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GIS-aided Analysis of Plant-Soil Ecological Water Requirement in Yanhe Watershed

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Although water has the central function of the bloodstream in the biosphere especially in arid or semi-arid regions such as Yanhe watershed in northwestern China, yet the very limited attention is paid to the role of the water-related processes in ecosystem. In this research, based on continuous 30-year weather condition report data and 10-year soil water content data in Yanhe watershed, a comparatively accurate method for measuring the minimum, moderate and maximum ecological water requirement of plant-soil landscapes has been put forward by using experiential models and GIS spatial analysis. Additionally, the change characters of ecological water requirement have been addressed from spatial-temporal dimensions. The results show that: (1) In Yanhe watershed, the ecological water requirement of plant-soil landscapes is more in summer than in other seasons; (2) The landscapes of ecological water presenting highest requirement are forest-cohesive loam, forest-loam and forest-sandy loam, while the landscapes of ecological water presenting lowest requirement are grass-sandy loam, grass-loam and grass-cohesive loam; (3) The mean annual precipitation in Yanhe watershed can only satisfy the minimum ecological water requirement, but cannot meet the moderate and maximum ecological water requirement.

Key words: Plant-soil landscapes, Ecological water requirement, GIS spatial analysis, Yanhe watershed.

Although water has the central function of the bloodstream in the biosphere especially in arid or semi-arid regions such as Yanhe watershed in northwestern China, yet the very limited attention is paid to the role of the water-related processes in ecosystem. Since the early 1990s, eco-hydrology research has been progressing in good time. Synchronously, the study on ecological water requirement has taken a prominent place in this domain (Wang *et al*., 2003; Wang *et al*., 2005; Liu, 2004; Peter, 1998; Petts, 1996). Accordingly, the issue of ecological water requirement has become a challenging problem confronting with many scholars. Gleick (1996) defined the conception of basic ecological water requirement, i.e. providing the natural habitat with a certain amount of qualified water to minimize the variation of the natural ecosystem, and protect the species diversity and ecological integrity. Zhao (2001) brought forward the threshold of ecological water requirement of vegetations; Zhang (2002) discussed the calculation method of the minimum ecological water requirement by taking Huang-huai-hai plain as an example; Zhang (2003) established the model to describe the relationship between the vegetation growing and water table; He (2004) counted the minimum and moderate ecological water requirement of vegetations in the Loess Plateau by using RS and GIS. Chinese scholars, as well as their foreign counterparts, have done much work on the conception and calculation of ecological water requirement. However, some transparent challenges still exit. For instance, how to

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quantificationally measure ecological water requirement of compound ecosystem such as plant-soil landscapes, how to confirm the thresholds of different water requirement grades, etc (Yang and Cui, 2004). Since that, we put forward a comparatively accurate method for measuring the minimum, moderate and maximum ecological water requirement of plant-soil landscapes by using experiment models, field tests combined with GIS spatial analysis. Also, the practice process is demonstrated by taking Yanhe watershed in northwestern China as a case.

Yanhe originates from Tianciwan village in Jingbian county of Shaanxi province, northwestern China. It flows from northwest to southeast through Zhidan county, Ansai county, Baota county as well as Yanchang county, respectively, and finally into Yellow River. It belongs to the primary subsidiary stream of Yellow River with the total length of 286.9km, and the water collecting area of 7689.1km^2 (Fig.1). Yanhe watershed lies in arid and semi-arid of Loess Plateau, northwestern China, between 35°21' ~37°30' N in latitude and 107°40'~110°33' E in longitude. Its terrain descends from northwest to southeast with mean altitude of 950m. It represents the typical characters of continental monsoon climate with mean annual air temperature of 9.2°C, mean annual precipitation of 500mmÿwhile mean evaporation of 1000mm. The zonal vegetations include deciduous broadleaf forest, conifer forest as well as shrub-grassland. Most of the deciduous broadleaf forests are heliophile with cold endurance. Most of the conifer forests are secondary vegetation with protection against soil denudation. The shrub-grasslands have the ecological functions of water and soil conservation. Mean annual runoff volume is 0.289 billion m^3. Runoff of summer occupies 50% volume of the total year. Mean annual sediment discharge into the Yellow River is 0.082 billion tons, and mean erosion modulus reaches 11200t per km^2. Due to the scarcity of natural precipitation coupled with the competitions between ecological water requirement and economic water need, there is a serious degeneration for ecosystem including break of river water, decline of water table, deterioration of water quality and serious soil erosion. Therefore, identifying ecological water requirement is not only a valid reference for managing the limited water resource, but also an effective planning tool for constructing water conservancy projects.

Fig. 1. Sketch map of Yanhe watershed

MATERIALS AND METHODS

Data collecting and processing

In this study, we collect continuous 30-year weather condition report data (1975-2004) that include latitude, longitude and altitude of meteorological stations, monthly mean precipitation, temperature, vapor pressure, wind velocity etc., and 10-year soil water content data (1995-2004), as well as some images such as TM (2010) of study area and the map of soil categories in Yanhe watershed.

According to the images, the interpretation of remote sensing images has been done in Erdas9.2 platform, and the map of vegetation categories can be obtained. And then, the 'intersect Command' is employed in ArcGIS9.2 platform to produce the map of plant-soil landscapes (Fig.2).

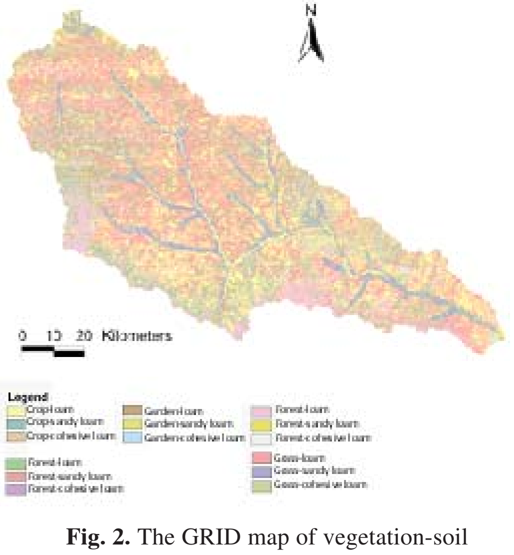

Fig. 2. The GRID map of vegetation-soil landscapes in Yanhe watershed

According to the weather condition report data, the method of 'Kriging interpolation' is adopted in ArcGIS9.2 platform to describe the spatial distribution of average evaporation, precipitation as well as runoff depth in one month or in one year. Also, the 'Zonal functions' is performed in Arcview3.3 platform to summarize the minimum, average and maximum of the evaporation, precipitation as well as runoff depth in a certain plant-soil category.

Measuring models

Towards the plant-soil landscapes, ecological water requirement mainly includes vegetation evaporation and soil water content. The measuring model is expressed as following equations:

$$SWC = W_q \times A \times H \quad ...(1)$$

$$ET_j = ETQ_j \times A / 1000 \quad ...(2)$$

$$EWQ_j = SWC + ET_j \quad ...(3)$$

$$EWQ = SWC + \sum_{j=1}^{12} ET_j \quad ...(4)$$

Where SWC (m^3) represents the soil water content in some vegetation region; W_q (m^3/m^3) refers to the soil water content ration, A (m^2) refers to the area of the certain vegetation region, H (m) refers to the soil depth. ET_j (m^3) represents the vegetation evaporation in month j, ETQ_j (mm) refers to the vegetation evaporation ration in month j. EWQ_j (m^3) represents the ecological water requirement in month j, and EWQ represents the mean annual ecological water requirement.

Generally, the ecological water requirement of vegetations mainly comes from soil water content. Commonly, the minimum, the moderate and the maximum of the soil water content rations should exist.

According to the characteristic of soil water movement and the degree of soil water being absorbed by vegetation, we classify the soil water content as emarcid moisture content, growth block water content, critical water content as well as field capacity content.

The minimum soil water content ration of different vegetation categories should maintain vegetation basic growth and survival, thereby, is defined as the growth block water content. Commonly, the minimum soil water content ration occupies 40%~50% of the field capacity content (Xu, 2003). In our research, 45% of the field capacity content is regarded as the minimum rating soil water content.

When the soil water content is larger than the field capacity content, soil pore space will be filled by water, which limits the vegetation roots to absorb oxygen, water and mineral matter. That shows the soil water content should not be more than field capacity content for a long time. Therefore, the field capacity content is regarded as the maximum soil water content ration.

The critical water content is between growth block water content and field capacity content. When the soil water content is between critical water content and field water capacity, the vegetation growth is not limited by soil water content. Thereby, it is defined as the moderate rating soil water content. Commonly, the critical water content occupies 70%~80% of the field capacity content (Milly, 1992). In our research, 75% of the field capacity content is regarded as the moderate soil water content ration.

The field capacity content is related with soil texture. In this study, according to continuous 10-year soil water content data from soil fertility observation stations in Yanhe watershed, using 'Saxton' model that reflects the relation between soil water content and soil grain (Saxton, 1986), we calculate field capacity content of different soil texture, and further to confirm the minimum, moderate and maximum soil water content ration (Table 1).

The vegetation evaporation capacity is mainly influenced by climate, soil water content and vegetation growth status. In arid or semi-arid region, it is difficult to achieve the optimal soil water content and vegetation growth status, so the actual vegetation evaporation is always less than the potential but with a certain proportion. FAO (Food and Agriculture Organization) recommends Penman-Monteith formula as the standard method to calculate the potential vegetation evaporation (Penman, 1948), and the formula can be used in China (Zhou, 2002). The measuring model is expressed as following equations:

Table1. The moisture parameter for soil texture classification

Soil texture categories	Minimum soil water content ration (m^3/m^3)	Moderate rating soil water content (m^3/m^3)	Maximum soil water content ration (m^3/m^3)
loam	0.160	0.267	0.356
sandy loam	0.142	0.237	0.316
cohesive loam	0.187	0.312	0.416

$$ET_a = \gamma \times ET_p \quad ...(5)$$

$$\gamma \approx \frac{w}{w_k} \quad ...(6)$$

Where ET_a represents the actual vegetation evaporation; ET_p refers to the potential vegetation evaporation; w refers to the actual soil water content; w_k refers to the critical soil water content; γ refers to the proportion of ET_a and ET_p, and it can be described as the ratio of w and w_k approximately.

RESULTS

According to the above models, we calculated the mean annual and mean monthly ecological water requirement of different plant-soil landscapes. In this process, we regard the growth block water content, critical water content and field capacity content as the minimum, moderate and maximum soil water content, respectively, additionally, consider the minimum, average and maximum of the continuous 30-year vegetation evaporation as the minimum, moderate and maximum vegetation evaporation. In arid or semi-arid region, because of the very limited water resources, we focused the minimum ecological water requirement of different plant-soil categories (Tab.2), and addressed the change characters from spatial-temporal dimensions.

The temporal characters analysis

Firstly, we discuss the character of ecological water requirement in a month. Table 2 reflects the minimum ecological water requirement in growing period (from April to October). Apparently, the ecological water requirement of

Table 2. The minimum ecological water requirement of vegetation-soil landscapes in Yanhe watershed

Vegetation-soillandscapes	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Growing period
Crop-loam	27.20	45.42	50.97	50.04	48.29	34.75	24.70	281.37
Crop-sandy loam	27.20	45.42	50.97	50.04	48.29	34.76	24.70	281.38
Crop-cohesive loam	27.19	45.46	51.00	50.03	48.29	34.73	24.68	281.38
Garden-loam	35.91	59.18	65.28	61.79	58.21	43.09	30.52	353.98
Garden-sandy loam	35.97	59.22	65.42	61.83	58.23	43.08	30.67	354.42
Garden-cohesive loam	36.23	59.22	64.99	61.48	58.07	42.81	30.17	352.97
Forest-loam	41.28	73.12	81.55	71.35	65.24	46.04	33.99	412.57
Forest-sandy loam	41.28	73.10	81.57	71.33	65.23	46.05	34.00	412.56
Forest-cohesive loam	41.35	73.25	81.53	71.41	65.23	45.98	33.88	412.63
Shrub-loam	26.50	41.97	48.92	49.68	47.29	33.70	20.86	268.92
Shrub-sandy loam	26.50	41.96	48.92	49.67	47.30	33.71	20.85	268.91
Shrub-cohesive loam	26.44	41.99	49.05	49.77	47.38	33.73	20.94	269.30
Grass-loam	21.21	31.54	39.27	44.49	43.52	31.18	20.60	231.81
Grass-sandy loam	21.21	31.55	39.27	44.49	43.53	31.17	20.60	231.82
Grass-cohesive loam	21.21	31.55	39.24	44.49	43.49	31.16	20.60	231.74

Explanation: The measure unit is (mm).

plant-soil landscapes is more in summer (from June to August) than that in other seasons. Concretely, the ecological water requirements of crop-loam, crop-sandy loam, and crop-cohesive loam in summer occupy 53.06%, 53.06% and 53.07% of the total volume in growing period, respectively; the ecological water requirements of garden-loam, garden-sandy loam, and garden-cohesive loam in summer occupy 52.34%, 52.33% and 52.28% of the total volume in growing period, respectively; the ecological water requirements of forest-loam, forest-sandy loam and forest-cohesive loam in summer basically occupy 52.87% of the total volume in growing period, similarly; the ecological water requirement of shrub-loam, shrub-sandy loam and shrub-cohesive loam in summer occupy 54.25%, 54.25% and 54.29% of the total volume in growing period, respectively; the ecological water requirement of grass-loam, grass-sandy loam and grass-cohesive loam in summer occupy 54.91%, 54.91% and 54.90% of the total volume in growing period, respectively.

The spatial characters analysis

According to the measuring models, we calculate the ecological water requirement by performing the mathematics operations of these correlative maps. And the result is described as Figure 3. Apparently, the locations of ecological water holding higher requirement mainly lie in the loess undulating ground with beam-figure in the south of Yanhe watershed. The locations of ecological water keeping lower requirement mainly lie in river valley terrace. Also, the landscapes of ecological water presenting highest requirement are forest-cohesive loam, forest-loam and forest-sandy loam, and, per area ecological water requirement of forest-cohesive loam is the largest with the volume of 502.31mm/a, and it is 1.29 times of the average of all landscape categories. The landscapes of ecological water presenting higher requirement are garden-cohesive loam, garden-loam and garden-sandy loam, and, per area ecological water requirement is between 422.27-443.51mm/a. The landscapes of ecological water presenting medium requirement are crop-cohesive loam, shrub-cohesive loam and crop-loam, and, per area ecological water requirements is between 358.27-371.17 mm/a. The landscapes of ecological water requirement presenting lower requirement are shrub-sandy loam, shrub-loam and crop-sandy loam, and, per area ecological water requirement is between 337.15-349.57 mm/a. The landscapes of ecological water presenting lowest requirement are grass-sandy loam, grass-loam and grass-cohesive loam, and, per area ecological water requirement of grass-sandy loam is the smallest with the volume of 300.01mm/a, and it is 0.77 times of the average of all landscape categories.

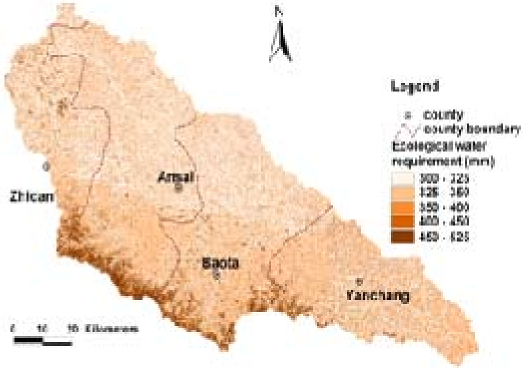

Fig. 3. The map of the minimum ecological water requirement of plant-soil landscapes in Yanhe watershed

CONCLUSIONS

In this study, according to the calculation of mean annual soil water content ration and vegetation evaporation ration, we define the threshold values including the minimum, moderate and maximum ecological water requirement of the plant-soil landscapes.

Concretely, in Yanhe watershed, the mean annual minimum ecological water requirement is $2541.25\times10^6 m^3$, and the mean annual precipitation can completely satisfy the minimum water need for plant-soil landscapes with the surplus of $374.60\times10^6 m^3$. The mean annual moderate ecological water requirement is $3608.58\times10^6 m^3$, and the mean annual precipitation cannot satisfy the moderate water need for plant-soil landscapes with the scarcity of $692.73\times10^6 m^3$. The mean annual maximum ecological water requirement is $4243.89\times10^6 m^3$, and the mean annual precipitation cannot satisfy the maximum water need for plant-soil landscapes with the scarcity of $1328.04\times10^6 m^3$. According to the above-mentioned data, we can conclude that there is a serious lack of ecological water in Yanhe watershed. At present, it is important to allocate water resource among different landscapes to make plant-soil landscapes healthy.

In this study, a comparatively accurate method for measuring the minimum, moderate and maximum ecological water requirement of plant-soil landscapes has been put forward. It is helpful for perfecting water information system and allocating water resource scientifically. However, some aspects need to be considered deeply and modified. (1) Definition of the thresholds: Internationally, at present, an accepted and general method for measuring the thresholds of vegetations ecological water requirement has not been defined. We regarded the minimum, average and maximum of the continuous 30-year vegetation evaporation as the minimum, moderate and maximum vegetation evaporation in virtue of GIS spatial analysis. From the angle of statistics, it is significative to adopt continuous 30-year weather data. If some field experiments can be done to test the calculation results, the conclusions will be more exact. (2) Time scale analysis: In the research, the mean annual ecological water requirements at different thresholds are measured. In the future study, the temporal differences of ecological water requirement in arid year and humid year will be analyzed, and it will be helpful for allocating ecological water among various landscapes at yearly scale.

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