Critical Depth of Groundwater Recharge for Vegetation in Semi-Arid Areas

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Abstract. Semi-arid area refers to the area where the precipitation is between 200~400mm and the annual mean evaporation is more than 1000mm. Because of insufficient rainfall that could not support the growth of vegetation, groundwater becomes an important replenishment to the ecological water demand of vegetation. Thus, research on the critical depth of groundwater recharge for vegetation in semi-arid areas is critically important to ecology. This paper mainly analyzed the basic principles of groundwater recharge for vegetation in semi-arid areas and deduced the theoretical calculation formula, which was quantitative calculated, of the critical depth of groundwater recharge for vegetation. The study selected Ordos, Xilingol, Hulunbuir and other semi-arid areas and conducted calculation and application. The conclusion was that the critical depth of groundwater recharge for vegetation in Hulunbuir City and Xilinhot City was 1.5~3.5m, with an insignificant difference, while the critical depth in Ordos was 3~5m, mainly related to vegetation types and soil types.

1. Introduction
In semi-arid areas of China, the precipitation is 200~400mm, and the annual mean evaporation is more than 1000mm, which is mainly the hydrological cycle of rainfall-runoff simulation in mountainous areas and runoff consumption in plain areas[1]. Due to scarce and unevenly distributed rainfall, it is unable to support the growth of vegetation, and the vegetation was mainly supported by recharge of local groundwater resources. However, as increasing speed of human groundwater usage in irrigation, the underground water level decreases, and the vegetation loses the support of groundwater, leading to desertification[2]. Therefore, determining the critical depth of groundwater recharge for vegetation is both an important part of groundwater management and the key to safeguarding vegetation and preventing desertification.

The combination of groundwater and ecological environment and geological environment is currently a research direction of hydrogeology, and significant research results have also been achieved. At present, the research is mainly by using statistical analysis to study the relationship between groundwater and organisms, trying to find a critical groundwater level that is most suitable for biological growth. Relationship between different groundwater levels and vegetation growth status was studied[3]. Study on physiological responses of two native riparian species at different groundwater levels was carried out[4]. Study on the relationship between groundwater, soil water and vegetation status in the Tarim River Basin was carried out, linking with the groundwater depth to the ecological and environmental conditions, and the water level was classified as the swampy water level, the salinized water level, the suitable ecological water level, the plant stress level and desertification water level, and
the corresponding buried depths was determined [5]. In 2005, based on the systematical introduction of ecology and hydrogeology knowledge, and learned from the latest research results of ecology and hydrogeology, Professor Wan Li discussed the relationship between vegetation and groundwater in detail [6]. Study on the groundwater ecological water level in the Lower Liaohe River Plain was carried out [7]. Based on many years’ monitoring data of the groundwater level at the lower reaches of the Tarim River, the impact of groundwater level changes on plant species diversity and population niche was analyzed [8].

At present, various methods for determining critical depths have their own analytical methods, and provide new research ideas for many scholars at the same time. However, the research methods are biased toward statistical analysis and field observation, lacking unified theoretical ideas. This paper proposed a new research idea in the study of the critical depth of groundwater recharge for vegetation in semi-arid areas of China, and used this new research idea to carry out the popularization calculation in semi-arid areas of China.

2. Materials and Methods

2.1. Research areas
Semi-arid areas are mainly distributed in the Inner Mongolia region in north China. In order to differentiate the calculation range, the main calculation cases selected in this paper were in the eastern, central and western regions of Inner Mongolia, which were Ordos, Xilinhot and Hulunbuir respectively. The location of the demonstration area is shown in Figure 1. Ordos is a prefecture-level city under the jurisdiction of Inner Mongolia Autonomous Region, which is located in the hinterland of the bend of the Yellow River and in the southwestern part of Inner Mongolia Autonomous Region. The average annual precipitation is 348.3mm, which mainly concentrates in July, August and September, accounting for about 70% of the annual precipitation. The annual mean evaporation is 2506.3mm, which is 7.2 times of precipitation, and reach the peak from May to July. The total area is 86,800km², and the area that belongs to the semi-arid area is about 59,400km². After interpretation, the concentrated part of the Ordos grassland is in the west part, and the grassland area is 35,100km², accounting for about 59% of the total area. Xilinhot City is located in the central part of Inner Mongolia Autonomous Region, which belongs to Xilingol League, and is in the north of Capital Beijing. The annual average precipitation is 294.9mm, and the grassland area is about 13,700km², accounting for about 87% of the total area. Hulunbuir is adjacent to Heilongjiang Province in the east, bordering Mongolia and Russia in the west and north. Its precipitation in summer is large and concentrated, which is 200~300mm in most areas, accounting for 65~70% of annual precipitation. The total area of Hulunbuir City is 262,000km², and the area that belongs to the semi-arid area is about 127,800km². After interpretation, the Hulunbuir grassland concentrated part is in the southwest, and the grassland area is 61,900km², accounting for about 48% of the total area.
2.2. Calculation method
As an important support for natural vegetation, the groundwater recharge for vegetation is achieved by the rise of phreatic water. At the phreatic water surface of the groundwater, due to the surface tension of the phreatic water surface and the soil pore capillary, the phreatic water rises into the soil, forming the rising water of the capillary and a layer of phreatic water with a certain thickness. And the upper vegetation roots have a root layer with a certain thickness. When the upper edge of the phreatic water layer intersects the lower edge of the root layer, the water absorbed by the vegetation roots is not only derived from the moisture retained by the soil, but also includes the groundwater in the phreatic water layer, so as to achieve groundwater recharge for vegetation. On the contrary, when the two layers do not intersect, the vegetation could not absorb groundwater, and the groundwater could not recharge the vegetation.

\[
\frac{2\sigma}{\rho_w g R} = h
\]  

(1)

Where: \( \sigma \) - the surface tension of water, \( \phi \) - the contact angle of the water surface with the capillary wall, \( R \) - the effective pore size, \( \rho_w \) - water density, \( g \) - acceleration of gravity, \( h \) - the lifting height of a capillary

The soil equivalent pore size \( R \) depends on the spatial distribution of soil texture and soil particles. In general, the spatial distribution of soil texture and soil particles could be expressed by two parameters of effective particle size \( d \) and porosity \( n \), and the soil porosity characteristic function is obtained by using the soil model. The relationship between effective particle size and porosity in two typical soil crystal distribution models of regular triangle and square were used, inferring the expressions for calculating the equivalent pore size and effective particle size and porosity as follows:

\[
R = [1.6(n - 39.5\%) + 0.077] \cdot d
\]  

(2)

Where: \( R \) - effective pore size, \( n \) - soil porosity, \( d \) - soil particle size.

Groundwater recharge for vegetation is achieved by phreatic evaporation. When the phreatic water impact layer is in contact with the root layer, groundwater recharge for vegetation could be achieved. On the contrary, when the two layers do not intersect, the vegetation could not absorb the groundwater, and the groundwater could not recharge the vegetation, as shown in Figure 2. Therefore, it is defined that the critical depth of groundwater that causes soil desertification was the sum of the phreatic water layer and the root layer.

Under the condition that the soil conditions are determined, considering the continuous physiological groundwater recharge in the whole physiological cycle of the vegetation, the height of the average phreatic water layer shall be taken, that is, the corresponding maximum rise height of the capillary water
when taking the average soil temperature. In a community-rich ecosystem, mixed growth of shallow root plants and deep root plants often occur. Due to the large root distribution of deep-rooted plants, the hydraulic lift effect could alleviate the water stress of other shallow-rooted plants, and facilitate the growth of shallow-rooted plants. Therefore, the maximum root depth of dominant species in a community shall be selected. The relevant formula is as follows:

\[
H = \frac{2\sigma \sqrt{\rho}}{\rho - 1} \left[ 1.6(n - 39.5\%) + 0.0774 \right] \cdot d + \max(D)
\]

(3)

Where: \(H\) - the critical depth of groundwater that prevents desert invasion, \(D\) - vegetation root thickness, the rest are as described above.

3. Results and Discussion

3.1. Parameter processing

(1) Effective soil pore size

According to the classification system adopted by the national soil species, there are 11 main soil types in the calculated demonstration area of critical depth of groundwater recharge for vegetation in Ordos. The main soil types in the Ordos grassland are chestnut soil and aeolian sandy soil, accounting for 15% and 58% respectively. There are 7 main soil types in the calculated demonstration area of critical depth of groundwater recharge for vegetation in Xilinhot. The chestnut soil accounts for the largest area, reaching 81%. There are 13 main soil types in the calculated demonstration area of critical depth of groundwater recharge for vegetation in Hulunbuir. The main soil types of the Hulunbuir grassland are chestnut soil and chernozem, accounting for 29% and 21% respectively.

According to the relevant research in Inner Mongolia Soil, the effective particle size and porosity of different types of soils in Inner Mongolia are shown in Table 1. Soil porosity of Black earth, Chestnut soil, Chestnut soil, Brown earth and Windy sand are 55%, 49%, 47% and 42%.[12]

| Classification of soil | \(d\) (mm) | \(h\) (m) |
|------------------------|-----------|----------|
| Coarse grain sand      | 0.7       | 0.08     |
| Medium grain sand      | 0.35      | 0.2      |
| Fine grain sand        | 0.1       | 0.5      |
| Powder granule sand    | 0.045     | 1.0      |
| Silt                   | 0.01      | 5        |
| Clay                   | 0.001     | >=50     |

(2) Vegetation root thickness

The root growth of vegetation is affected by many factors such as soil moisture, fertility and symbiotic environment. In this study, the root thickness of vegetation was the general value of vegetation root type.

The vegetation types in different regions were obtained based on the national vegetation type distribution map of the Chinese Academy of Sciences, combined with the results of the vegetation root system survey in the West Liaohe River Plain, with reference to the Inner Mongolia Grassland Plant Root Types and the Northern China Grassland Plant Roots, the root depth, type and plant characteristics of each survey site were systematically summarized.[13]

Sandy vegetation was the main vegetation type in the area. Liu Yingxin also gave the range of root depth of sandy plants. Shi Xiaohong et al. summarized the root types of Khorchin sandy vegetation and believed that the roots of herbaceous plants were 50cm, the semi-shrub roots were between 50cm and 150cm, and the shrub roots were between 100cm and 300cm.[2]

The same community has different root depth due to different plant types. For the same type of plants, the root depths are also differentiated due to limitation of water conditions. Therefore, it is difficult to determine the thickness of the root layer of the vegetation. The most representative root depth of the dominated plants widely distributed in the study area was shown in this paper. According to vegetation
survey and root depth survey of different types of vegetation, the roots of herbaceous vegetation were basically determined to be within 0.5~1.5m, natural grassland was 0.5m, desert grassland was 1.5m, and shrub and semi-shrub vegetation root depth was determined to be 1.5~3.0m.

3.2. Calculation results

After consulting relevant data, the main soil types of the Ordo s grassland are brown soil and aeolian sandy soil. The main soil type of Xilinhot grassland is chestnut soil. The main soil types of Hulunbuir grassland are chestnut soil and chernozem. The query of relevant soil particle size and porosity refers to Table 4 and Table 5, the effective aperture is calculated by formula (2), the theoretical rise height of capillary water in different demonstration areas is calculated by formula (1) after substituting the relevant parameters. The relevant calculation results are shown in Table 2.

| Citys          | Soil Type      | Soil texture | d (mm) | R(mm) | T (℃) | $\sigma$ (10$^{-3}$N/m²) | h (m) |
|---------------|----------------|--------------|--------|-------|-------|------------------------|-------|
| **Ordos**     | Brown earth    | Sandy        | 0.045  | 0.0089|       |                        | 1.66  |
|               | Windy sand     | Loamy        | 0.1    | 0.0207|       |                        | 0.71  |
| **Xilinhot**  | Chestnut soil  | Clay loam    | 0.045  | 0.0093| 20~23 | 72.5                   | 1.59  |
|               | Black earth    | Sandy        | 0.045  | 0.01458|      |                        | 1.59  |

After calculation, the critical depth of groundwater in Ordos grassland was about 1.5~3m, the critical depth of groundwater in Xilinhot grassland was about 2~3m, and the critical depth of groundwater in Hulunbuir grassland was about 1.5~3m. See Table 3 for details.

| Soil type       | Vegetation Types | maxD (m) | H (m) |
|-----------------|------------------|---------|-------|
| Brown earth     | Herb             | 1.5     | 3.16  |
| Windy sand      | shrub            | 3.0     | 4.66  |
| Chestnut soil   | Herb             | 1.5     | 2.21  |
|                 | shrub            | 3.0     | 3.71  |
| Black earth     | Herb             | 0.5     | 2.09  |
|                 | shrub            | 2.0     | 3.59  |

4. Discussion

Aiming at the soil desertification in arid and semi-arid regions, many studies on the relationship between groundwater and vegetation have been carried out, but most of which were biased by statistical analysis and field observation. At present, the theoretical formula is less used from the aspect of the mechanism of groundwater recharge for vegetation. Groundwater recharge for vegetation in arid and semi-arid areas is very important, which is an important supplement to vegetation ecological water demand besides rainfall. After the roots of the plant leave the capillary zone between the saturated zone and the vadose zone, the water content of the soil in the root zone gradually decreases, resulting in insufficient water intake of the vegetation roots, decreased water content of the plant tissue, and reduced water transport capacity and transpiration capacity of the roots [11]. The calculation of the rise height of the capillary water in the vadose zone is important to the calculation of the critical depth of groundwater recharge for vegetation.

According to the research results on the Ordos Plateau, the most suitable groundwater level for natural vegetation growth was 2.0~4.5m. If the groundwater depth is less than 2m, soil salinization is prone to occur. If the groundwater depth is shallower, that is, less than 1m, the soil gradually evolves into swamps and mire. If the groundwater level decreases below 4m, the growth and development of the vegetation is limited, and the number of biological populations will gradually decrease. If the groundwater continues to fall below 6m, the arid grasslands will develop to desertification [12]. The critical water level of Ordos groundwater recharge for vegetation calculated in this study was 4.66m,
which is more accurate. According to the latest remote sensing image data in 2015, due to unreasonable water resources development and climate change, Xilinhot currently has 39.73% of mild degraded grassland, 24.34% of moderately degraded grassland, and 21.11% of heavily degraded grassland\cite{13}, indicating that the grassland degradation trend is serious, and the development and utilization of local water resources shall be controlled. Hulunbuir City has established an electric energy base in the hinterland of the grassland. The production water supply for each major coal power project was taken from groundwater, and the natural precipitation supply was small, resulting in a drop of more than 1.2m of the groundwater level in the past five years, and thus leading to grassland degradation\cite{14}. It has proved that the degradation of Hulunbuir grassland was closely related to the decrease of groundwater depth. Therefore, it is critically important to determine the critical depth of groundwater recharge for vegetation.

Ordos is a plateau region with many desert grasslands. The length of vegetation roots is generally larger than that of Xilinhot and Hulunbuir grasslands. In addition, differences between the soil types are also large. Ordos is mainly brown soil and aeolian sandy soil, while Xilinhot and Hulunbuir are mainly chestnut soil and chernozem, which are the main soil of typical grasslands.

5. Conclusion
In this paper, the quantitative calculation formula of the critical depth of groundwater recharge for vegetation was proposed aiming at semi-arid areas, and the calculation method of soil equivalent pore size in the theoretical formula was derived. Quantitative calculations were conducted in different selected regions crossing multiple latitude and longitude in semi-arid areas of China, and the results were analyzed and compared. The calculation results of the Ordos grassland area indicated that the critical depth of groundwater recharge for vegetation was 2~5m, the critical depth of groundwater recharge for vegetation in Xilinhot was 2~3.5m and the critical depth of groundwater recharge for vegetation in Hulunbuir was 1.5~3m. The management threshold of groundwater depth in different regions was proposed, which has certain guiding significance for local grassland protection.

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