RS and GIS Aided Study on Tempo-spatial Differences of Ecological Water Requirement at Landscape Scale in Weihe Sub-watershed

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Abstract
At present, the related studies mainly target single ecosystem, but the further studies on the critical thresholds of ecological water requirement for composite ecosystem are needed. Therefore, we select the plant-soil combined system in Weihe sub-watershed as a research object. Firstly, we obtain the spatial distribution maps of plant and soil types based on the TM remote sensing images and the soil texture data. Also, we use the corresponding mathematical models to evaluate the ecological water requirement of the plant-soil composite system at landscape scale and analyse the tempo-spatial distribution characteristics based on RS and GIS technologies. Then, we get the following results: 1) According to the spectral and texture characteristics of TM remote sensing images, we divide the land cover into woodland, arable land, grassland, waters, construction land and unused land. From 2000 to 2010, the areas of woodland and construction land increased obviously while the areas of arable land and unused land decreased. These changes indicate the ecological improvement and economic development. 2) At the temporal scale, with the increase of plant areas year by year, the amount of minimum ecological water requirement in Weihe sub-watershed increased accordingly. Therein, the amount of minimum ecological water requirement of woodland-clay loam changed most obviously, with an increase of 656.215×10^3 m^3; while the amount of minimum ecological water requirement of woodland-gravel loam decreased a little with the value of 7.966×10^3 m^3. 3) At the spatial scale, the amounts of minimum ecological water requirement are different significantly among the plant-soil landscapes in Weihe sub-watershed. Therein, the landscape types of higher ecological water requirement per unit area are woodland-clay loam, woodland-loam, woodland-sandy loam and woodland-gravel loam, and the water requirements ranged from 0.4621 to 0.5023 m^3/m^2. The landscape types of lower ecological water requirement per unit area are grassland-clay loam, grassland-loam, grassland-sandy loam and grass-gravel loam, and the water requirements ranged from 0.2813 to 0.3216 m^3/m^2. In general, because of the higher evapotranspiration from woodlands, the ecological water requirements of woodlands are higher than that of grasslands. The study offers scientific references for making the target of the regional hydrological ecological environment protection and plays a positive role in rational allocation of water resources.

Key words: GIS, Remote Sensing, Plant-soil systems, Ecological water requirement, Weihe Sub-watershed

1. INTRODUCTION

In the 20th century, with the population growth and rapid economic development, the depth and breadth of the use of water resources have been increasing, leading to water shortage, water pollution and ecological damage and so on, which have affected the modernization process seriously and become the bottleneck of sustainable development. The traditional ways of using water resources show that freshwater resources are inexhaustible and totally neglected the relationship between water resources and ecological environment system, which directly lead to the degradation of ecological environment, the reduction of biodiversity, groundwater level decline and many other issues. The Chinese government also pointed out that "water is the source of life, the key of production, the base of ecology". Therefore, eco-hydrology is one of the most important subjects to study the regional development (Han et al. 2010; Hughes and Louw 2010; Bai et al. 2015). And the ecological water requirement is one of the frontiers and core contents of this subject (Shokoohi and Hong 2011; Yang et al. 2012; Hao and Li 2014). Many scholars have defined the concept of ecological water requirement from different perspectives. The basic idea is that ecological water requirement is the minimum amount of water resources to maintain the normal and basic functions of the ecosystems (Gleick, 1998; Li 2012; Nilsalab et al. 2017). At present, the researches of ecological water requirement mainly focus on single eco-environmental water requirement, such as river eco-environmental water requirement (Han et al. 2009; Sun et al. 2012; Wang et al. 2013; Shokoohi and Amini 2014), lake eco-environmental water requirement (Si et al. 2015; Jiang et al. 2016; Sajedipour et al. 2017), wetland eco-environmental water requirement (Yang et al. 2008; Zhong et al. 2008; Sarhadi and Soltani 2013, Dong et al. 2015), urban eco-environmental water requirement (Jia et al. 2011; Nouri et al. 2013; Xu et al. 2014), plant ecological water requirement (Zhang et al. 2010; Zhang et al. 2010; Renata et
al. 2012; Wang et al. 2012), crop ecological water requirement (Hadinia et al. 2017; Ragab et al. 2017; Zamani et al. 2017; Zhou et al. 2017) and so on, but the studies on the composite systems are limited.

The calculation of the ecological water requirement is different according to the research content and the target. Abbaspour and Nazaridoust (2007) calculated the lake water requirement with an ecological approach and identified three variables: ecology, water quality, and water quantity index environmental indicators of Lake Urmia, Iran. Wan et al. (2008) evaluated of ecological water requirement based on hydrological cycle analysis. Kuźniar et al. (2011) used the Penman-Monteith method to assess the water requirement of a mountain pasture sward in the Polish Western Carpathians. Men (2011) estimated watercourse ecological water requirement based on the theory of ecological hydraulic radius model (EHRM). Surendran et al. (2015) used FAO-CROPWAT to model the crop water requirement and assess water resources in Palakkad District of Humid Tropical Kerala, India.

In recent years, remote sensing technology has been widely used in the studies of ecological environment. Sun et al. (2010) presented a new method of validating the remote-sensing (RS) retrieval of evapotranspiration (ET) under the support of a distributed hydrological model: Soil and Water Assessment Tool (SWAT). Jaber et al. (2014) used time series of Satellite Images based on RS technology to detect vegetation cover change in Dhaka City. Wu and Liu (2014) used Moderate Resolution Imaging Spectroradiometer (MODIS) medium-resolution data to document the tempo-spatial variation characteristics of water inundation areas of Poyang Lake. Ahmed et al. (2017) studied the dynamic response of NDVI to soil moisture variations during different hydrological regimes in the Sahel region. Nian et al. (2017) obtained the land cover of the Ejin Delta by interpreting and analysing the image data of four periods to balance water resource competition between irrigation agriculture and ecological demand. Zeng et al. (2017) used Sentinel-1 synthetic aperture radar imagery to analyse changes of the Poyang Lake water area.

In our study, the tempo-spatial differences of ecological water requirement are evaluated at landscape scale. The study provides the scientific references for making the target of the regional hydrological ecological environment protection. It is of great significance to the harmonious development of economy and ecological environment.

2. Data and processing

2.1. Overview of the study region

Weihe Watershed (Xianyang to Tongguan) is located in the southeast of Weihe Watershed, mainly including Xi’an City, Xianyang City, Weinan City and Tongchuan City, which is located at the starting point of the Silk Road Economic Belt (Figure 1). Topography north-south high, low in the middle. It belongs to the temperate semi-arid and semi-humid region with annual average temperature of 6°C-14°C, annual average rainfall of 450-700mm and annual evaporation of 1,000-2,000mm. Natural vegetation is rich in wild plant resources, as one of the important "gene pool" of Chinese seed plants. The soil types are complex and diverse, which provide favourable conditions for the multi-species combination of crops in the region. In recent years, the industrialization and urbanization of the Xi’an and other cities have been advanced rapidly. The contradiction between environmental protections and social economic development has become increasingly prominent. It is of great significance to evaluate the ecological water requirement of plant-soil systems in this area.

\[\text{Figure 1. The geographical location map of the study region}\]
2.2. Data

The image data include 2000 and 2010 Landsat TM (Thematic Mapper) and DEM (Digital Elevation Model) in Weihe Watershed (Xianyang to Tongguan). The thematic data includes 1: 2500000 Shaanxi soil texture types map. The measured data include the meteorological data (latitude, longitude, altitude, mean monthly temperature, mean monthly precipitation, mean monthly wind speed and mean monthly vapour pressure) from the main meteorological stations, and the soil moisture values from soil-fertility stations. These data are used to calculate the ecological water requirement of plant-soil systems in the study region.

2.3. Processing

In the ArcGIS10.2 platform, we use the DEM data for hydrological analysis to extract the watershed boundaries. Then, we get the soil distribution map by digitization of the soil texture data.

In the ENVI5.1 platform, based on the TM remote sensing images, we use the method of supervised classification to generate plant distribution maps. According to the spectral and texture characteristics of TM remote sensing images, we divide the land cover into woodland, arable land, grassland, waters, construction land and unused land. Firstly, we divide the land cover into six types by visual interpretation methods. Then, we establish region of interest, select samples, and compute ROI separability. And we use the maximum likelihood method for supervisory classification. Finally, we use the confusion matrix to evaluate the interpretation accuracy. The Kappa coefficients are 0.9163 and 0.8952 in 2000 and 2010 respectively, and the overall accuracies are separately 90.3759% and 88.9047%. They are better to meet the research demands. The land use maps of the study area are shown below (Figure 2).

![Figure 2](image_url). The land use maps of the study area in 2000 and 2010

3. Assessment model

3.1. Plant ecological water requirement assessment model

Plant ecological water requirement refers to the amount of water needed to maintain the normal growth of plant or maintain the health of the vegetation ecosystem. It is mainly reflected by water consumption for evapotranspiration. Evapotranspiration plays a very important role in plant regulation of hydrological process and water balance analysis of vegetation ecosystem. Plant ecological water requirements are related with the plant areas and evapotranspiration. The main factors affecting plant evapotranspiration are climatic conditions, soil moisture and plant growth. Based on the FAO (Food and Agriculture Organization of the United Nations) crop coefficient method, we take into account the limiting factors of soil water conditions and combine with original meteorological data to calculate the ecological water requirement of plant. The model is expressed as:

$$W_p = E_p \times A_p = (ET_0 \times K_c \times K_s) \times A_p$$

In the formula, $W_p$ is the plant ecological water requirement (m$^3$); $E_p$ is the plant evapotranspiration (mm); $A_p$ is the plant distribution area (m$^2$); $ET_0$ is the reference crop potential evapotranspiration (mm); $K_c$ is the plant coefficient; $K_s$ is the limiting coefficient of soil moisture.
In this paper, the reference crop potential evapotranspiration (ET0) is calculated by standardized and unified Penman-Monteith method recommended by FAO. Researchers have found that the P-M method is also applicable in China (Zhou et al. 2002; Wu et al. 2010; Wang et al. 2013; Fan et al. 2017).

3.2. Soil ecological water requirement assessment model

For different areas, if the plant is not completely covered, only the part of the soil moisture that supports the plant growth is the meaningful soil water requirement. Soil water requirement of dry land is closely related to plant growth and plant water requirement. The ecological water requirements of various soil types are not same because of the differences in the field water holding capacity, soil bulk density, soil thickness and other characteristics. If the amount of soil water is too low, then the concentration of salt in plant cells will rise, causing the death of the plant. If the amount of soil water is too high, the aeration situation will deteriorate, then the root system of plant will be in an anoxic environment, making it hard to absorb water and minerals, thus affecting the growth and development of vegetation. Taking into account the water shortage of the study region, 45% of the field water holding capacity is selected as the minimum water quota of the soil. The model is expressed as:

\[ W_s = \alpha_s \times H_s \times A_s \]  

(2)

Where, \( W_s \) is the soil water requirement (m\(^3\)) under soil depth \( H_s \); \( \alpha_s \) is soil water quota (m\(^3\)/m\(^3\)); \( H_s \) is soil depth (m); \( A_s \) is plant area (m\(^2\)).

The ecological water requirement has different grades for different ecological targets. Therefore, considering the study region being a typical semi-arid area with scarce water resources, we estimate the minimum ecological water requirement for maintaining plant survival and basic growth. Therein, we choose the minimum annual average plant evapotranspiration as the minimum of plant ecological water requirement. Also, we choose the 45% of the field water holding capacity as the minimum of soil water requirement.

4. Results and discussions

Firstly, by the overlay analysis of plant and soil distribution maps, we get the plant-soil landscape maps in watershed (Figure 3). Then, by using the above models we calculate the ecological water requirement at landscape scales.

![Figure 3. The plant-soil distribution maps in Weihe sub-watershed in 2000 and 2010](image)

4.1. Temporal distribution characteristics of ecological water requirement

The minimum ecological water requirement at plant-soil landscape scale in Weihe Watershed (Xianyang to Tongguan) in 2000 and 2010 are shown in Table 1 and Figure 4. It can be seen that the most significant changes in the minimum ecological water requirement are grassland-clay loam and woodland-clay loam. From 2000 to 2010, the amount of minimum ecological water requirement of woodland-clay loam increased by 656.21×10\(^6\)m\(^3\), with an annual average increase rate of 15.25%. If woodland-clay loam increased 1km\(^2\), then the amount of ecological water requirement would increase 0.502×106m\(^3\) correspondingly. The amount of minimum
ecological water requirement decreased by 443.34×10⁶ m³ in grassland-clay loam, with an annual average reduction rate of 5.62%. If grassland-clay loam decreased 1 km², then the amount of minimum ecological water requirement would decrease 0.32×10⁶ m³ correspondingly. The small changes in the minimum ecological water requirement are grassland-gravel loam and woodland-gravel loam. The minimum ecological water requirement of grassland-gravel loam increased by 14.849×10⁶ m³, with an annual average growth rate of 0.61%. And if grassland-gravel loam increased 1 km², then the amount of ecological water requirement would increase 0.281×10⁶ m³ correspondingly. The minimum ecological water requirement of grassland-gravel loam increased by 14.849×10⁶ m³, with an annual average growth rate of 0.61%. And if grassland decreased 1 km², then the amount of ecological water requirement would decrease 0.462×10⁶ m³ correspondingly.

### Table 1. Minimum ecological water requirement of plant-soil systems in Weihe sub-watershed in 2000 and 2010

<table>
<thead>
<tr>
<th>Landscape area (km²)</th>
<th>The amount of soil water requirement (10⁶ m³)</th>
<th>The amount of plant water requirement (10⁶ m³)</th>
<th>The amount of ecological water requirement (10⁶ m³)</th>
<th>2000</th>
<th>2010</th>
<th>2000</th>
<th>2010</th>
<th>2000</th>
<th>2010</th>
<th>2000</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grassland-Loam</td>
<td>406.724</td>
<td>279.459</td>
<td>31.277</td>
<td>21.491</td>
<td>94.279</td>
<td>64.779</td>
<td>125.556</td>
<td>86.269</td>
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<td></td>
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<tr>
<td>Grassland-Clay Loam</td>
<td>2451.83</td>
<td>1073.14</td>
<td>6</td>
<td>9</td>
<td>220.101</td>
<td>96.337</td>
<td>248.760</td>
<td>345.093</td>
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<tr>
<td>Grassland-Sandy Loam</td>
<td>582.478</td>
<td>344.823</td>
<td>9</td>
<td>39.725</td>
<td>23.517</td>
<td>79.930</td>
<td>174.743</td>
<td>103.447</td>
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</tr>
<tr>
<td>Grassland-Gravel Loam</td>
<td>860.08</td>
<td>912.866</td>
<td>42.574</td>
<td>199.367</td>
<td>211.602</td>
<td>788.437</td>
<td>345.093</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Woodland-Loam</td>
<td>5.101</td>
<td>309.583</td>
<td>0.392</td>
<td>0.392</td>
<td>2.105</td>
<td>127.734</td>
<td>2.497</td>
<td>151.541</td>
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<tr>
<td>Woodland-Clay Loam</td>
<td>856.437</td>
<td>2162.67</td>
<td>76.882</td>
<td>353.366</td>
<td>892.320</td>
<td>430.248</td>
<td>1086.463</td>
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<tr>
<td>Woodland-Sandy Loam</td>
<td>88.774</td>
<td>378.249</td>
<td>6.054</td>
<td>25.797</td>
<td>36.628</td>
<td>156.066</td>
<td>42.683</td>
<td>181.862</td>
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<tr>
<td>Woodland-Gravel Loam</td>
<td>2652.24</td>
<td>2635.00</td>
<td>5</td>
<td>6</td>
<td>131.286</td>
<td>130.433</td>
<td>1094.316</td>
<td>1087.204</td>
<td>1225.602</td>
<td>1217.636</td>
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</tr>
<tr>
<td>Arable Land-Loam</td>
<td>1760.16</td>
<td>1486.26</td>
<td>14</td>
<td>135.357</td>
<td>114.294</td>
<td>495.311</td>
<td>418.235</td>
<td>630.667</td>
<td>532.528</td>
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<tr>
<td>Arable Land-Clay Loam</td>
<td>3877.10</td>
<td>3454.00</td>
<td>3</td>
<td>134.048</td>
<td>310.066</td>
<td>1091.017</td>
<td>971.957</td>
<td>1439.065</td>
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<tr>
<td>Arable Land-Sandy Loam</td>
<td>1850.73</td>
<td>1636.55</td>
<td>7</td>
<td>126.221</td>
<td>111.613</td>
<td>520.797</td>
<td>460.527</td>
<td>647.017</td>
<td>572.140</td>
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<tr>
<td>Arable Land-Gravel Loam</td>
<td>441.432</td>
<td>194.424</td>
<td>21.851</td>
<td>9.624</td>
<td>124.219</td>
<td>54.711</td>
<td>146.070</td>
<td>64.335</td>
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</tr>
</tbody>
</table>
4.2. Spatial distribution characteristics of ecological water requirement

The spatial distribution of the minimum ecological water requirement per unit area is shown in Figure 5. It can be seen that landscape types of high ecological water requirement per unit area are woodland-clay loam, woodland-loam, woodland-sandy loam and woodland-gravel loam, and the water requirements ranged from 0.4621 to 0.5023 m³/m². The landscape types of moderate ecological water requirement per unit area are arable land-clay loam, arable land-loam, arable land-sandy loam and arable land-gravel loam, and the water requirements ranged from 0.3309 to 0.3712 m³/m². The landscape types of low ecological water requirement per unit area are grassland-clay loam, grassland-loam, grassland-sandy loam and grass-gravel loam, and the water requirements ranged from 0.2813 to 0.3216 m³/m². The main reason for the analysis is that the evapotranspiration of forest is relatively large and the amount of water needed to sustain its normal growth is relatively high. Therefore, the ecological water requirement per unit area of woodland is higher. The evapotranspiration of grass is small, and its water requirement is relatively low for the normal growth, thus the ecological water requirement per unit area of grassland landscape is relatively low.
4.3. Discussions

1) Water is the key factor for ecosystem maintenance and development. The health of the ecosystem can be guaranteed only by ensuring a virtuous cycle of water and the minimum threshold. In this paper, the minimum ecological water requirement for the plant and soil of the watershed is respectively calculated according to the minimum average of many years of plant evapotranspiration and the 45% of the field water holding capacity. However, under different geographical regions, different watershed ecosystems and different protection targets, the requirements for ecological water requirement in watershed are not the same. It is necessary to explore more accurate and reasonable methods to define the threshold.

2) From 2000 to 2010, the area of woodland and construction land increased obviously while the area of arable land and unused land decreased. The reduction of arable land and the increase of woodland show that the policy of "returning farmland to forest and grass" has been implemented. The reduction of unused land and the increase of construction land show that urban construction has developed rapidly. Therefore, the studies on ecological water requirements rules at temporal-spatial scales are helpful for the allocation of water resources and land resources. Also, the sustainable use of water resources can provide the important security for social economy development and ecosystem balance.

3) It can be seen that the change of woodland area has the larger contribution to the amount of ecological water requirement of the plant-soil composite system in the watershed, followed by the arable land from tempo-spatial differences. However, the change of the grassland area has a smaller impact on the amount of ecological water requirement of the plant-soil. And indirectly show that "returning arable land to grassland" has a relatively smaller impact on the water supply and demand balance than "returning arable land to woodland" in the watershed.

4) The traditional ecological water requirement evaluation at the regional scale is based on the background of the administrative divisions. In our study, the evaluation at watershed scale is based on the background of the landscape divisions. The results are helpful to reflect the ecological and environmental problems of natural geographical units, besides, provide scientific references for the regional ecological environment protection and ecosystem management.

5) In the research, we use mathematical models to calculate the ecological water requirement of the plant and soil systems. The potential evapotranspiration of plants is calculated by the unified Penman-Monteith method, and the soil moisture content is calculated by soil-fertility stations data. In order to improve the measurement accuracy, next, we will combine with remote sensing inversion and water determination apparatus to correct the results. Additionally, our present study area is located at the starting point of the Silk Road Economic Belt. In the future, we will conduct the research at the whole Silk Road in order to explore the regularity of ecological water requirement at a larger tempo-spatial scale. It is very important for establishing the database of Europe-Asia ecosphere.

5. Conclusions

In this paper, we apply the technology of RS and GIS as well as the corresponding mathematical models to evaluate the tempo-spatial characteristics of the ecological water requirement in Weihe Watershed (Xianyang to Tongguan) based on multi-source data. The main conclusions are as follows:

1) At the temporal scale, the change of ecological water requirement is related with the landscape areas. Also, the change of landscape area is related with the promulgation and implementation of policies and the economic development. The change of woodland area has the largest contribution to the amount of ecological water requirement of the plant-soil composite system in Weihe sub-watershed.

2) At the spatial scale, the variabilities of ecological water requirement in Weihe Watershed (Xianyang to Tongguan) are obvious. Therein, the landscape types of high ecological water requirement per unit area are woodland-clay loam, woodland-loam, woodland-sandy loam and woodland-gravel loam. The landscape types of low ecological water requirement per unit area are grassland-clay loam, grassland-loam, grassland-sandy loam and grass-gravel loam.

3) The ecological water requirement per unit area of woodland is the highest, the grassland is the lowest, and the arable land is in the middle. The reason is that the evapotranspiration of forest is larger with more ecological water consumption while that of grass is smaller with less ecological water consumption for the normal growth. The ecological water requirement per unit area of clay loam is the highest, gravel loam is relatively lower, and the loam is between them. This is because clay loam has less soil voids and weaker water permeability, while gravel loam has larger soil voids and stronger water permeability.
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Disclosure statement
No potential conflict of interest was reported by the authors.

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