded fraction, different uniform *T*, and different uniform rainfall are applied, the mapped distribution of WI varies as a consequence of these different data inputs.

The distribution of WI at different uniform *T* values would have different responses even at the same uniform rainfall and other parameter inputs(See Table 1). Distribution of WI in Figure 5a and 5b is just in this case to show different resulting classes in the catchment area.　In Figure 5a, WI on 83% of the area ranged from 0.25~0.50, and 16% of area ranged from 0.50~1.0, respectively. By comparison, the two indices as shown in Figure 5b are 60% and 36%, respectively, reflecting a wetter catchment when uniform rainfall is greater. And this difference showed that redistribution of soil moisture is strongly affected by soil transmissivity values. Soil wetness (indicative of potential waterlogging) within some stream areas may extend faster to a bigger scale in adjacent elements, given a bigger uniform *T* value as shown in Figure 5b.

The uniform *T* value of 3.0 m^{2}·d^{-1}and uniform rainfall value of 4.0 mm·d^{-1} we re next set to the same values two times for modelling of radiation-weighted drainage index, while the shaded fraction parameter was set to 0.02 and 0.05, respectively. The differences between them are shown in Figure 5b and Figure 5c. In Figure 5c the mapped distribution of WI was 12% of area in the range from 0.125 to 0.25, 81% of area in the range from 0.25 to 0.50, and 7% of the area in the range from 0.50 to 1.0. This difference between them indicated that increased solar radiation would result in spatially different re-distribution of

Table 1 Parameter values for steady-state modelling of wetness indices

T(uniform transmissitvity)/ ($m^2 \cdot d^{-1}$)	*R*(uniform rainfall)/ ($mm \cdot d^{-1}$)	*Es*(shaded fraction energy)	Applied to
2.0	3.0	0.02	Figure 5a
3.0	4.0	0.02	Figure 5b
3.0	4.0	0.05	Figure 5c
4.0	5.0	0.05	Figure 5d
2.0	5.2	0.05	Figure 5e

soil moisture content.

Finally, we compared a uniform *T* value of 4.0 $m^2 \cdot d^{-1}$ and uniform rainfall of 5.0 $mm \cdot d^{-1}$, with a uniform *T* value of 2.0 $m^2 \cdot d^{-1}$ and uniform rainfall of 5.2 $mm \cdot d^{-1}$. The resulting s patial differences in radiation-weighted drainage index are shown in Figure 5d and Figure 5e. The mapped distribution of soil moisture content（WI）in Figure 5d shows 35% of the area in the range from 0.25 to 0.50, 62% of area in the range from 0.50 to 1.0. In Figure 5e with lower transmissivity and slightly higher rainfall, the distribution of WI was 11% and 86% of the area in

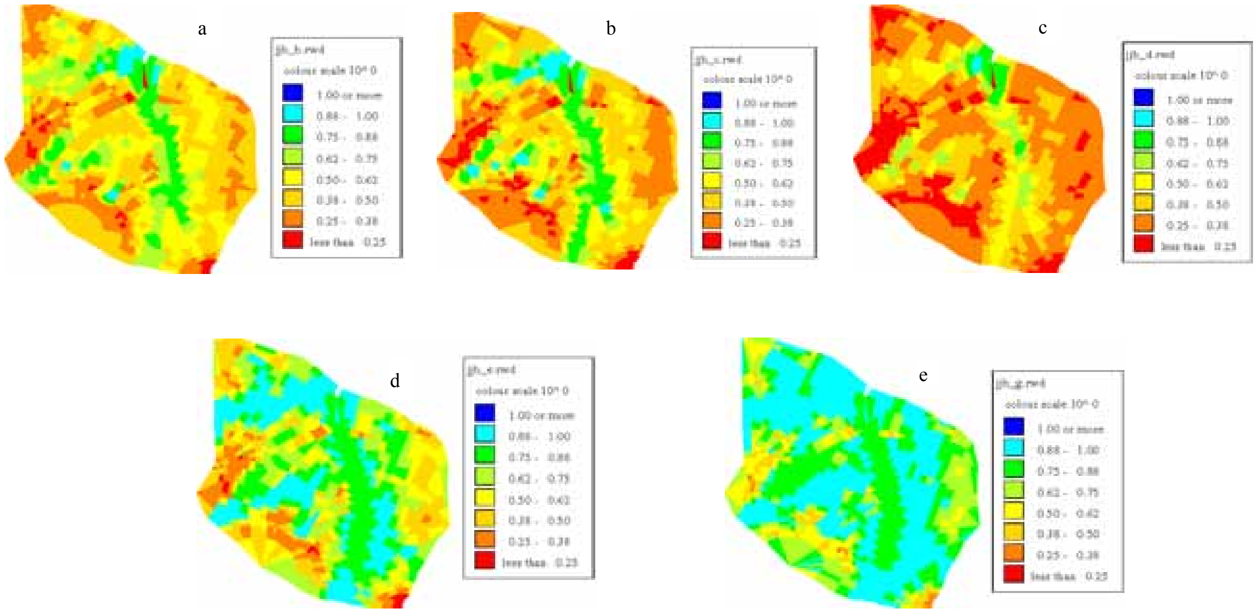

Fig. 5 Distribution of solar radiation-weighted WI over the catchment in different conditions. Shown (a) for uniform *T* assumed as 2.0 $m^2 \cdot d^{-1}$ (b) for *T* 3.0 $m^2 \cdot d^{-1}$; and (c) for shaded fraction of 0.05 with the same uniform *T* value as (b); and (d) for uniform rainfall of 5.0 $mm \cdot d^{-1}$ and uniform *T* of 4.0 $m^2 \cdot d^{-1}$; and (e) for uniform rainfall of 5.2 $mm \cdot d^{-1}$ and uniform *T* of 2.0 $m^2 \cdot d^{-1}$

the corresponding classes. Results from this modelling indicate that lower soil transmissivity leads to a more uniform spatial distribution of WI over the catchment, as shown in Figure 5d and Figure 5e.

We made a comparison of parameter data input for Figure 5e with the rest of the results from 5a to 5d, we found that there is a trend that soil moisture within the catchment increases with uniform rainfall value.

3 Conclusions

The hydrological processes at a catchment scale are driven by climate, soil and vegetation factors, which are not fully addressed in this preliminary analysis. The results obtained above should provide a preliminary appreciation of influences of topography, rainfall, radiation and soil transmissivity on hydrological responses. The appropriate niche for physical models such as Topog is most likely to simulate catchment behaviour under alternative management systems. Catchment management, for most purposes, requires a good understanding of the system's response to change. Topog is a useful tool to predict that response[12]. The wetness index (WI) as calculated by Topog can serve as a useful diagnosis to land managers concerned with protecting landscapes sensitive to disturbance. With the aid of Topog, we can provide alternative cost-effective solutions for decision-making by managers and local residents. Those who would plan the land-use should have some idea of the areas within the catchment which are most subject to high and low soil moisture conditions. At the same time, the results from DEM and steady-state modelling could provide a basis for more detailed dynamic analysis of catchment runoff and groundwater recharge in relation to climate and vegetation changes.

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雷州桉树人工林小集水区地形分析与静态水文学模拟

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摘要：利用小集水区生态水文学模型－Topog 模型对雷州半岛桉树人工林纪家示范小集水区进行了地形分析和静态水文学模拟。地形分析表明，该集水区地表较为平坦，集水区总面积为 0.63 km^2，夏季、冬季与春（秋）分平均太阳辐射值分别为 44 $MJ·m^{-2}·d^{-1}$、25 $MJ·m^{-2}·d^{-1}$ 和 34 $MJ·m^{-2}·d^{-1}$。在考虑太阳辐射影响与不考虑太阳辐影响两种情况下进行了集水区土壤含水量指数（WI）静态模拟。设定不同的静态壤中流参数值，Topog 模型模拟结果表明，静态壤中流越大，在集水区内高 WI 的分布范围越大，也即土壤含水量越高。在考虑太阳辐射影响的条件下，分别设置不同的土壤导水率（*T*）、地表阴蔽系数（*Es*）、平均降雨量（*R*）进行了模拟。模拟结果表明，WI 分布依各参数的不同而变化。*T* 越大，在集水区内的 WI 重新分布越快；*T* 越小，在集水区内 WI 趋向于平均分布。*Es* 越大，集水区土壤所保持的含水量越高。集水区 *WI* 随 *R* 增大而有升高趋势。
关键词：桉树人工林；Topog 模拟；土壤含水量指数；雷州半岛