Study on the critical groundwater depth of controlling risk management in a semi-arid irrigated area in China based on recharge-discharge relationship

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Abstract

The imbalance between exploitation and recharge and the yearly decline in water tables is a common water resource problem in semi-arid areas in China. To ensure the sustainable use of groundwater and the stability of the regional hydrological cycle, a reasonable groundwater control table need to be determined to achieve a balance between groundwater exploitation and recharge. Based on the characteristics of the vertical hydrological cycle in semi-arid irrigation areas, this paper used a combination of in situ field experiments and software simulations to calculate the groundwater infiltration recharge under three types of subsurface conditions, namely, drip irrigation under mulch, border irrigation, and bare area, and to analyze the relationship between groundwater infiltration recharge and groundwater table. Based on the relationship between groundwater recharge and discharge, the critical groundwater depth of maintaining exploitation and recharge balance (CGDM) for drip irrigation under mulch was calculated to be 131.52-187.15 cm, and the critical groundwater depth of disrupting exploitation and recharge balance (CGDD) was 307.66-363.67 cm. For border irrigation, the CGDM was 80.00-84.34 cm and the CGDD was 198.87-248.44 cm. It also proposed a groundwater table management strategy to address the risk of imbalance in regional groundwater exploitation and recharge. The critical groundwater depth of controlling risk management (CGDC) can be used for regional groundwater management and guidance for agricultural irrigation, providing technical support for achieving regional groundwater exploitation and recharge balance and maintaining a stable hydrological cycle.

1. Introduction

In the semi-arid areas of China, where annual precipitation is low and evaporation is high, surface water is relatively poor and groundwater reserves are abundant and easily exploited. With the development of agriculture, industry, and economy, the scarcity of surface water can hardly meet the needs of normal production and living. The abundant local groundwater resources become the main source of water supply for the region (Zhong, Y. et al. 2018). The long-term sustainable utilization of groundwater is fundamental to agricultural and economic development in semi-arid regions, so it is vital to study the groundwater table and develop a sound groundwater management strategy. (Macdonald, D. M. et al. 2014; Zhang, Z. et al. 2021).

Semi-arid irrigation areas are currently facing many water sources problems such as river break and groundwater over-exploitation, which have led to an imbalance in groundwater exploitation and recharge and a rapid decline in groundwater table (Fu, Y. et al. 2016). The continuous decline in groundwater tables has led to a reduction in groundwater recharge, which has exacerbated the imbalance between exploitation and recharge and seriously affected the stability of the regional hydrological cycle. The core issue of groundwater management in semi-arid irrigation areas is to maintain the stability of the hydrological cycle and to ensure the infiltration and recharge of groundwater by precipitation and return flow from irrigation. The depth of the groundwater table is the main factor affecting groundwater infiltration and recharge, therefore it is vital to determine a reasonable groundwater control table.

Current research on groundwater control tables is mainly focused on the depth of critical groundwater (DCD), which has been proposed for different problems faced in the study area. The current research mainly includes the following aspects: (1) research on the depth of critical groundwater to prevent soil salinization (Qi, Z. et al. 2021; Mu, E. L. et al. 2020; Rengasamy, P. 2006). (2) research on the depth of critical groundwater to maintain vegetation growth and ecosystem stability (Wang, Y. et al. 2020; Eamus, D. et al. 2006; Martinetti, S. et al. 2021). (3) research on the depth of critical groundwater to prevent surface subsidence and seawater intrusion (El Kamali, M. et al. 2021; Malik, K. et al. 2019; Chidambaram, S. et al. 2022; Ma, F. et al. 2005).

To maintain the stability of the hydrological cycle in semi-arid irrigation areas so that groundwater resources are not depleted by extraction, the long-time average annual value of groundwater exploitation and recharge should maintain balance. The balance of exploitation and recharge is the basic principle of groundwater control and is an important prerequisite for the long-term sustainable use of groundwater. Based on the relationship between groundwater recharge and discharge in a semi-arid irrigated area, this paper proposes the critical groundwater depth of controlling risk management (CGDC), including the critical groundwater depth of maintaining exploitation and recharge balance (CGDM) and the critical groundwater depth of disrupting exploitation and recharge balance (CGDD), and studies the quantitative calculation method of CGDC.

The measurement of groundwater infiltration recharge is currently based on in situ field experiments, water balance methods, and numerical simulations. In this paper, a combination of in situ field experiments and numerical simulations was chosen to simulate the infiltration recharge of groundwater. The Hydrus-2D model is a finite element computational model for simulating water, solute, and energy transport in saturated-unsaturated porous media. The software can describe complex boundary conditions and is now widely used to simulate soil moisture movement (Shan, G. et al. 2019; Karandish, F. et al. 2019).

The objectives of this paper were (1) to quantify the amount of groundwater infiltration and recharge under the combined effects of precipitation and irrigation for three subsurface conditions: drip irrigation under mulch, border irrigation, and bare ground at different groundwater levels. (2) quantitatively calculate CGDC based on the principle of groundwater exploitation and recharge balance. (3) discuss the risk of imbalance in regional groundwater exploitation and recharge at different groundwater tables and strategies to control groundwater tables.

2. Materials And Methods

2.1. Characteristics of the hydrological cycle in semi-arid irrigation areas

The semi-arid areas are located on a plain, with gentle topography, few rivers, active infiltration of precipitation, almost no surface runoff. The hydrological cycle is characterized by predominantly groundwater recharge-discharge, with the main processes of the hydrological cycle being: precipitation-evaporation, infiltration to recharge groundwater-transpiration. Due to the small surface runoff, the hydrological elements show vertical movement characteristics in the circulation exchange and can be seen as a vertical hydrological cycle (Wang, Y., et al. 2021). Under natural conditions, groundwater is mainly recharged by precipitation and discharged through evapotranspiration of natural vegetation. Under irrigation conditions, the relationship between groundwater recharge and discharge changes. Groundwater recharge is accomplished by precipitation and return flow from irrigation, and discharge changes from natural vegetation evapotranspiration to irrigated crops evapotranspiration.

2.2. The critical groundwater depth of controlling risk management (CGDC)

According to the characteristics of the hydrological cycle in the semi-arid regions, comprehensive consideration of regional climate characteristics, soil types, crop species, based on the recharge-discharge relationship, different CGDC is set for the risks that may be encountered at different groundwater tables in the actual groundwater exploitation process. CGDC includes CGDM and CGDD.

2.2.1. CGDM

Groundwater is the main source of agricultural water in the region. To maintain the stability of the vertical hydrological cycle in irrigation areas and to make groundwater resources sustainable, the annual average exploitation should be balanced with the annual average recharge, and the groundwater dynamic process line should fluctuate up and down around a particular value and should remain stable over time. Crop irrigation exploitation of groundwater makes the water table drop, precipitation, return flow from irrigation recharge groundwater, making the water table rise. When the groundwater exploitation and recharge are in balance, the groundwater table is in a relatively stable state, at this time can reach a balanced state of exploitation and recharge.

2.2.2. CGDD

As the depth of groundwater burial increases, all types of infiltration are gradually consumed before reaching the groundwater. The amount of infiltration recharge that groundwater can receive from precipitation and irrigation gradually decreases and the recharge capacity gradually decreases. When the groundwater table is above the CGDD, groundwater can receive the infiltration recharge from the ground, when the groundwater table is below the CGDD, groundwater cannot be recharged by precipitation and irrigation, and groundwater cannot be replenished after exploitation. When the groundwater exploitation and recharge are in unbalance, at this point in a state of imbalance between exploitation and recharge.

2.3. Study area

The experiment was carried out at Jianping Irrigation Experimental Station in Chaoyang City, Liaoning Province, China, which is located at 119°18' E, 41°47' N and 461m above sea level. The average annual temperature is 5–6°C, the average annual precipitation is 440 mm and the average annual evapotranspiration is 1800–2100 mm. It has a typical semi-arid monsoon climate with low rainfall and high evaporation. The soil properties of the study area are shown in Table 1. The local irrigation methods are mainly traditional border irrigation and drip irrigation under mulch, and the main crop is maize. The experimental area is representative in hydrological cycle, climatic characteristics, and soil properties. The depth of groundwater in 2019 is 280cm, and the nearby river (Laoha River) has been broken for many years, with little lateral recharge of groundwater (Jin, J. et al. 2020).

Table 1
Physical properties of soil in the study area.

Soil depth /cm	Volume weight /($g \cdot cm^{-3}$)	Field capacity /($cm^3 \cdot cm^{-3}$)	Saturated soil water content ($cm^3 \cdot cm^{-3}$)	Soil type
0–40	1.54	0.21	0.44	Loamy sand
40–70	1.65	0.35	0.44	Sandy loam
70–110	1.59	0.24	0.43	Sand
110–250	1.62	0.14	0.41	Sand
250–300	1.51	0.10	0.36	Sand

2.4. Design and measurement

Two monitoring sections were set up in the drip irrigation under mulch, in the middle of the furrow (MFD) and the middle of the mulch (MMD), with the maize rows spaced 40cm apart. A monitoring section (MB) was set up in border irrigation, in the middle of two rows of maize with the rows spaced 50cm apart. A monitoring section (MA) was set up in the bare area. Each monitoring section was sampled at 20cm intervals to a maximum depth of 300cm. The monitoring section settings are shown in Fig. 1. A soil sampler was used to take a sample along the vertical direction of the soil profile and the mass moisture content of the sample was measured using the drying method. The volume water content of the sample was obtained by multiplying the mass water content with the volume weight.

Meteorological data on rainfall, temperature, humidity and wind speed were obtained from nearby weather stations during the experiment. The experiment started in April 2019 - ended in October 2019 and started in April 2021 - ended in October 2021. Irrigation information is shown in Table 2.

Table 2
Irrigation information.

Drip irrigation under mulch		**Border irrigation**	
Data	Irrigation amount(mm)	Data	Irrigation amount(mm)
2019-5-9	30.00	2019-5-9	60.00
2019-6-20	33.00	2019-6-19	61.05
2019-7-04	34.50	2019-7-03	75.00
2021-5-12	30.00	2021-4-26	60.00
2021-6-20	33.00	2021-6-19	61.05

3. Establishment Of Soil Water Flow Model

3.1. Model description

3.1.1 Main equations

Hydrus-2D uses a modified Richard's equation to describe the soil moisture movement model under three forms of subsurface drip irrigation under mulch, border irrigation, and bare area, which is expressed as:

$$\frac{\partial \theta}{\partial t}=\frac{\partial}{\partial x}\left[K\left(h\right)\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial z}\left[K\left(h\right)\frac{\partial h}{\partial z}\right]+\frac{\partial}{\partial z}K\left(h\right)-S$$

1

Where θ is the soil volume water content ($cm^3 \cdot cm^{-3}$), h is the pressure head (cm), K(h) is the unsaturated hydraulic conductivity function ($cm \cdot day^{-1}$), t is the time parameter (day), x and z are the spatial coordinates (cm), S is a sink term (day^{-1}).

The Van Genuchten-Mualem model was selected for the soil hydraulic properties model. Its expression form is:

$$\theta=\begin{cases}\theta_r+\frac{\theta_s-\theta_r}{\left[1+(\partial|h|)^n\right]^m};h<0\\ \theta_s;h\geq 0\end{cases}$$

2

$$K(\theta)=K_sS_e^l\left[1-\left(1-S_e^{1/m}\right)^m\right]^2 \qquad (3)$$

$$S_e=\frac{\theta-\theta_r}{\theta_s-\theta_r},m=1-1/n,n>1 \qquad (4)$$

Where θ_s is the saturated water content ($cm^3 \cdot cm^{-3}$), θ_r is the residual water content ($cm^3 \cdot cm^{-3}$), K_S is the saturated hydraulic conductivity ($cm \cdot day^{-1}$), α (cm^{-1}), n (-) and m (-) are empirical coefficients. l is the pore connectivity parameter (-).

3.1.2 Root water uptake

The sink term S represents the volume of water removed per unit time from a unit volume of soil due to plant water uptake:

$$S\left(h\right)=\alpha\left(h\right)b\left(x,z\right)S_tT_p$$

5

Where α(h) is the water stress response function, Tp is the potential transpiration ($cm \cdot day^{-1}$), St is the width of the soil surface associated with the transpiration process, and b(x, z) is the normalized water uptake distribution, calculated by the following equation:

$$b\left(x,z\right)=\left(1-\frac{z}{Z_m}\right)\left(1-\frac{x}{X_m}\right)e^{-\left(\frac{P_z}{Z_m}|z^*-z|+\frac{P_x}{X_m}|x^*-x|\right)}$$

6

Where X_m and Z_m are the maximum rooting lengths in the x- and z- directions (cm), respectively, x and z are the distances from the origin of the x- and z- directions (cm), respectively. P_x, P_z, x^*, and z^* are the empirical parameters.

3.1.3 Evaporation and transpiration

Daily reference evapotranspiration was calculated according to the Penman−Monteith model recommended by the FAO-56 as follows:

$$ET_0=\frac{0\cdot 408\varDelta\left(R_n-G\right)+\gamma\frac{900}{T+273}u_2\left(e_s-e_u\right)}{\varDelta+\gamma\left(1+0.34u_2\right)}$$

7

Where ET_0 is the reference evapotranspiration ($mm \cdot d^{-1}$), R_n is the net radiation ($MJ \cdot m^{-2}$), G is the soil heat flux (MJ $m^{-2} \cdot day^{-1}$), u_2 is the average wind speed at the height of 2m ($m \cdot s^{-1}$), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), Δ is the slope of the saturation vapor pressure-temperature curve ($kPa \circ C^{-1}$), γ is the psychometric constant ($kPa \circ C^{-1}$).

In HYDRUS-2D, Potential evaporation and transpiration are required as inputs in Hydrus-2D, which can be calculated as follows:

$$ET_C=k_CET_0$$

8

$$E_P=ET_cexp\left(-k\cdot LAI\right)$$

9

$$T_p=ET_C\left[1-exp\left(-k\cdot LAI\right)\right]$$

where ET_c is the evapotranspiration of the crop (mm·d^{-1}); T_p is the potential transpiration; E_p is the potential evaporation; LAI is the leaf area index and k is the attenuation coefficient of canopy radiation.

3.2. Initial and boundary conditions

Assume that the moist district on the vertical plane was bilateral symmetry (Chen, L.J. et al., 2014), zero moisture exchanged between left and right at the vertical boundary line, and No Flux boundary was adopted on the left and right sides. The drip irrigation pipe in drip irrigation under mulch was set to Variable Flux condition, and the moist district was calculated by iterative computation (Gärdenäs, A.I. et al, 2005). The part of film mulching that was not in contact with the atmosphere was set to No Flux boundary, the soil profile in contact with the atmosphere was set to Atmospheric boundary. The lower boundary was set to Free Drainage boundary. The top soil for surface border irrigation was set to Atmospheric boundary, converting irrigation amount and precipitation. The boundary conditions for border irrigation and bare area were set with reference to drip irrigation under mulch, as shown in Fig. 2. In situ field experiments from 2019 to 2021, the initial soil moisture was similar, and the initial soil moisture in 2019 was used as the initial condition.

3.3. Calibration of model parameters

Hydraulic parameters were initially predicted from the proportion of the soil particle size and soil water retention curve using the Rosetta program. The inverse module and the experimental data from 2019 were used to optimize the hydraulic parameters. The optimized Soil hydraulic parameters are shown in Table 3.

Table 3
Soil hydraulic parameters.

Depth	θr	θs	α	n	Ks	l
(cm)	(cm^3·cm^{-3})	(cm^3·cm^{-3})	(cm^{-1})	(-)	(cm^3·day^{-1})	(-)
0–40	0.065	0.44	0.114	1.53	348.00	0.5
40–70	0.057	0.44	0.106	1.38	41.10	0.5
70–110	0.025	0.43	0.124	1.27	435.07	0.5
110–250	0.026	0.41	0.129	1.70	450.00	0.5
250–300	0.027	0.36	0.145	2.00	500.00	0.5

3.4. Model validation and accuracy evaluation

The model was validated using experimental data from 2022. The performance of the model was evaluated using the following three statistical indicators: mean absolute error (MAE), root mean square error (RMSE), and coefficient of determination (R^2):

$$RMSE = \sqrt{\frac{1}{N} \cdot \sum_{i=1}^{N} (S_i - M_i)^2}$$

11

$$MAE = \frac{\sum_{i=1}^{N} |M_i - S_i|}{N}$$

12

$$R^2 = 1 - \frac{\sum_{i=1}^{N} (S_i - M_i)^2}{\sum_{i=1}^{N} \left(M_i - \bar{M}\right)^2}$$

13

Where S_i is the simulated value, $\bar{S_i}$ is the simulation average value, M_i is the observed value, $\bar{M}$ is the observed average value, N is the total number of observed values.

The experimental data from 2022 and optimized soil hydraulic parameters were used to verify the model. Due to the large number of observation points set up, only the simulated and measured values of some representative observation points are shown. 20cm,40cm for areas directly influenced by maize roots; 80cm,120cm for areas indirectly influenced by maize roots; 260cm for areas barely influenced by maize. The simulated soil moisture content had the same trend as the measured values. As shown in Fig. 3 and Table 4.

Table 4
The error analysis of soil water contents for different treatments.

Depth (cm)	Drip irrigation under mulch			Bare area			Border irrigation		
	MAE (cm^3/cm^3)	R^2	RMSE (cm^3/cm^3)	MAE (cm^3/cm^3)	R^2	RMSE (cm^3/cm^3)	MAE (cm^3/cm^3)	R^2	RMSE (cm^3/cm^3)
20	0.015	0.79	0.021	0.010	0.94	0.011	0.012	0.80	0.016
40	0.015	0.78	0.024	0.016	0.92	0.020	0.014	0.77	0.022
80	0.033	0.79	0.040	0.025	0.80	0.046	0.024	0.83	0.029
120	0.010	0.74	0.014	0.022	0.79	0.029	0.009	0.78	0.011
260	0.010	0.75	0.011	0.015	0.86	0.017	0.003	0.76	0.004

The overall R^2 was 0.94, 0.94, and 0.95 for drip irrigation under mulch, bare area, and border irrigation respectively. The overall RMSE was 0.024, 0.027, and 0.018 for drip irrigation under mulch, bare area, and border irrigation respectively. The overall MAE was 0.016, 0.017, and 0.012 for drip irrigation under mulch, bare area, and border irrigation respectively. The graphical and statistical results showed that the R^2, RMSE, and MAE of all layers of drip irrigation under mulch, bare area, and border irrigation meet the standards. Simulated and measured soil moisture content showed good agreement. Simulated and measured soil moisture content showed good agreement. Considering the complexity of the in-situ field experiments, many disturbing factors (e.g. soil spatial variability, uneven distribution of rainfall and irrigation, the effects of uneven distribution of crop roots, etc.) might be encountered. It was considered that the model meets the accuracy criteria and can simulate soil moisture movement better.

4. Result

4.1. Infiltration recharge amount

Calculation of evaporation and transpiration values for 1990–2019 used the single crop coefficient approach of FAO-56, the meteorological data source was the China meteorological data service center (http://data.cma.cn). Irrigation amounts were calculated using the water-balance method. Using the Subregions and Cumulative Fluxes modules in Hydrus-2D, iterative calculations were carried out to determine when irrigation should be carried out in conjunction with Irrigation amounts and meteorological data. The irrigation data and rainfall data obtained were reused as an input to obtain the infiltration recharge amount at different groundwater tables for different underlying surfaces from 1990 to 2019. The result is shown in Fig. 4.

Figure 7 shows that as the depth of groundwater table increases, the infiltration recharge amount from rainfall and irrigation is gradually depleted and the infiltration recharge capacity gradually decreases. The cumulative infiltration of drip irrigation under mulch was greater than that of bare area and greater than that of border irrigation. Taking the depth of groundwater table at 80cm as an example, the annual average cumulative infiltration of drip irrigation under mulch was 183.04 mm, which was greater than the 122.05 mm of bare area and 104.31 mm of border irrigation. As the depth of groundwater table increases, the cumulative infiltration rate decreased at a similar rate for drip irrigation under mulch and bare area but decreased more rapidly for border irrigation.

Irrigation keeps the moisture in the planned wetting depth at a reasonable level, while rainfall becomes the main source of infiltration and recharge of groundwater. Different subsurface have different degrees of influence on the infiltration and recharge of rainfall. The impermeability of film mulching allows water vapor to circulate under the film, reducing the evaporation from the soil compared to border irrigation. The furrow of drip irrigation under mulch has the effect of rain-catching and the impermeability of the mulch does not reduce the infiltration of rainfall. The soil in the experimental area is sandy and has a strong infiltration capacity. Therefore, drip irrigation under mulch allows more water to enter the deeper layers of the soil. For bare area, although there is no infiltration recharge from irrigation water, groundwater recharge is dominated by rainfall infiltration recharge and there is no plant transpiration consumption, so the infiltration recharge from bare area is greater than that from border irrigation.

4.2. CGDM

Infiltration recharge of groundwater increases with increasing groundwater table. When the groundwater table is at a certain height, the total amount of irrigation extracted from groundwater in that year is equal to the cumulative infiltration recharge to groundwater from precipitation and irrigation in that year. At this point, the groundwater table is the critical groundwater depth of maintaining exploitation and recharge balance in that year.

Using the annual irrigation amount, and the relationship between groundwater infiltration recharge and groundwater table, the CGDM from 1990 to 2019 was obtained, and the interval estimation of the obtained CGDM was carried out. The CGDM with 95% design guarantee rate of drip irrigation under mulch was 131.52-187.15 cm, and the CGDM with 95% design guarantee rate of border irrigation was 63.61–84.34 cm. The result is shown in Fig. 5. Due to a large amount of irrigation and the small amount of infiltration and recharge of groundwater, the CGDM in the border irrigation was too high, and the high groundwater table would lead to soil salinization, crop waterlogging, and other ecological problems. According to local experience, the depth of groundwater should not be lower than 80cm (Cheikh, N. B. et al. 2012; Wang, Y. et al. 2020; Zhang, H. et al. 2018). The CGDM of border irrigation was adjusted to 80.00-84.34 cm.

4.3. CGDD

The amount of groundwater infiltration recharge decreases with the groundwater table decreases, when the groundwater table is below a certain height, the cumulative infiltration recharge to groundwater from precipitation and irrigation in that year is zero, and this groundwater table is the CGDD in that year.

Using the relationship between annual groundwater infiltration recharge and groundwater table, the CGDD from 1990 to 2019 was obtained, and the interval estimation of the obtained CGDD was carried out. The CGDD with 95% design guarantee rate of drip irrigation under mulch was 307.66-363.67 cm, the CGDD with 95% design guarantee rate of border irrigation was 198.87-248.44 cm, and the CGDD with 95% design guarantee rate of bare area was 227.87-306.61 cm. The result is shown in Fig. 6.

5. Discussion

5.1. Groundwater table control strategy

The groundwater table control strategy is shown in Fig. 7.

Areas in a reasonable state of development and utilization: When the groundwater table is between the CGDM, it corresponds to the Areas in a reasonable state of development and utilization. At this time, the groundwater depth is appropriate, which can maintain the self-renewal of groundwater, so that groundwater resources are not depleted due to exploitation. The annual average exploitation amount is in dynamic balance with the annual average recharge amount.

Areas in a reduced state of development and utilization: Areas in a reduced state of development and utilization: When the groundwater table is between CGDM and CGDD, it corresponds to the Areas in a reduced state of development and utilization. At this time, the imbalance risk of groundwater exploitation and recharge gradually increases, and the infiltration and recharge capacity of precipitation and irrigation in this area is gradually weakened with the decrease of the groundwater table. The exploitation of groundwater resources should be reduced.

Areas in a further reduced state of development and utilization: Areas in a further reduced state of development and utilization: When the groundwater level is between CDGG, it corresponds to the Areas in a further reduced state of development and utilization. At this time, the recharge capacity of groundwater from rainfall and irrigation is further reduced. In the years with less rainfall, groundwater cannot be replenished normally after exploitation, which will disrupt the groundwater cycle and further increase the imbalance risk of groundwater exploitation and recharge. At this time, the development and utilization of groundwater should be further reduced.

Areas in a prohibitive state of development and utilization: When the groundwater level is below the CGDD, it corresponds to the Areas in a prohibitive state of development and utilization. If the groundwater table is in this area, groundwater cannot be replenished after exploitation, and the groundwater cycle will be seriously disrupted, facing a serious risk of imbalance between exploitation and recharge, which will seriously harm the local ecology and regional water security.

5.2. Optimized adjustment of CDGC

The CDGC is not fixed as a control index for groundwater development and utilization. When the regional groundwater table is lower than the CDGC, measures can be taken to adjust and optimize it based on regional resources conditionality and economic development objectives, so that the groundwater table is within a reasonable control level range. The specific measures are as follows:

1. Expand the area of water-saving irrigation such as drip irrigation under mulch (Xu, W. et al. 2019; Zhang, H et al. 2017). The CDGM of drip irrigation under mulch is lower than that of border irrigation, and by expanding the area of drip irrigation under mulch, the regional CDGC level can be lowered so that the groundwater table is in a reasonably controlled water level interval.
2. Appropriate increase in rain-fed crops agricultural area (Liu, B. et al. 2017). In rain-fed crops agricultural areas, where rainfall infiltration recharges groundwater without groundwater exploitation, this measure can lower the CDGC. However, under the climatic conditions of the semi-arid region, the yield of rain-fed crops is low and low and the compatibility between crop yields and water resources should be fully considered. The size of rain-fed crops agricultural areas should be appropriate.
3. Interregional water transfer (Zhao, M. et al. 2021). Interregional water transfers can be used for groundwater recharge to raise groundwater table, or for agricultural irrigation to reduce groundwater exploitation, lowering CDGC, and keeping groundwater table at a reasonable control table.

6. Conclusions

Based on the characteristics of the vertical hydrological cycle in semi-arid irrigation areas, this paper used a combination of in situ field experiments and software simulations to calculate the groundwater infiltration recharge under three types of subsurface conditions, namely, drip irrigation under mulch, border irrigation, and bare area, and to analyze the relationship between groundwater infiltration recharge and groundwater table. Based on the relationship between groundwater recharge and discharge, the CGDM for drip irrigation under mulch was calculated to be 131.52-187.15 cm and the CGDD was 307.66-363.67 cm. For border irrigation, the CGDM was 80.00-84.34 cm and the CGDD was 198.87-248.44 cm.

Drip irrigation under mulch reduces inefficient water consumption and improves water use efficiency compared to traditional surface border irrigation, with CGDC significantly lower than that of border irrigation. It can be seen that under the premise of considering resource constraints and economic development, improving irrigation water use efficiency is an important measure to solve water shortage and maintain a stable hydrological cycle in semi-arid irrigation areas.

In 2019, the depth of groundwater table in the experimental area was 280cm, and according to the division of risk control area, it belonged to the areas in a reduced state of development and utilization of drip irrigation under mulch and the areas in a prohibitive state of development and utilization of border irrigation, and the groundwater was in a state of imbalance between exploitation and recharge. The depth of groundwater table has dropped to 420cm by 2021. If no control strategies are taken, the groundwater table will drop year by year, the risk of imbalance in groundwater exploitation and recharge will increase year by year, and groundwater will be at risk of depletion. Therefore, it is necessary to maintain a stable groundwater table through measures such as increasing groundwater recharge and improving water use efficiency, to achieve groundwater sustainable use and balance of groundwater exploitation and recharge.

Declarations

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Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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Figures

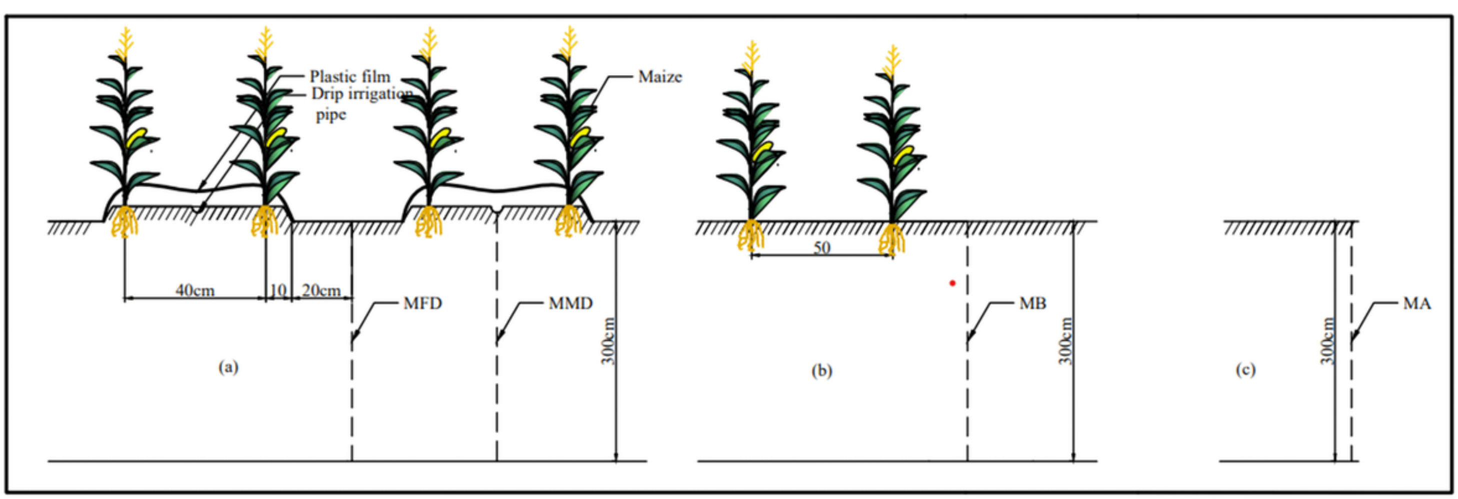

Figure 1

Settings of monitoring sections. (a) is drip irrigation under mulch, (b) is border irrigation, and (c) is bare area

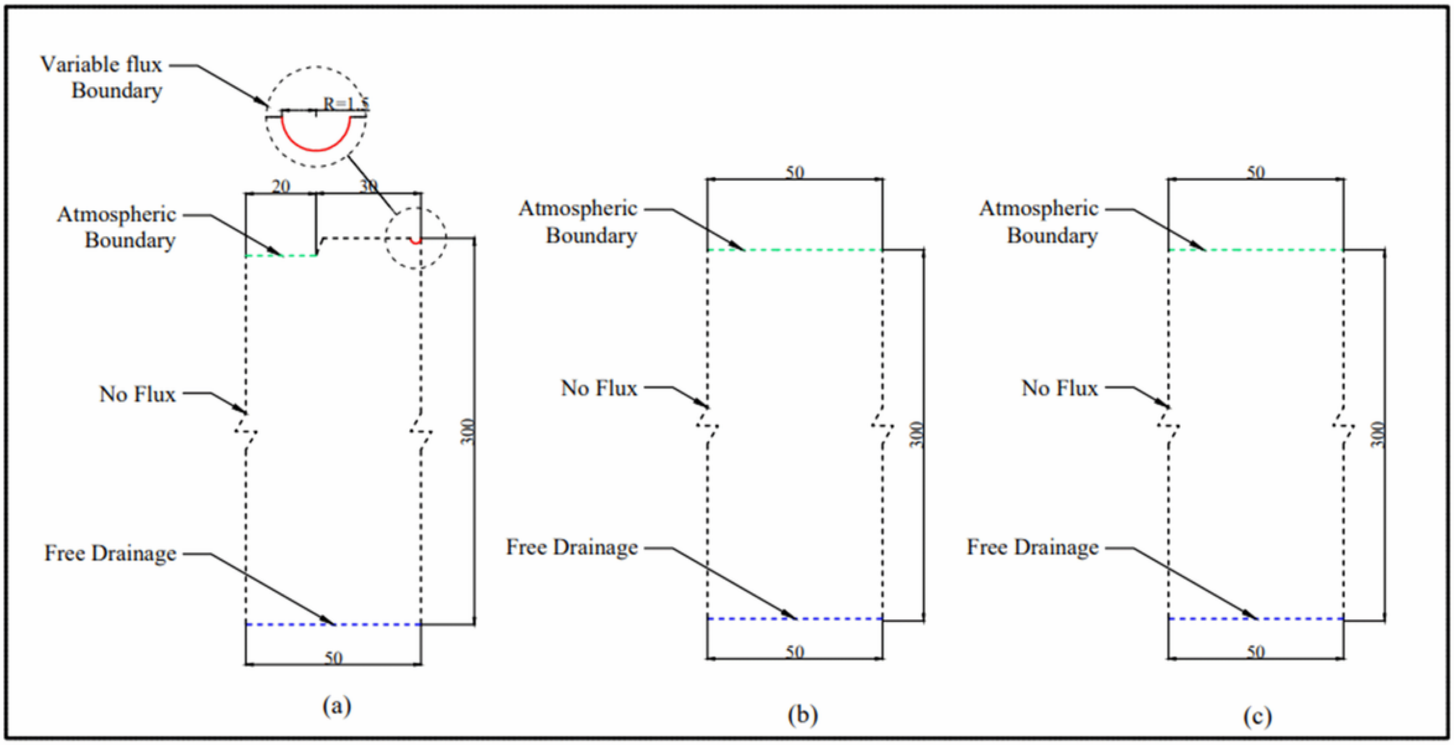

Figure 2

Settings of boundary conditions. (a) is drip irrigation under mulch, (b) is border irrigation, and (c) is bare area

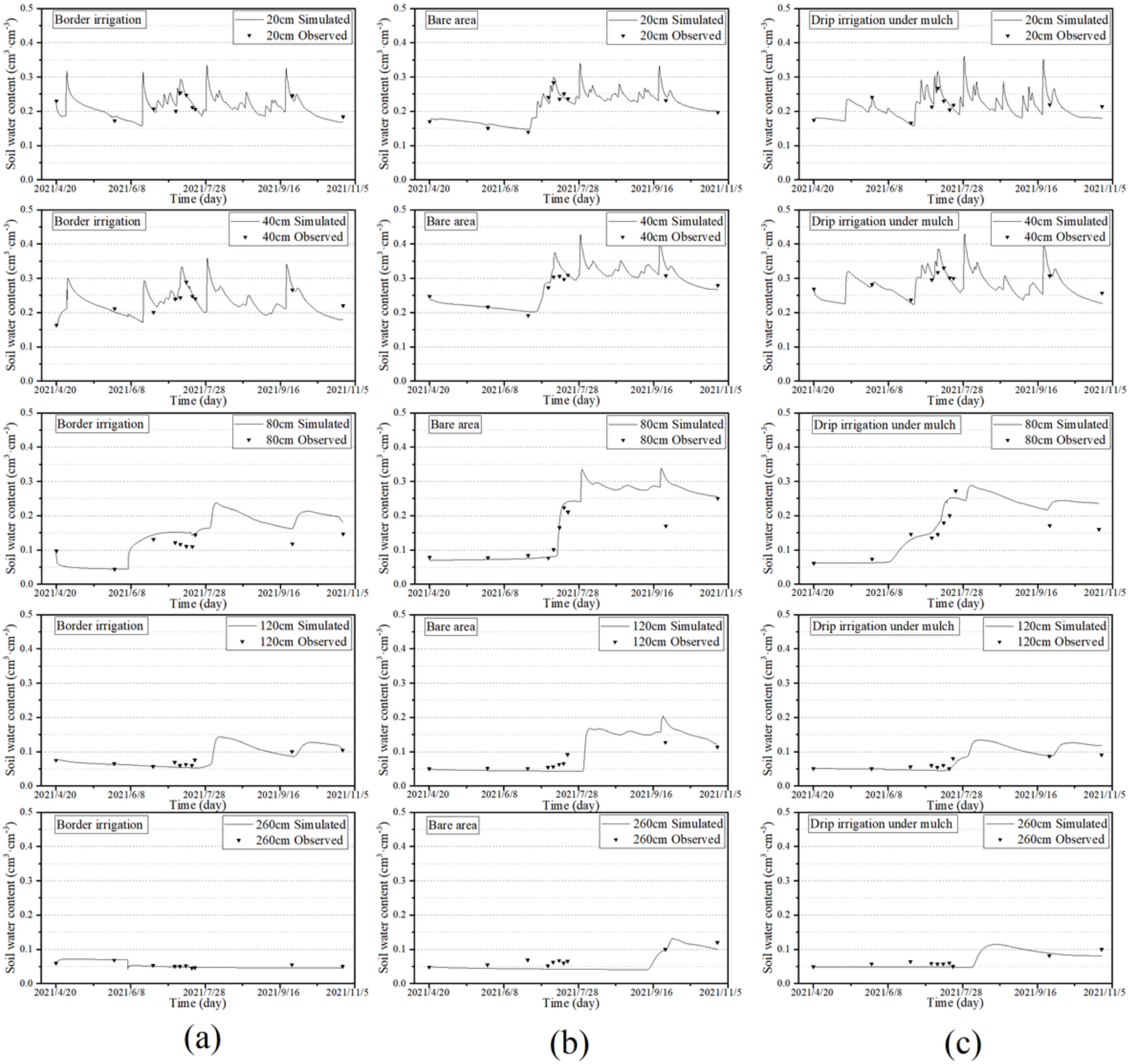

Figure 3

Simulated and measured soil water contents at different soil depths for different treatments. (a) is border irrigation, (b) is bare area, and (c) is drip irrigation under mulch

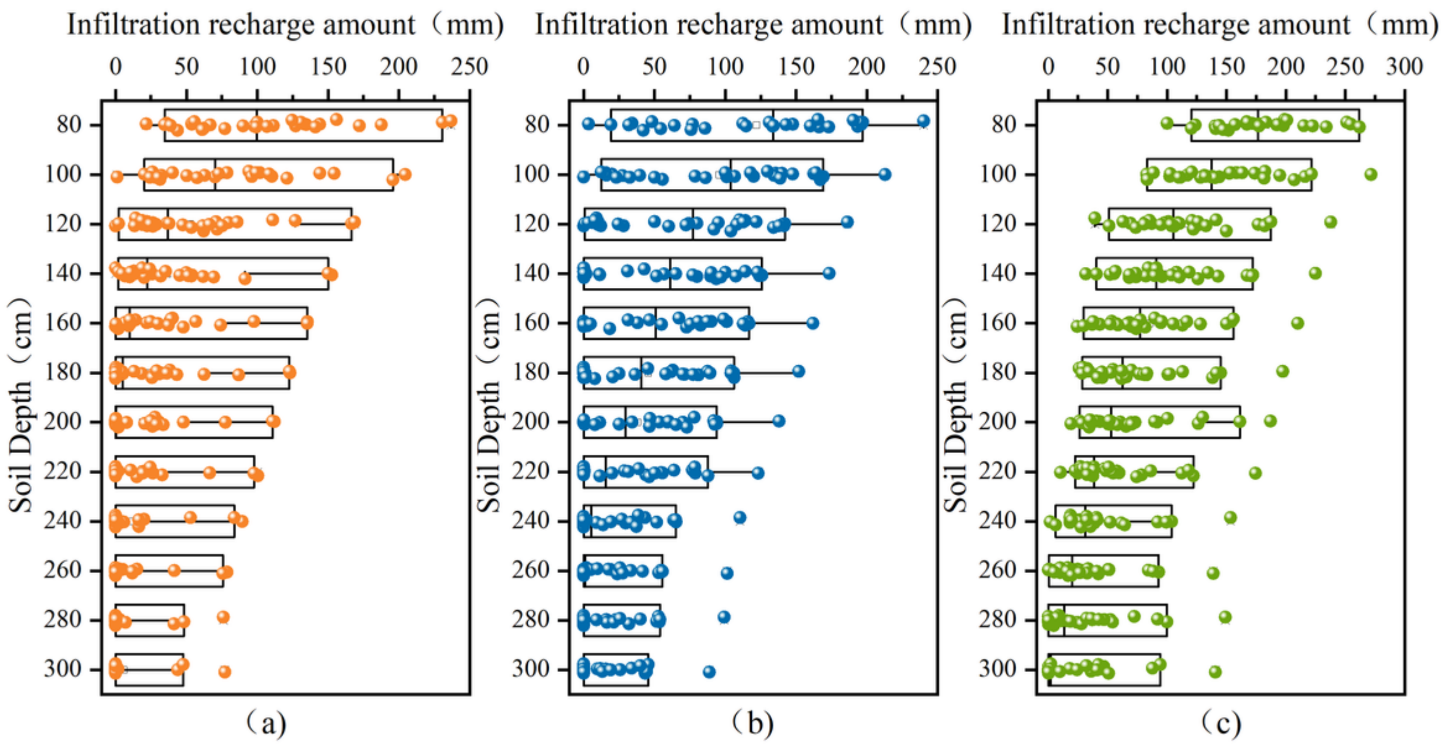

Figure 4

Infiltration recharge amount. (a) is border irrigation, (b) is bare area, and (c) is drip irrigation under mulch

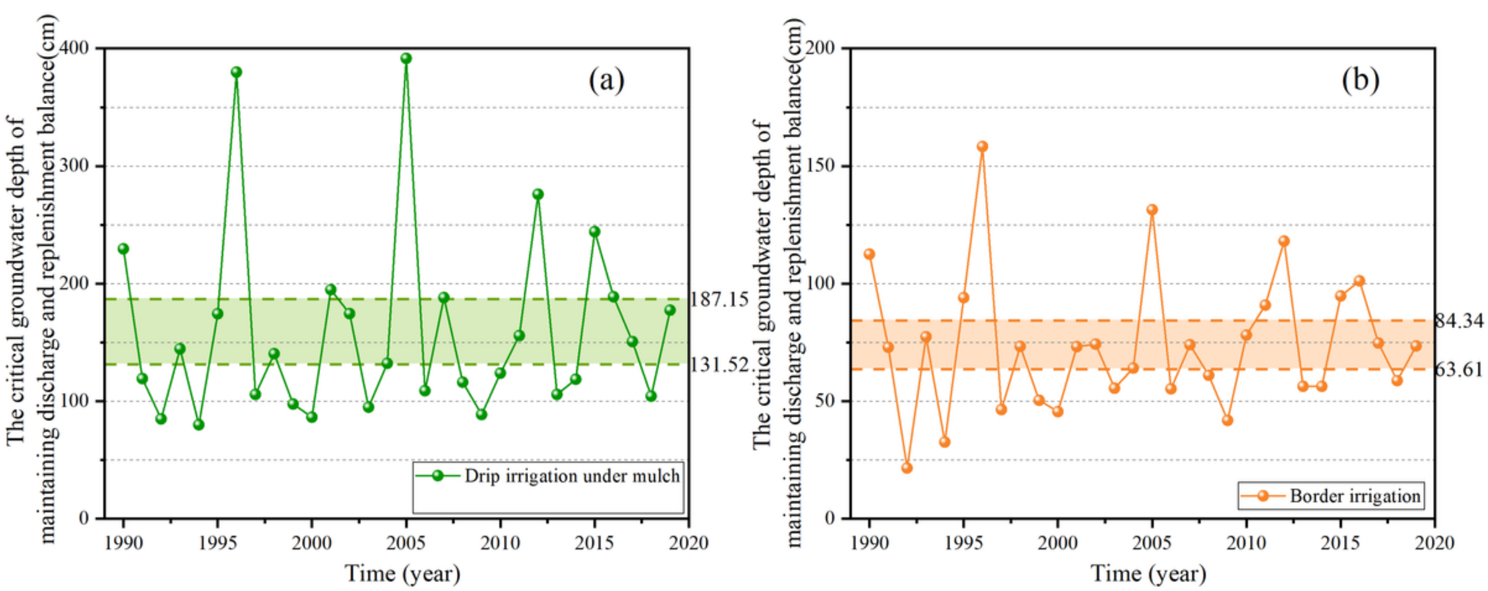

Figure 5

The CGDM. (a) is drip irrigation under mulch, (b) is border irrigation.

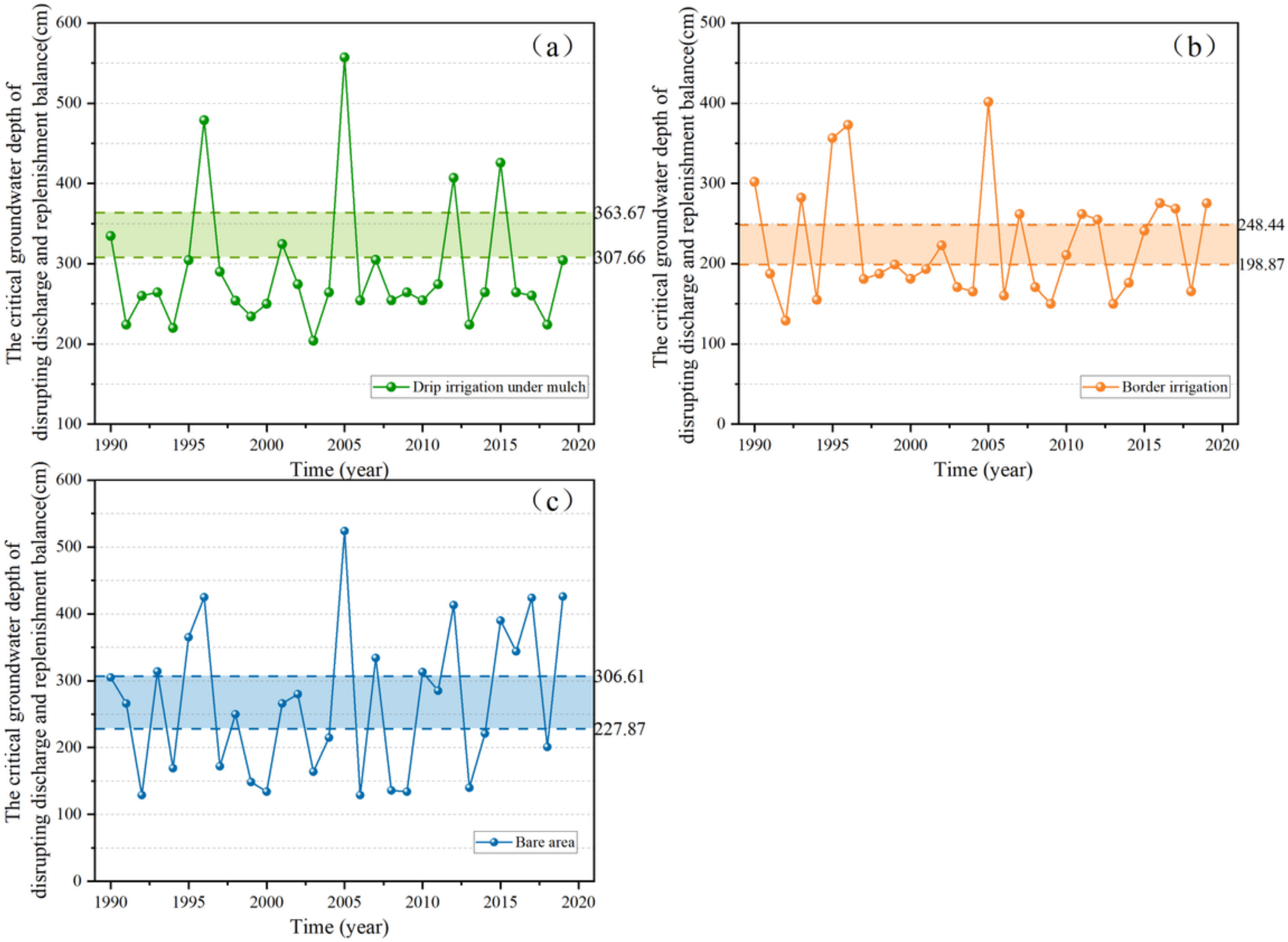

Figure 6

The CGDD. (a) is drip irrigation under mulch, (b) is border irrigation, and (c) is bare area.

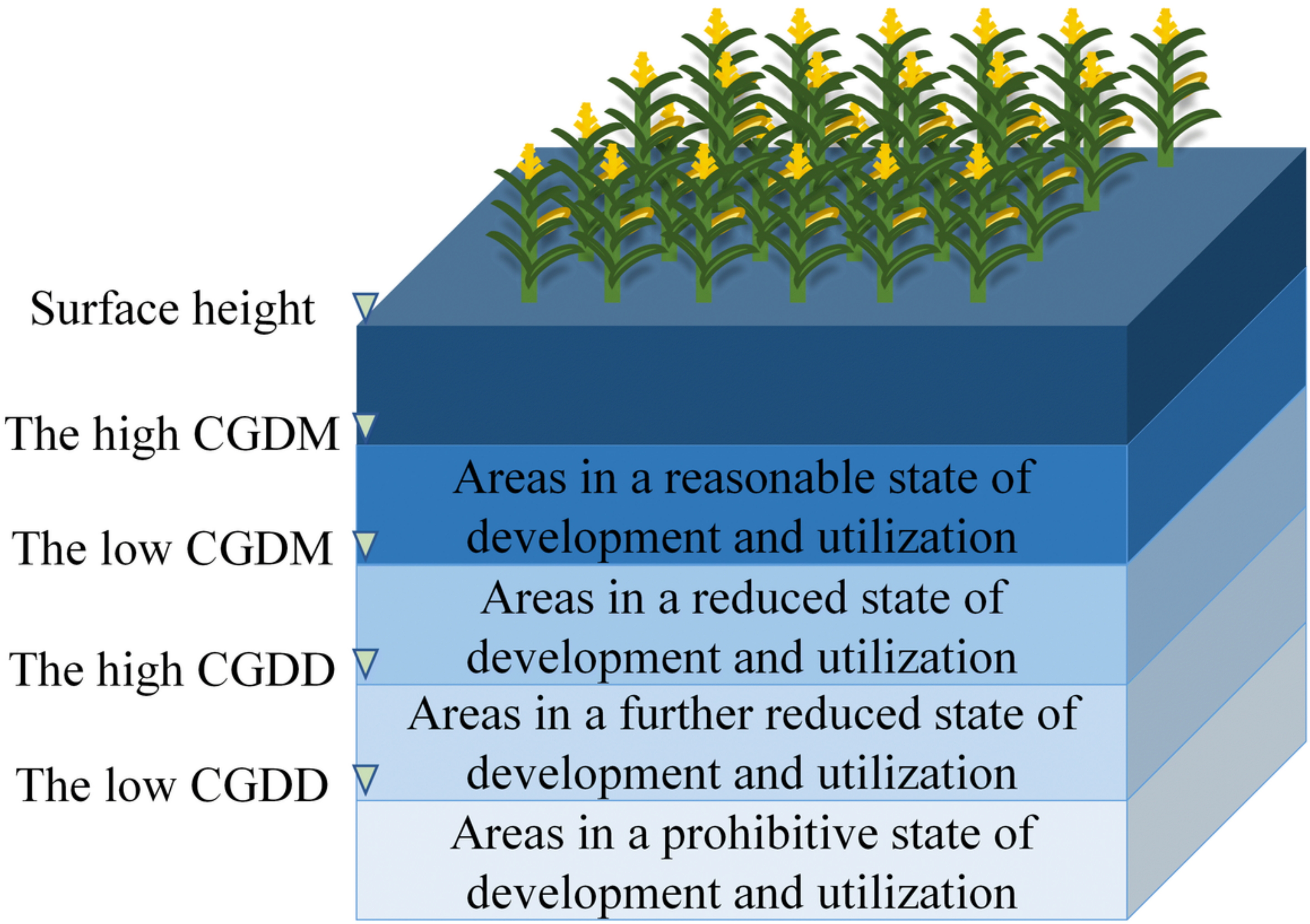

Figure 7

Schematic diagram of groundwater table control strategy.