

# An analysis on the influence of precipitation infiltration on groundwater under different irrigation conditions in the semi-arid area

Long Yan, Min-jian Chen, Peng Hu, Di-li Li and Yong Wang

## ABSTRACT

The West Liaohe Plain is a typical semi-arid area, where the process of rainfall infiltration to replenish groundwater is a key link in its vertical hydrological cycle. In this paper, we compare and analyze the impact upon soil moisture movement and water infiltration after the shift of irrigation method from flood irrigation to mulched drip irrigation under mulch through setting up in-field in-situ observation points and carrying out groundwater depth dynamic observation. The results show that compared with mulched drip irrigation under mulch, flood irrigation has a stronger response to rainfall infiltration and a quicker response time in the rise of underground depth. With the decrease of groundwater level, the effect of rainfall infiltration to replenish groundwater is significantly weakened. In the flood irrigation area, the groundwater depth at about 8 m already has no obvious response to a small amount of rainfall. However, the groundwater depth at 6 m in the area of mulched drip irrigation under mulch already has no response to rainfall. Therefore, when groundwater extraction is carried out in irrigation areas, reasonable groundwater extraction levels should be designated in light of different irrigation methods to maintain the sustainable utilization of groundwater.

**Key words** | groundwater level, irrigation conditions, precipitation infiltration, soil moisture content

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## HIGHLIGHTS

- Observed rainfall infiltration realized through flood irrigation and mulched drip irrigation under mulch.
- Analyze the mechanism of the influence of irrigation conditions on rainfall infiltration.
- Analyze the change of soil moisture content.
- Analyze their impacts upon rainfall infiltration.
- The promotion of mulched drip irrigation under mulch will exert a significant impact on rainfall infiltration.

## INTRODUCTION

The impact of human activities and of climate change is exacerbating the contradiction between the supply and demand of water resources in various regions (Xia & Shi

2016). As the contradiction becomes more and more prominent, human beings continue to develop towards high-efficiency water-saving agriculture. At the same time, when water-saving measures are contributing to the increase of crop yield, we should also pay attention to the impact that these water-saving measures will exert on groundwater replenishment in related regions. For instance, with the

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popularization of refined irrigation measures such as sprinkler irrigation and micro-drip irrigation, measures like concrete lining adopted in various levels of the channel system in the water delivery and distribution system have played a positive role in reducing deep water leakage and water loss along the channels and have achieved the purpose of improving the utilization rate of irrigation water in irrigation areas (Arbat *et al.* 2008; Bufon *et al.* 2012; Skaggs *et al.* 2012; Qin *et al.* 2016). Meanwhile, however, water replenished to groundwater in related regions from irrigation return water has also decreased accordingly. In addition, the popularization of high-yield and high-quality crop varieties as well as the implementation of high-efficiency fertilization technologies have led to a significant increase in the output of biomass per unit area, which has also led to a substantial consumption of soil water. This means substantial decrease in the amount of underground water replenished from rainfall and irrigation water. In their researches on water quantitative transformation relationship between crop structure, crop yield, irrigation system, etc. and water quantity, Xuzhou Hanwang Hydrological Experiment Station and Baoding Ranzhuang Water Resources Experiment Station pointed out that high-efficiency agricultural water utilization measures improve hydrological utilization efficiency along with their negative impact on groundwater replenishment (Wei & Ba 2003).

Traditionally, flood irrigation has always been adopted for crops in the West Liaohe Plain. Since 2005, mulched drip irrigation under mulch has been promoted and applied as an efficient water-saving irrigation facility in the area around Tongliao City. A stable area of approximately 40,000 mu of farmland was applied with mulched drip irrigation under mulch from 2008 to 2011, accounting for 0.43% of the total effective irrigation area. With the advancement of the Water Saving and Yield Increase Action Plan, the corn farmland area with mulched drip irrigation under mulch had dramatically increased from 344,000 mu in 2012 to 1.678 million mu in 2015, accounting for 17.1% of the total effective irrigation area. As of 2015, a total of 1.311 million mu of farmland with mulched drip irrigation under mulch had been established in Horqin District, Horqin Zuoyi Middle Banner and Kailu County, accounting for 78% of the total farmland area with mulched drip irrigation under mulch across the whole city. The whole region

has become a major area where mulched drip irrigation under mulch is mainly applied.

Rainfall is an important replenishment factor for vertical hydrological cycle in semi-arid areas (Yan *et al.* 2018). Aiming at the problem of groundwater recharge by precipitation infiltration, many scholars have studied the spatial variability and influencing factors of precipitation infiltration coefficient (Shi *et al.* 2007; Huo & Jin 2015). Zhang *et al.* (2007) analysed the influence of unsaturated zone thickness on precipitation infiltration for recharge of groundwater; the result shows that following the continuous dropping of the groundwater table, the recharged rate tends to decrease in a limited period due to the increase in the infiltration path length. Rainfall infiltration replenishment for underground water is a key link in the process of the vertical hydrological cycle, but changes in irrigation conditions in farming irrigation areas will have an impact on this key link. Therefore, it is necessary to observe rainfall infiltration realized through flood irrigation and mulched drip irrigation under mulch respectively and analyze their impacts upon rainfall infiltration because of the change of irrigation method.

## MATERIALS AND METHODS

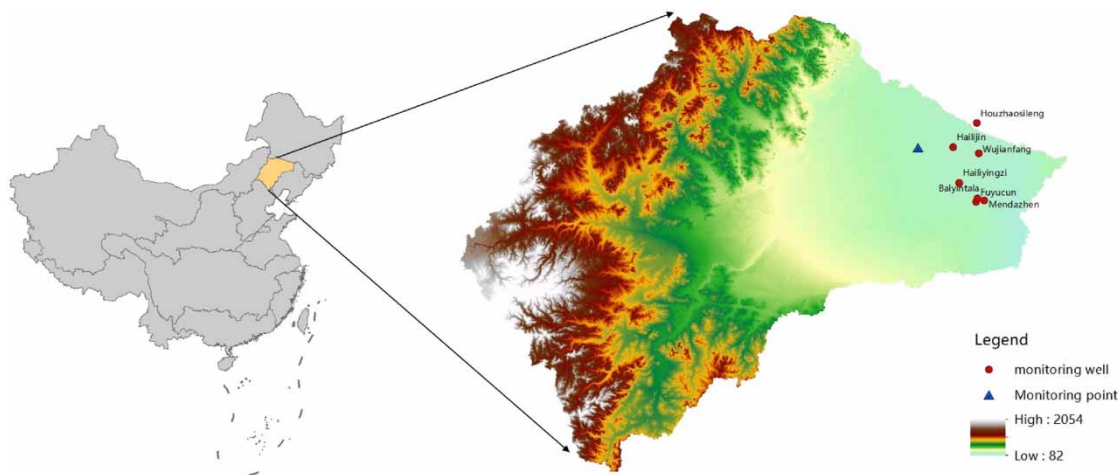
### Study areas

The West Liaohe Plain is located in the eastern part of the Xiliao River Basin, with its major part in Tongliao City, and lies between 41°05' to 45°13'N and 116°10' to 123°35'E. Its area is approximately 65,000 km<sup>2</sup>. Within this region, the annual average precipitation is less than 380 mm, and the annual average water surface evaporation is more than 1,000 mm. Typically characterized with semi-arid features, this area normally has no direct surface runoff after rainfall. Vertical precipitation infiltration is an obvious phenomenon here, the groundwater is abundant and vertical recharge for groundwater is stable. As a relatively intact watershed within the farming-pastoral zone in the semi-arid area, the West Liao River has hydrological cycle characteristics that typically belong to the farming-pastoral zone in the semi-arid area. Its plain area fully exhibits the rainfall-evaporation-infiltration cycle, especially the process of rainfall infiltration to replenish groundwater. In recent years, the irrigation

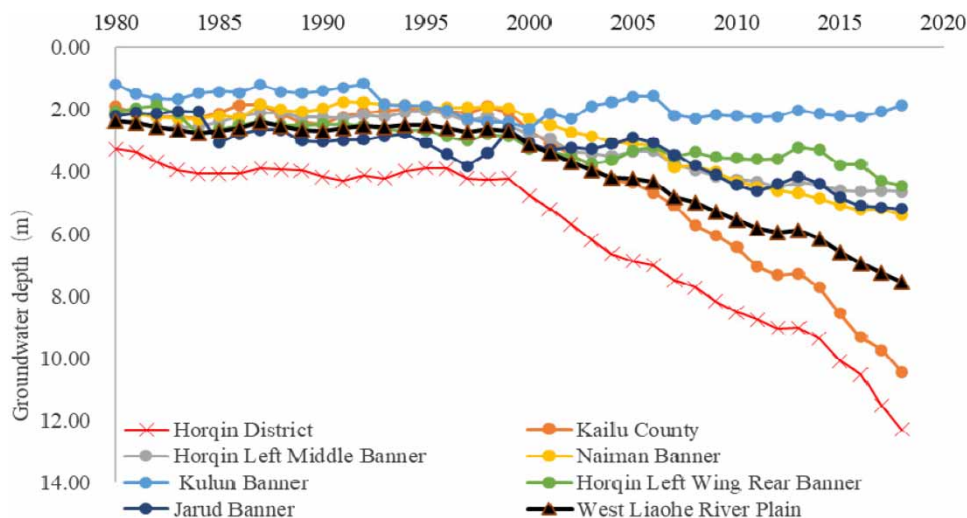
mode in the West Liaohe Plain has shifted from flood irrigation to mulched drip irrigation under mulch. Therefore, this paper takes the West Liaohe Plain as an example to study the impact of changes in irrigation method upon groundwater in a semi-arid farming-pastoral zone (Figure 1).

With the continuous expansion of the irrigated area, the increase in the number of irrigation wells, and the over-exploitation of groundwater, the groundwater depth shows a declining trend. This paper collected and sorted out the groundwater depth data of 74 groundwater monitoring

wells in West Liaohe River Plain since 1980. In 1980, the average groundwater depth of West Liaohe River Plain was 2.33 m, and dropped to 7.55 m by the end of 2018, with an annual decline rate of 0.13 m/a (Figure 2). Before 2000, the downward trend of groundwater depth was not obvious, and the groundwater depth was between 2 and 4 m. After 2000, the groundwater depth decreased significantly, and the average groundwater depth in the plain area decreased by about 5 m. The most obvious decrease of groundwater burial depth was shown in Horqin District



**Figure 1** | Study area. The map were created using ArcGIS 10.2 (<http://www.esri.com/software/arcgis/arcgis-for-desktop>).



**Figure 2** | The change of groundwater depth in West Liaohe River Plain from 1980 to 2018.

and Kailu County, two counties with the largest distribution of irrigated areas. The groundwater depth in Horqin area showed the maximum changes, falling from 3.2 m in 1980 to 12.29 m in 2018.

### Mechanism analysis

Rainfall in the West Liaohe Plain basically does not lead to surface runoff, so replenishment for groundwater mainly comes from rainfall. This area has the rainfall-evaporation-infiltration vertical hydrological cycle characteristics. The farming irrigation area in the plain area is the guarantee for the social and economic development of the West Liaohe Plain. According to the development of agricultural and grazing industry in the West Liaohe Plain, the artificial ecological environment marked by the farming irrigation area has played a key role in this area. However, within the farming irrigation area of the West Liaohe Plain, rainfall cannot meet the water demand for the growth of crops, and irrigation has become a necessary means for the development of agriculture. Traditional flood irrigation has always been the main irrigation method in this area, and the return water produced in this way has played a certain role in the replenishment of groundwater in the area.

In terms of replenishment, atmospheric precipitation is intercepted by vegetation and falls to the ground surface to form net rainfall. Net rainfall infiltrates into the soil to replenish it with water. Part of the water can be transported through the unsaturated zone to the groundwater surface and replenish with underground water (Rimon *et al.* 2007). Under the condition of flood irrigation, irrigation return water will be produced and re-infiltrate to replenish with underground water. In terms of discharge, the whole process consists of interception evaporation, water surface evaporation, soil and vegetation evapotranspiration, and artificial extraction, among which vegetation transpiration and soil evaporation are reflected in unsaturated zone evapotranspiration and phreatic evaporation. As groundwater enjoys an absolute advantage in the composition of water resources in the West Liaohe Plain, and agricultural development must rely on the extraction of groundwater for irrigation, artificial extraction is the largest groundwater discharge item in the West Liaohe Plain. To maintain the stability and renewability of groundwater in farming irrigation

areas, it is necessary to ensure the effective replenishment of groundwater through rainfall infiltration.

When the irrigation mode is shifted from traditional flood irrigation to mulched drip irrigation under mulch, mulch on the ground surface changes the path through which water flows between the atmosphere and the soil, and thus exerts an impact on the soil microenvironment (Li *et al.* 2015). After the field water cycle is changed to a minor cycle of water under mulch, the water continuously condenses into water droplets on the inside of the mulch and then drips into the soil. In this way, the limited water in the soil circulates between the soil and the mulch, thus reducing the soil evaporation of crops (Zhao *et al.* 2015). In addition, mulched drip irrigation mainly increases the soil moisture in the root-mixture of the crop. It carries out controlled irrigation at fixed times, fixed locations and with fixed water quantity according to the water demand for the growth of crop. This means that there will be no irrigation return water in mulched drip irrigation. Therefore, compared with traditional flood irrigation, the impact of mulched drip irrigation under mulch upon groundwater is mainly reflected through the following two changes after it is implemented: first, the ground surface mulch changes the conditions of the underlying surface. Due to the impermeability of the mulch, the rainwater falling on the mulch cannot directly penetrate into the soil after it falls on the mulch. It only pools into the bare land (ridge and furrow) between mulches and infiltrates into the soil after it overflows the water interception surface on the mulch. During this process, part of the water is lost and the amount of infiltrated water is thus reduced; second, due to refined irrigation settings, irrigation return water will no longer be generated. This reduces the potential replenishment of groundwater, and thus affects the hydrological cycle process.

### Design and measurement

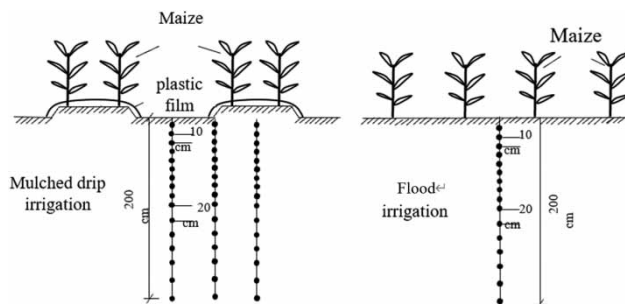
In this paper, South Tallin Aile Village, Yaolin Maodu Town, Horqin Zuoyi Middle Banner, is selected as the observation point, which is located at 44°06'44"N and 122°18'21"E and belongs to the Shebotu Irrigation Area. The soil parameters are shown in Table 1.

HOBO-U30 is adopted to automatically monitor the dynamic situation of soil water content in the section

**Table 1** | Soil parameters

Depth (cm)	Soil	Field capacity (%)	Saturated water content (%)
0–30	Sandy loam	26.6	44.8
30–60	Clay	31.2	49.4
60–200	Sandy soil	21.0	28.5
>200	Sandy soil	21.0	28.5

plane. A monitoring section is set up for flood irrigation and mulched drip irrigation under mulch respectively, with 10 probes evenly arranged between 0 to 100 cm and 5 probes between 100 to 200 cm. The maximum monitoring depth for both of the two irrigation methods is 2 meters, and the observation period is from May 24 to August 22, 2017. The data are recorded at an interval of 2 hours. The specific arrangement of the probes for the two irrigation methods is shown in Figure 3. The rainfall data is from the weather station in the monitoring area. As shown in Table 2, a total of 7 rainfalls has been recorded, of which the maximum rainfall was recorded as 72 mm on August 3.

**Figure 3** | The arrangement of the probes for the two irrigation methods.**Table 2** | Rainfall information

No.	Date	Rainfall (mm)	Rainfall duration (h)
1	2017/7/7	11.6	3
2	2017/7/9	5.2	3
3	2017/8/3	72	23.5
4	2017/8/10	32.5	10
5	2017/8/11	5.4	1.5
6	2017/8/14	7	1.5
7	2017/8/15	4.2	2.5

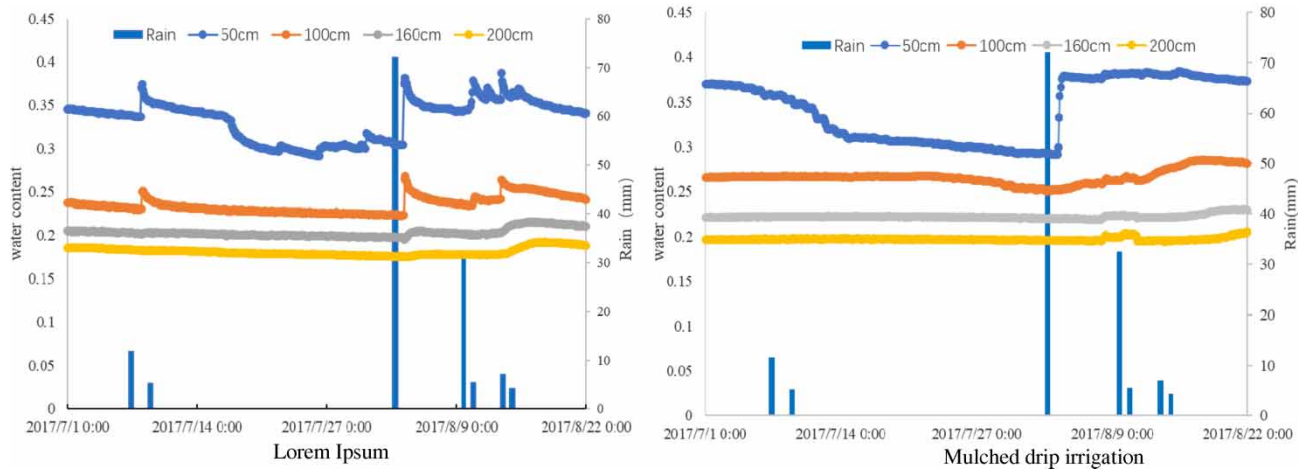
## RESULTS AND DISCUSSION

### Changes in soil moisture content

As shown in Figure 4, in terms of soil moisture content, the flood irrigation area responds more quickly to rainfall than the area of mulched drip irrigation under mulch in general. In the flood irrigation area, each rainfall increases the soil moisture content at the depth of 50 and 100 cm. In the area of mulched drip irrigation under mulch, however, there is no rise in the soil moisture content under the condition of a small rainfall; the soil moisture content at the depth of 50 cm rises rapidly and the soil moisture content at the depth of 100 cm and below rises slowly only when the rainfall reaches 72 mm.

Under the condition of a small rainfall, for instance a rainfall of 11.6 mm on July 7: for the flood irrigation area, the soil moisture content at the depth of 50 cm increased by 3.3% two hours after the rainfall, and the soil moisture content at the depth of 100 cm increased by 2% four hours after the rainfall; in the area of mulched drip irrigation under mulch, however, since the ground surface mulch has changed the condition of the underlying surface, rainwater falling on the mulch cannot directly infiltrate into the soil. It only pools into the ridge and furrow and infiltrates into the soil after it overflows the water interception surface on the mulch. During this rainfall, there was no significant change in the soil moisture content at the depth of 50 cm and below. It shows that when the rainfall is small, flood irrigation is more conducive to rainfall infiltration and replenishment of groundwater than mulched drip irrigation under mulch. Under the condition of a small rainfall, however, the rainfall infiltration depth in the flood irrigation area is less than 1.6 m, which is still within the phreatic limit evaporation depth. If no heavy rainfall occurs in a short period of time, the impact of rainfall infiltration on the water content of the soil aquifer will eventually disappear with the effect of evaporation.

Under the condition of a rainstorm, for instance a rainfall of 72 mm on August 3: in the flood irrigation area, the soil moisture content at the depth of 50 cm increased by 7% two hours after the rainfall, the soil moisture content at the depth of 100 cm increased by 4.1% four hours after the rainfall, and the soil moisture content at the depth of



**Figure 4** | Effect of precipitation infiltration on soil moisture content.

160 cm increased by 0.9% one day after the rainfall; the changes in the soil moisture content in the area of mulched drip irrigation under mulch, however, lagged behind compared with those in the flood irrigation area. Within one day after the rainfall, only the soil moisture content at the depth of 50 cm gradually increased by 8.3% 12 hours after the rainfall, and the soil moisture content at the depth of 100 cm only increased by 0.1% one day after the rainfall. It is worth noting that after the rainstorm, a rainfall of 32.5 mm occurred in the study area on August 10. As the interval between the two rainfalls was only one week, the soil moisture content at the depth of 2 m increased by 1.4% 14 days after the rainstorm; in the area of mulched drip irrigation under mulch, however, the soil moisture content at the depth of 2 m increased by 0.9% 19 days after the rainstorm, which proves that under the condition of a rainstorm, both the rainfall infiltration depth and the infiltration replenishment amount in the flood irrigation area are greater than those in the area of mulched drip irrigation under mulch.

### Changes in groundwater depth

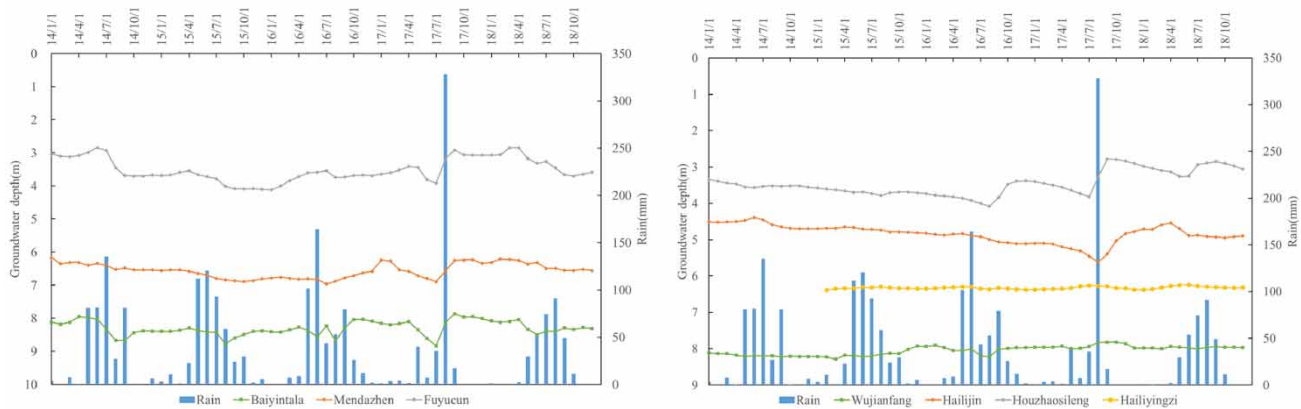
There are few studies on the critical level of groundwater recharge by rainfall infiltration: Zhang (2012) expounded the physical mechanism of infiltration for groundwater supply critical depth, built the rainfall infiltration depth

calculation model, and the result shows that the general infiltration depth is 7 m to 10 m.

Due to the limited conditions of the research, only soil moisture content within the depth of 2 m were monitored in this study. In the study area, however, the groundwater depth were all over 3 m. In order to analyze the replenishment effect of rainfall infiltration upon groundwater under different irrigation conditions, the monthly groundwater depth average data of seven groundwater monitoring wells in Horqin Left Wing Middle Benner from 2014 to 2018 were collected and compiled in this study, among which four monitoring wells are located in the area of mulched drip irrigation under mulch, namely Wujianfang, Hailijin, Houzhaosileng and Hailiyingzi respectively, and three monitoring wells are located in the flood irrigation area, namely Baiyintala, Mendazhen and Fuyucun respectively (Figure 5).

As shown in Figure 5, in both the flood irrigation area and the area of mulched drip irrigation under mulch, it shows that under the same rainfall conditions, the shallower the groundwater depth, the more severe the impact of rainfall infiltration on the groundwater. As the groundwater depth deepens, the groundwater level rises only when heavy monthly rainfall occurs, and the greater the rainfall is, the earlier the groundwater level rises.

In comparison, more dramatic response to rainfall infiltration and quicker response time for groundwater depth to rise occur in flood irrigation than in mulched drip irrigation under mulch. In the flood irrigation area, the groundwater



**Figure 5** | Effect of precipitation infiltration on groundwater depth. Flood irrigation. Mulched drip irrigation.

depth at about 8 m has already no obvious response to a small amount of rainfall. But when the monthly rainfall exceeds 300 mm, the groundwater depth rises by 0.98 m one month after the rainfall. In the area of mulched drip irrigation under mulch, when the groundwater depth is 4 to 5 m, it rises by 0.77 m three months after the rainfall only when the monthly rainfall exceeds 300 mm; when the groundwater depth is 6 m, there is no obvious response to rainfall.

It is shown that for the West Liaohe Plain, where flood irrigation is a major means of irrigation, the promotion of mulched drip irrigation under mulch will exert a significant impact on rainfall infiltration and the quantity of irrigation return water, and change the critical depth of rainfall infiltration replenishment. On the one hand, there will be basically no irrigation return water generated, and on the other hand, the shift will affect rainfall infiltration and replenishment of groundwater, a key process of the hydrological cycle, both of which will affect the balance of extraction and replenishment of underground water. Therefore, appropriate groundwater extraction levels should be set for flood irrigation and mulched drip irrigation.

## CONCLUSIONS

For the West Liaohe Plain, which is a typical semi-arid area, the process of rainfall infiltration to replenish with groundwater is a key link in its vertical hydrological cycle. With different irrigation methods, the replenishment depth of

groundwater through rainfall infiltration is different. In this paper, we compare and analyze the impact upon soil moisture movement and water infiltration after the shift of irrigation method from flood irrigation to mulched drip irrigation under mulch through setting up in-field in-situ observation points in the Horqin Left Wing middle Benner in West Liaohe Plain and carrying out groundwater depth dynamic observation. According to monitoring data of soil moisture content, each rainfall in the flood irrigation area increases the soil moisture content. In the area of mulched drip irrigation under mulch, however, there is no rise of the soil moisture content under the condition of a small rainfall; the soil moisture content at the depth of 50 cm rises rapidly and the soil moisture content at the depth of 100 cm and below rises slowly only when the rainfall reaches 72 mm. In terms of the effect of rainfall infiltration to replenish with groundwater, flood irrigation has a stronger response to rainfall infiltration and has a quicker response time in the rise of underground depth compared with mulched drip irrigation under mulch. With the decrease of groundwater level, the effect of rainfall infiltration to replenish with groundwater is significantly weakened. It shows that in the flood irrigation area, the groundwater depth at about 8 m has already no obvious response to a small amount of rainfall. Only when the monthly rainfall exceeds 300 mm, the groundwater depth rises by 0.98 m one month after the rainfall. However, the groundwater depth at 6 m in the area of mulched drip irrigation under mulch has already no response to rainfall. Therefore, when groundwater extraction will be carried out in irrigation areas, reasonable groundwater

extraction levels should be designated in light of different irrigation methods to maintain the sustainable utilization of groundwater.

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## DATA AVAILABILITY STATEMENT

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

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