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Groundwater management zones and their groundwater level thresholds in the Tongliao Plain

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ABSTRACT

The West Liao River (WLR) Basin located in Inner Mongolia, is an important food production area in China. In recent years, the problem of groundwater over-exploitation has become increasingly prominent in the Basin due to the expansion of agriculture. This paper developed adaptive management initiatives of the local groundwater resources using Tongliao, located in the east part of the WLR Basin, as a case study. Groundwater management zones were divided based on hydrogeology, precipitation, land use, the groundwater over-exploitation areas, groundwater depth, and the administrative units (Banners/Counties/Districts). The Tongliao Basin was divided into 21 management zones. Subsequently, assessment rules for determining groundwater level thresholds in each groundwater management zone were developed based on groundwater observation conditions and the current groundwater depth. Based on the assessment rules, in 2020 the management threshold of groundwater level for each zone were determined. The results provided a scientific basis for the 'Water Availability Based Local Development Initiative' in the Tongliao Plain.

Key words: groundwater management zone, threshold of groundwater level, Tongliao basin

HIGHLIGHTS

- First, groundwater management zones were divided based on hydrogeology, precipitation, land use, groundwater over-exploitation area, groundwater depth, and the administrative units (Banners/Counties/Districts).
- Second, the article developed the principle of regional groundwater level assessment, and in 2020 the management threshold of groundwater level was determined based on the principle.

1. INTRODUCTION

Groundwater is one of the key source of freshwater (Zhang *et al.* 2019; Zhou *et al.* 2020) and with its high water supply guarantee degree and excellent water quality, is the choice for the main water supply sources in northern China. With continuous and rapid economic and social development, the intensity of groundwater development and utilization in most regions of China has shown a sustained growth trend, especially in the northern region (Konikow & Kendy 2005; Cao *et al.* 2013). The development and utilization of groundwater has brought the balance between supply and demand of water resources as well as promoted the development of economy and society. However, due to the over-exploitation of groundwater, the continuous decline in groundwater levels has caused a series of ecological and geological environmental problems (Ding & Zhang 2002; Sheng *et al.* 2006; Feng *et al.* 2013; Wang *et al.* 2020). China has taken some effective measures to deal with these problems, which are caused by irrational exploitation of groundwater. However, most of them belong to remedial management methods, adopted after the occurrence of problems, without fundamentally preventing of groundwater over-exploitation (Tang *et al.* 2012). Consequently, scientific management of groundwater, based on the characteristics of different zones, is particularly important. Division of management zone is a prerequisite for groundwater resources management (Ye & Xie 2009). The purpose of establishing and dividing groundwater management zone is to monitor specific changing trends of groundwater status in each management zone in real time, and provide support and decision-making basis for scientific guidance, differentiated management, supervision of groundwater resource development and utilization. Additionally,

groundwater management zones are more convenient for the management department to take timely measures to solve and deal with problems according to the characteristics and problems of each management zone.

Some countries in the world have put forward corresponding water resources management measures since the 1960s. Especially in recent years, the shortage of water resources has become more and more serious. Countries all over the world have carried out relevant research and established modern water resources management systems that meet the requirements of sustainable development. However, the content of groundwater zoning research provides little reference (Feinerman & Knapp 1983; Calow *et al.* 1997; Burke & Moench 2000; Braune *et al.* 2002; Dawoud *et al.* 2005; Cools *et al.* 2006; Jha *et al.* 2007; Carrera & Gaskin 2009). Since the beginning of the 21st century, China has implemented the 'Technical Outline for Groundwater Function Zoning' and the 'Evaluation and Technical Requirements for Groundwater Function', which provide a theoretical basis and an important basis for the division of groundwater function zones (Tang *et al.* 2012). The 'Technical Outline for Groundwater Function Zoning' is simple and feasible for zoning, based on the dominant functions of groundwater, but the universality of groundwater function division is still insufficient. The 'Evaluation and Technical Requirements for Groundwater Function' is based on the groundwater function evaluation for zoning, and the theoretical method is systematic. However, there are too many indicators to conduct in-depth and systematic analysis and research. Secondly, it cannot adapt to the high-precision division of groundwater functional areas at the watershed scale (Wang *et al.* 2020). The WLR Basin is one of the most arid regions in Northeast China. As an important food base in China, unreasonable development and utilization have caused the problem of over-exploitation of groundwater (Tang *et al.* 2019). According to local conditions, how to divide zones and carry out specific management is an urgent problem to be solved. The plain area of the Tongliao City in the east part of WLR Basin is used as the research area of this paper to carry out the following research. (1) Groundwater management zones in the Tongliao Plain were divided based on hydrogeology, precipitation, land use, groundwater over-exploitation area, groundwater depth, and the administrative units (Banners/ Counties/ Districts). (2) Assessment rules for determining groundwater level thresholds in each groundwater management zone were developed based on the critical water level of groundwater, groundwater observation conditions and the groundwater depth. Using the assessment rules, the management threshold of groundwater level for each zone were determined. The results can provide a scientific basis for the 'Water Availability Based Local Development Initiative'.

2. MATERIALS AND METHODS

In groundwater management zoning, hydrogeological and precipitation conditions have a direct impact on the groundwater level, which should be taken into consideration. The over-exploitation area and non-over-exploitation area should be separated, and several main land use types should be distinguished to implement different levels of control measures for management zones. In addition, the management and control objectives of different groundwater levels are also different, so groundwater depth areas should be divided in management zones. Therefore, groundwater management zones were divided based on hydrogeology, precipitation, land use, groundwater over-exploitation area, groundwater depth, and the administrative units (Banners/Counties/Districts) (Jaiswal *et al.* 2003; Lee *et al.* 2012; Gumma & Pavelic 2013; Gou *et al.* 2015; Thapa *et al.* 2017; Golkarian *et al.* 2018; Chen *et al.* 2019). In order to control the groundwater level in the management zone, this article developed the principles of regional groundwater level assessment. The details of these aspects are as follows.

2.1. Study area

The WLR, with a total length of 829 km, is in the upper reaches of the Liao River and originated in Pingquan County, Hebei Province. The drainage area is 138,000 km^2, and comprises the Jilin, Liaoning, Inner Mongolia and Hebei provinces. Tongliao Plain in the WLR Basin is a typical semi-arid area of agro-pastoral transition zone, all of which are within the territory of Tongliao City (Liang *et al.* 2009; Bai & Bai 2016; Gao *et al.* 2017).

The western part of the Tongliao Plain in the WLR Basin is mainly formed by the accumulation of Quaternary alluvial deposits carried by the outflowing rivers. The surface is covered with aeolian sand topography, flat terrain, with easy precipitation recharge. The east area is mainly alluvial plain, which is composed of Quaternary alluvial deposits. Figure 1(a) shows the main hydrogeological units obtained after comprehensive analysis and processing according to 1:3,000,000 hydrogeological map of Inner Mongolia Autonomous Region and hydrogeological zoning map of the Songliao Plain.

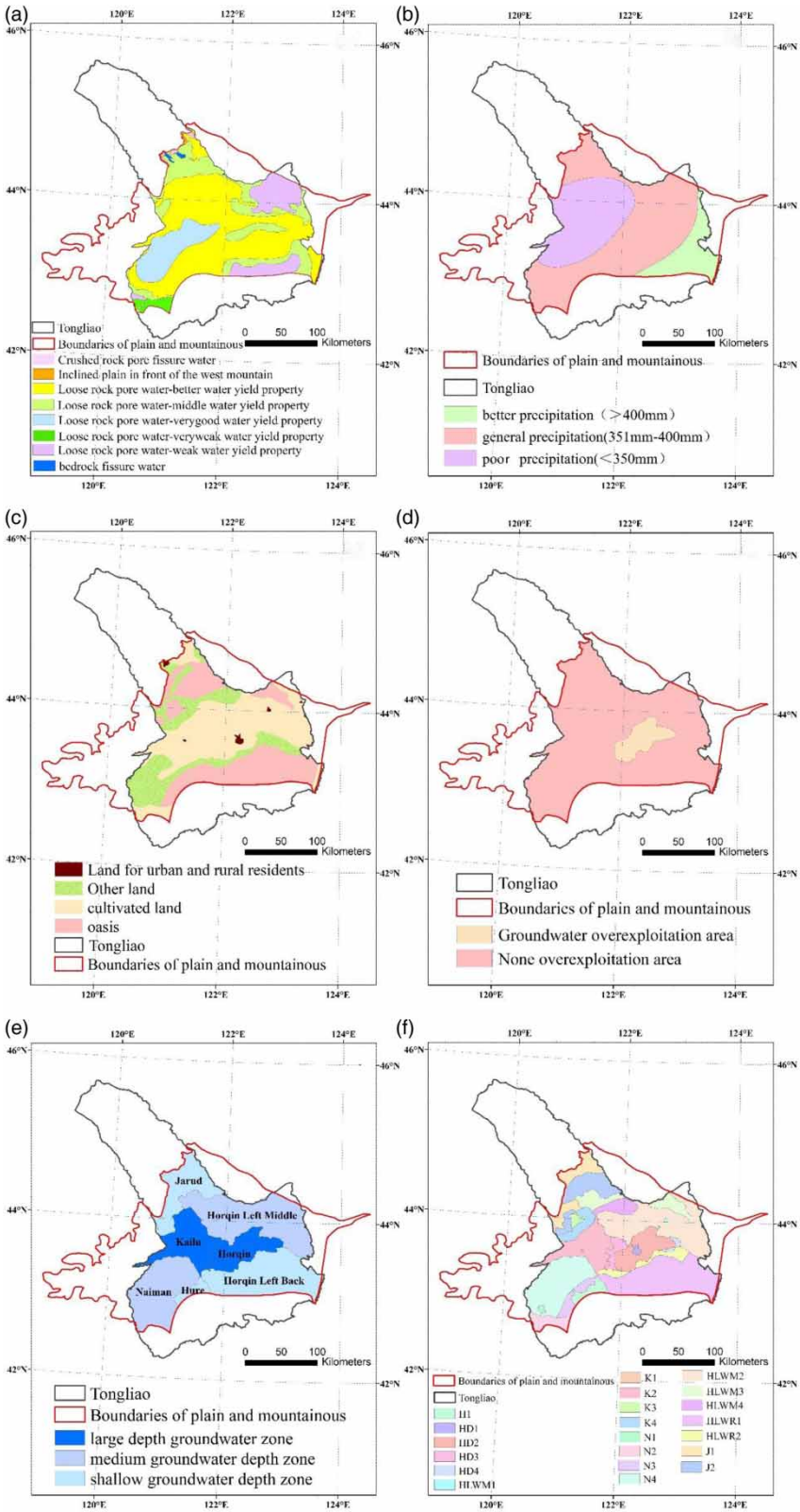

Figure 1 | Division of management zone: (a) hydrogeological condition, (b) precipitation condition, (c) land use, (d) groundwater over-exploitation area, (e) groundwater depth zone, (f) groundwater management zone.

The records of precipitation were obtained from rain-gauge stations in the study area. Precipitation conditions in the Tongliao Plain can be spatially divided into three regions, namely poor (precipitation less than 350 mm/year), general (precipitation 350–400 mm/year) and better (precipitation 400–450 mm/year), as shown in Figure 1(b).

2.2. Land use classification

The oasis in Tongliao Plain is the main component of Horqin Sandy Land, also known as Horqin oasis. Horqin oasis is a typical farming-pastoral ecotone, mainly composed of dunes, mire meadows and plains. Due to the special form of farming and animal husbandry activities in recent years, the alternation of farming and animal husbandry production activities, as well as excessive human reclamation and grazing, coupled with the fluctuation of drought and flood climate and specific environmental conditions, the original ecosystem of the Horqin Sandy Land has a degradation trend. With a clear trend of degradation, the ecosystem appears to be extremely fragile. Based on the land use distribution of the WLR Basin obtained by satellite image inversion in 2018, and the scope planning of Tongliao City for oasis, this article divides the distribution of general cultivated land, main residential areas and oasis in the WLR Basin, as shown in Figure 1(c).

2.3. Groundwater over-exploitation area

The Horqin over-exploitation area is characterized by the over-exploitation area of 3,056.4 km^2, with an average over-exploitation volume of 258 million m^3/year (groundwater over-exploitation area were designated by the people's government of the Inner Mongolia Autonomous Region in 2015). The over-exploitation area as one of the criteria for delimiting the groundwater management zone, as shown in Figure 1(d).

2.4. Division of groundwater depth

Groundwater level is the most direct data index to evaluate the regional groundwater storage dynamics. The final effect of various initiatives to restrain groundwater over-exploitation should be reflected in the restoration of groundwater level in over-exploitation areas. The assessment indicators were based on the groundwater level management objective in the 'Plan for development based on water availability in the WLR Basin in Inner Mongolia' (referred to as the 'Plan'), which comes from the Ministry of Water Resources of the People's Republic of China. According to the groundwater level, the 'Plan' divided the administrative regions in the plain area of Tongliao into three types: shallow groundwater depth zone, medium groundwater depth zone and large groundwater depth zone, and gave the maximum allowable depth of groundwater by 2030, as shown in Table 1. Figure 1(e) shows the division of groundwater depths in the Tongliao Plain.

2.5. Principles of regional groundwater level assessment

In this paper, the formulation of groundwater level management objectives considers factors such as the changing trend of the water level over the years, the current state, and the gap between the current state and the objective value after treatment. Assessment of principles are as follows:

(1) When the change trend of groundwater is stable in the past and in the present, the groundwater depth of the previous year of the evaluation year should be less than or equal to the objective groundwater depth, and the groundwater level of the evaluation year should maintain the status quo.

Table 1 | Groundwater level management objective in the Tongliao Plain

Zone	Banner/County/District	Maximum allowable groundwater depth at the end of 2030	
		$P = 75\%$	Average
Shallow groundwater depth zone	Hure Banner	2.1	2.1
	Horqin Left Wing Back Banner	3.8	3.8
	Jarud Banner	4.3	4.3
Medium groundwater depth zone	Naiman Banner	7.7	7.2
	Horqin Left Wing Middle Banner	7.5	7
Large groundwater depth zone	Kailu County	12.6	11.8
	Horqin District	13.5	12.7

(2) When the changing trend of groundwater belongs to the increase of historical groundwater depth and now stable and if the groundwater depth of the previous year of the evaluation year is less than or equal to the objective groundwater depth, the groundwater level of the evaluation year should maintain the status quo. Conversely, if the groundwater depth of the previous year of the evaluation year is greater than the objective groundwater depth, the groundwater level of the assessment year should be reduced according to the groundwater depth of the previous year.
(3) When the change trend of groundwater is that the historical groundwater depth increases significantly and the current groundwater depth increases slightly and the groundwater depth of the previous year of the evaluation year is less than the objective groundwater depth, it should refer to the groundwater depth of the previous year and allow the groundwater depth to increase slightly. However, the increase of groundwater depth should not be greater than the previous year. If the groundwater depth of the previous year of the evaluation year is greater than or equal to the objective groundwater depth, the groundwater depth of the evaluation year should be kept unchanged or reduced according to the groundwater depth of the previous year.
(4) When the change trend of groundwater depth belongs to the historical depth and the current depth increases significantly, and the groundwater depth of the previous year of the evaluation year is less than the objective depth, the groundwater depth of the evaluation year may be allowed to increase slightly, but the increase should not be greater than the previous year. If the groundwater depth of the previous year of the evaluation year is greater than or equal to the objective groundwater depth, the groundwater depth of the evaluation year can be increased by referring to the groundwater depth of the previous year, but the increase should be much smaller than the previous year.

It is necessary to further refine and determine whether local fine tuning is needed within the county according to different management zones. In addition, the established management groundwater level and the critical groundwater level are mutually checked to ensure that the management groundwater level is within the maximum and minimum ranges of the critical groundwater level.

3. RESULTS AND DISCUSSION

3.1. Groundwater management zone

In order to develop the groundwater management zone, ArcGIS layers of groundwater management zones were drawn and overlayed by five layers: hydrogeological condition, precipitation, land use, groundwater over-exploitation area, and groundwater depth. Layers were classified and generalized according to the following priority order: groundwater over-exploitation area > groundwater depth area > land use > hydrogeological condition > precipitation condition.

When categorizing hydrogeological conditions, as the difference in water yield property of loose rock pore water is relatively small in practical applications, only areas with better water yield properties in loose rock pore water were marked. The area of water yield properties from medium to weaker was uniformly marked as loose rock pore water. Finally, after ensuring that the layers with the same attributes in each county were generalized according to the importance priority within the boundaries of each county, the areas that were too small or not representative were merged. It was ensured that there were no more than four management zones in each county to avoid the fragmentation of zones that could result in difficulties in groundwater management. Figure 1(f) shows 21 groundwater management zones. Table 2 shows the 21 groundwater management zones and attributes in the Tongliao Plain.

3.2. Critical groundwater level

Various resources, ecological and geological environmental problems or disasters may be caused by the change in groundwater level. The groundwater level threshold to prevent such situations is called the critical groundwater level. Based on the regulations on the critical groundwater level of different types in China (Luo 2015), the WLR Basin in Inner Mongolia, is an ecologically fragile zone that needs to be protected. Therefore, it is necessary to combine the ecological water level standards in the natural oasis area specified in the *Technical Requirements for Determination of Groundwater Control Indicators* (Trial) and the following restrictions should be imposed on the critical groundwater level: (1) the upper limit of groundwater depth in urban residential areas should not be less than 6 m to protect underground facilities; (2) the groundwater level of agricultural irrigation area in the Tongliao Plain is generally low, and there is no soil secondary problem caused by high groundwater level; therefore, there is no upper limit of groundwater depth in agricultural irrigation area, and the lower limit of groundwater depth is only a reference; (3) the groundwater depth in ecologically fragile areas should not be greater

Table 2 | Division and properties of the groundwater management zone in the Tongliao Plain

Banner/County/District	Name	Attribute
Hure Banner	H1	Shallow groundwater depth zone, Oasis, Pore water in better water yield property, The general precipitation condition
Horqin Left Wing Back Banner	HLWR1	Shallow groundwater depth zone, Mixed land dominated by cultivated land, Pore water in better water yield property, Better precipitation condition
	HLWR2	Shallow groundwater depth zone, Mixed land dominated by oasis, Pore water of loose rock, General precipitation condition
Jarud Banner	J1	Shallow groundwater depth zone, Cultivated land, Pore water of clastic rock, General precipitation condition
	J2	Shallow groundwater depth zone, Oasis, Pore water of clastic rock, General precipitation condition
Horqin Left Wing Middle Banner	HLWM1	Medium groundwater depth zone, Land for urban and rural residents
	HLWM2	Medium groundwater depth zone, Cultivated land, Pore water of loose rock, General precipitation condition
	HLWM3	Medium groundwater depth zone, Oasis, Pore water of loose rock, General precipitation condition
	HLWM4	Medium groundwater depth zone, Mixed land use, Pore water in better water yield property, General precipitation condition
Naiman Banner	N1	Medium groundwater depth zone, Land for urban and rural residents
	N2	Medium groundwater depth zone, Cultivated land, Pore water of loose rock, General precipitation condition
	N3	Medium groundwater depth zone, Oasis, Pore water of loose rock, General precipitation condition
	N4	Medium groundwater depth zone, Mixed land, Pore water in better water yield property, General precipitation condition
Kailu County	K1	Large groundwater depth zone, Land for urban and rural residents
	K2	Large groundwater depth zone, Cultivated land, Pore water of loose rock, Poor precipitation condition
	K3	Large groundwater depth zone, Oasis, Pore water in better water yield property, Poor precipitation condition
	K4	Large groundwater depth zone, Mixed land, Pore water in better water yield property, Poor precipitation condition,
Horqin District	HD1	Groundwater over-exploitation area, Land for urban and rural residents
	HD2	Groundwater over-exploitation area, Cultivated land, Loose rock in better water yield property, General precipitation condition
	HD3	Large groundwater depth zone, Cultivated land, Loose rock in better water yield property, General precipitation condition
	HD4	Large groundwater depth zone, Mixed land, Pore water of loose rock, General precipitation condition

than 10 m. For the management areas where the groundwater depth is already greater than the lower limit, the short-term goal can appropriately exceed the critical water level, but the long-term goal needs to ensure that it meets the critical water level.

3.3. The observation condition of groundwater in management zone

For the time-varying factors such as groundwater observation condition, it plays a restrictive role in the division of management zone, especially the setting of groundwater level threshold in the management zone. The observation well data of 110 national control stations in WLR Basin were collected. The number of observation points, the density of observation wells, the minimum and maximum groundwater depth at the end of 2019 in each groundwater management zone are shown in Table 3. The density of observation points in groundwater management zone is mostly 2–15 wells/1,000 km^2. The groundwater monitoring in agricultural irrigation areas is relatively reasonable. However, there are no or fewer observation points in many zones of oasis, which will cause some difficulties in future groundwater monitoring and management.

3.4. Groundwater level threshold in 2020

The groundwater level threshold, mainly refers to factors such as the critical groundwater level in the Tongliao Plain, observation conditions in the groundwater management zone, and the current change trend of groundwater depth. The

Table 3 | Observation well conditions of groundwater management zone in the Tongliao Plain

Banner/County/District	Name	The number of state-controlled observation	Density (well/1,000 km^2)	Groundwater depth in 2019 minimum/ maximum	
Hure Banner	H1	4	5.9	0.61	1.68
Horqin Left Wing Back Banner	HLWR1	15	2.3	0.7	4.27
	HLWR2	0	No observation condition		
Jarud Banner	J1	5	2.7	5.27	13.73
	J2	1	0.4	2.8	
Horqin Left Wing Middle Banner	HLWM1	1	–	2.36	
	HLWM2	18	2.8	3.27	12.39
	HLWM3	0	No observation condition		
	HLWM4	2	2.2	2.84	2.85
Naiman Banner	N1	1	13.6	13.39	
	N2	2	2.2	18.34	18.79
	N3	0	No observation condition		
	N4	15	3.1	4.09	13.74
Kailu County	K1	0	No observation condition		
	K2	24	7.6	8.7	13.65
	K3	1	4.3	9.87	
	K4	1	1.1	6.23	
Horqin District	HD1	1	7.9	15.48	
	HD2	25	10.3	5.71	16.97
	HD3	1	1.6	9.29	
	HD4	3	14.8	7.58	8.63

groundwater depth of Hure Banner and Horqin Left Wing Back Banner was stable in the past and in 2019. The groundwater depth of Jarud Banner and Horqin Left Wing Middle Banner increased slightly in the past, the average annual increase of groundwater depth was less than 0.1 m, but was stable in 2019. The groundwater depth of Naiman Banner, Kailu County and Horqin District increased in different degrees both in the past and in 2019. Based on the principle of regional groundwater level assessment, the phased objective for the management threshold of the groundwater level in each zone of the Tongliao Plain in 2020 was determined, and the data are shown in Table 4.

Firstly, Hure Banner and Horqin Left Wing Middle Banner belong to shallow groundwater depth zones. At present, the pressure on groundwater resource is relatively small. Maintaining the status quo without increasing groundwater pumping can accomplish the objective in the 'Plan'. Secondly, Horqin District is the traditional over-exploitation area. After the governance in the past few years, except for individual wells in urban residential areas and agricultural areas, the groundwater levels in other areas have greatly recovered. Thirdly, some cultivated land zones, J1 and HLWM2 are classified as a shallow groundwater depth zone and a medium groundwater depth zone, but have large groundwater depth observation wells, which will bring difficulties to subsequent groundwater management. Fourthly, although Naiman Banner was classified as a medium groundwater depth zone, there are still some observation wells with large groundwater depths, and the current water level is far off the objective of the 'Plan', which should be taken seriously. Fifth, a large area of oasis lacks groundwater observation conditions, which should be improved. For example, there is no observation well in HLWR2, N3, and there is only one observation well in J2 and K3.

4. CONCLUSION

In order to control the continuous development of groundwater over-exploitation, this article proposes a method to division the management zone, and the principle of groundwater level assessment was developed to manage the groundwater level in each zone. In the Tongliao Plain, 21 groundwater management zones were divided based on the hydrogeology, precipitation, land use, the groundwater over-exploitation areas, groundwater depth, and the administrative units (Banners/Counties/

Table 4 | Phased objectives for the groundwater level threshold in the Tongliao Plain in 2020

Banner/County/District	Name	The management threshold of the GD*	Management requirement in 2020
Hure Banner	H1	2.1	The GD (1.66 m) in 2019 was less than the objective (2.1 m), and the maximum GD in 2020 cannot be lower than 2.1 m.
Horqin Left Wing Back Banner	HLWR1	3.8	The GD in 2019 was 2.82 m. The maximum GD should not be less than 3.8 m, while the maximum GD in 2019 was 4.27 m, mainly caused by natural water level fluctuations.
	HLWR2	–	Lack of observation condition in the zone.
Jarud Banner	J1	4.3	The observation depth of individual wells was more than 10 m. The GD in 2019 (5.6 m) was higher than 4.3 m and the maximum GD in 2020 should not exceed the average in 2019.
	J2	4.3	The GD in 2019 met the objective, GD in 2020 also according to the management threshold of the GD (4.3 m).
Horqin Left Wing Middle Banner	HLWM1	6.0	The GD (2.36 m) of the well met the objective in 2019, but exceeded the critical groundwater level in urban areas. In 2020, it was controlled by the upper limit water level (6 m) in urban areas.
	HLWM2	7.5	In 2019, the GD (7.69 m) was greater than 7 m, but the maximum GD was 12.39 m. In 2020, the GD should slightly stricter than in 2019.
	HLWM3	–	Lack of observation condition in the zone.
	HLWM4	7.0	The GD met the objective in 2019, GD in 2020 also in accordance with the management target (7 m).
Naiman Banner	N1	13	The GD (13.39 m) in 2019 exceeded the objective, but met the critical groundwater level of the urban area, and was controlled in 2020 slightly stricter than the current GD.
	N2	18	In 2019, the GD (>18 m) greatly exceeded the objective (7.2 m), and this area should be regarded as the important management zone. In 2020, it should be controlled in accordance with a slightly stricter.
	N3	–	Lack of observation condition in the zone.
	N4	7.2	The average GD (8.27 m) in 2019 exceeded 7.2 m, and the maximum GD in 2020 was not greater than the average value in 2019.
Kailu County	K1	–	Lack of observation condition in the zone.
	K2	11.8	The average GD (9.52 m) in 2019 met the objective (11.8 m), but the maximum GD was 13.65 m. In 2020, the maximum GD was required not to exceed the objective.
	K3	10	In 2019,the GD (9.87 m) was in line with the objective and the critical groundwater level in ecologically vulnerable areas. The GD was recommended not to exceed the lower limit of ecologically vulnerable areas (10 m) in 2020.
	K4	7	In 2019, the GD (6.23 m) met the objective. In 2020, it should be slightly looser than 2019.
Horqin District	HD1	15	In 2019, the GD (15.48 m) exceeded the objective (12.7 m), but it met the critical groundwater level in urban areas. In 2020, it was controlled according to the target slightly stricter than 2019.
	HD2	12.7	In 2019, the GD (12.67 m) met the objective (12.7 m), but the maximum GD (16.97 m) exceeded. In 2020, the maximum GD should not exceed the target.
	HD3	10	In 2019, the GD (9.29 m) was in line with the objective and critical groundwater level in ecologically vulnerable areas. The GD was recommended not to exceed the lower limit of ecologically vulnerable areas (10 m) in 2020.
	HD4	12.7	In 2019, the GD (7–9 m) met the objective (12.7 m) and was controlled by a slightly looser target in 2020.

*GD, groundwater depth.

Districts). In view of the 21 groundwater management zones, based on the principle of regional water level assessment, the constraint of critical groundwater level, observation conditions and the groundwater depth in 2019, the management threshold of groundwater level of each zone in 2020 was determined, and the corresponding conclusions and subsequent management suggestions were put forward.

In 2020, nine zones meet the groundwater level objective, some individual wells of two zones cannot meet the objective, four zones lack the observation condition, and six zones cannot meet the groundwater level objective. At present, the current status of groundwater level in Hure Banner and Horqin Left Wing Back Banner can meet the management objective of plan. The groundwater level in Horqin District has been restored to a certain extent after several years of treatment. Some cultivated land zones and Naiman Banner are not classified as large groundwater depth areas, but have many large groundwater depth observation points. These zones need to take measures to restore the groundwater level. Some oasis zones lack observation points, which should be improved. The results will provide a support and decision-making basis for management departments to implement scientific quantitative management in the Tongliao Plain.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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