MATHEMATICAL MODEL VALIDATION AND ANALYSIS OF SOIL WATER AND NITROGEN TRANSPORT IN WATER STORAGE PITS

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蓄水单坑土壤水氮运移的数学模型验证分析研究

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ABSTRACT

Water storage pit irrigation is a common irrigation method widely used in the northern part of China which can combine water-saving irrigation with soil and water conservation. Applying this method, this study analyzed different temperature and water content of the soil and established correlative models to study the water and nitrogen transport of soil in water storage pits. The results showed that the difference between the measured values of water and nitrogen obtained from the models and the actual values was small, either under different temperature or irrigation amount, suggesting that the models were correct.

摘要

蓄水坑灌法是北方地区普遍使用的浇灌方法，该种方法浇灌的优点是将节水灌溉与保持水土有机结合起来，本文在此种浇灌方法上，对土壤的不同温度、不同水量进行分析研究，并建立相关模型，重点研究蓄水单坑下的土壤的水氮运移。结果发现，不同温度下，水分和氮素的模型测出来了的值与实际测出来的值误差较低，不同灌水量的情况下也能准确检测出吻合度较高的数据，说明该模型是正确的。

INTRODUCTION

Since ancient times, China has long been a big agricultural country. Currently, despite its abundant total water resources, China is in a noticeable lack of fresh water resources *(Holland et al., 2015)*.

The development of agriculture is inseparable from water and fertilizer and fertilizer is rich in nutrients and is an important nutriment for crop growth. Nitrogen is the mostly absorbed nutrient element by crops, so the use of fertilizer in China is also wide *(Zhang, 2016)*. In recent years, with the continuous increase of population, the shortage of water resources is becoming more and more serious. At the same time, the combination of water resources and water fertilizer is an important way to realize agricultural high yield and high efficiency, thus how to achieve scientific irrigation of water and fertilizer on crops has become a key technology.

Water storage pit irrigation method was initially put forward for solving the water shortage and soil erosion problems in northern China *(Fang, et al., 2014)*. For the fact that nitrogen cannot be adequately absorbed and used since agricultural irrigation and fertilization have long been carried out separately in China, the application of storage pit irrigation method can not only save water, but also reduce soil erosion *(Ma, et al, 2010)*.

Many experts have studied this irrigation method. Fan Xiaobo et al *(Fan et al., 2013)* established a TRIME-PICO IPH system and revealed the water content in the soil under the condition of water storage pit irrigation, thereby improving the utilization of water. In an indoor soil column evaporation experiment, Wang Zengtao et al *(Wang, et al., 2011)* studied the law of soil evaporation, and analyzed the mechanism of soil water movement under the water storage pit irrigation condition during evaporation.

B Askri et al. (2014) used the HYDRUS-1D model on the basis of the water storage pit irrigation method in the study of the water of date palm and achieved good results.

Sepaskhah A R et al. (2012) studied the effects of different N rates and water-saving irrigation on rapeseed yield and nitrogen leaching.

In this paper, the soil water and nitrogen transport model in water storage pits was tested under different temperature and different irrigation amount. The results show that the model can well reflect the water and nitrogen transport situation in the soil, thus it is applicable.

MATERIAL AND METHODS

Water storage pit irrigation method

Water storage pit irrigation method is to dig around the trunk 5-7 water storage pits and place on the bottom of the water storage pits waterproof material to avoid deep percolation of the irrigation water. During irrigation, the water is led into the water storage pits through the circular canals and then penetrates into the root of the soil through the pit walls. In the farming areas, this method consists of water storage pits, solid wall facilities, annular ditches, covering facilities, and ditches *(Li et al., 2016)*.

The specific design is shown in figure 1.

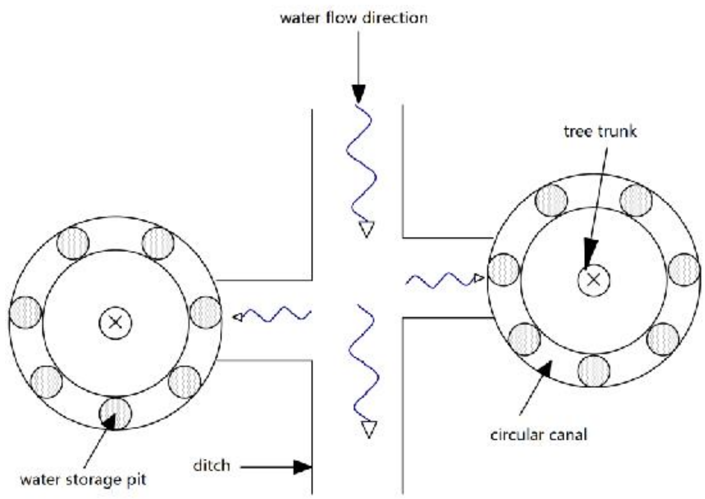

Fig. 1 – Field area engineering schematic diagram

The diameter of a single storage pit is determined according to the volume of irrigating water quota and is about 30 cm generally. The number of water storage pits needed by a single plant depends on the soil irrigation rate, which must ensure that the middle layer soil is completely wet in the neighbouring pit and realize the pit volume required by the irrigation rate. The circular canal locates at the lower part of the trunk and is a shallow canal which connects all the water storage pits. In addition to water delivery, it can also share the water volume under large rainfall conditions. The ditch is a fixed channel connecting the main irrigation system with the annular canal. It is generally divided according to the contour line and located in the upper trunk, which is beneficial to the artesian flow of the water during irrigation and can block the water produced by excessive rainfalls to reduce water and soil loss. The size of the section of the ditch is determined by the amount of water conveyed *(Zhang et al., 2010)*.

MODEL CONSTRUCTION

Each layer of soil is assumed to be homogeneous and isotropic, ignoring the biological effects and chemical effects of soil on water production and the impact of solutes on soil moisture. The soil can be considered as porous media without skeleton deformation and soil water is a kind of incompressible continuous liquid. During the infiltration with different system temperature, the irrigation water achieves a uniform spread to the surrounding area, taking the centre axis of the water storage pit as the symmetric axis. Therefore, the water storage pit irrigation can be considered a two-dimensional plane situation.

Fig. 2 is the infiltration profile of the water storage pit, where:

OG is the water storage pit axis *Oy;*
OB - the ground plane *r,* (i.e., the soil surface);
AF - the puddle wall;
EF - the bottom of the pit;
EG, *GH, BH*are respectively the left border, lower border and right border of the model boundary.
H1 - initial depth of the puddle,
h2 - depth of the water storage pit,
h3 - total height of the soil,
r1 - radius of the water storage pit,
r2 - calculated radius of the soil.

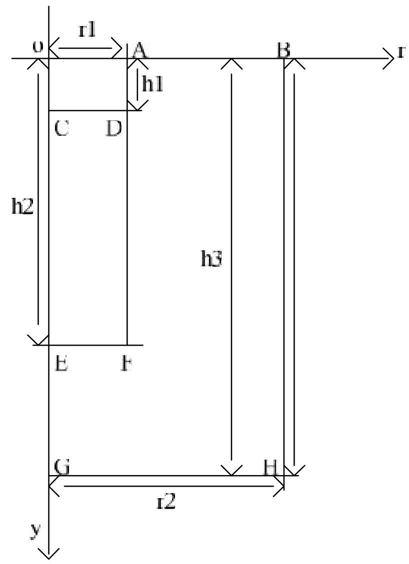

Fig.2– Profile diagram of a water storage pit

Water movement model

Because the water in the single reservoir is the positive pressure water and the pothole is the negative pressure, the governing equation of the model chooses the basic equation of the saturated-unsaturated soil water movement, and *g* is the dependent variable of the negative pressure head.

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{r\times\partial r}\left(rK(g)\frac{\partial g}{\partial r}\right)+\frac{\partial}{\partial y}(K(g)\frac{\partial g}{\partial y})-\frac{\partial K(g)}{\partial y} \tag{1}$$

where:

θ is the water content in the soil;

$K(g)$ -unsaturated soil hydraulic conductivity;

t -infiltration time;

r-horizontal coordinate of the puddle;

y-depth of the soil below the surface.

In order to obtain the unsaturated hydraulic conductivity, the soil water characteristic curve and the soil saturated hydraulic conductivity were solved at first, as follows:

$$\theta(g)=\begin{cases}\theta r+(\theta m-\theta r)\left[1+\left|\rho g\right|^{b_o}\right]^{-a_o} & (g<0)\\ \theta m & (g\geq 0)\end{cases} \tag{2}$$

$$K(h)=Km\cdot S_{\omega}^{j_0}[1-(1-S_{\omega}^{1/a_0})^{a_0}]^2,\quad S_{\omega}=\frac{\theta-\theta r}{\theta m-\theta r} \tag{3}$$

where:

θm is the volume water content of saturated soil;

θr -soil residual volume water content;

Km - saturated soil hydraulic conductivity;

S_{ω} - effective volume water content;

ρ - inverse of the intake air pressure;

b_0 - soil pore size distribution index;

a_0 - 1-1/b_0;

j_0- porosity connectivity parameter.

The two-dimensional convection-diffusion equation describes the transformation process of urea in soil as follows:

$$\frac{\partial(\bar{\ } c_i + «m_i)}{\partial t} = \frac{\partial}{\partial r}\left(\bar{\ } D_{rr}\frac{\partial c_i}{\partial r} + \bar{\ } D_{ry}\frac{\partial c_i}{\partial y}\right) + r^{-1}(\bar{\ } D_{rr}\frac{\partial c_i}{\partial r} + \bar{\ } D_{ry}\frac{\sim c_i}{\partial y}) + \frac{\partial}{\partial y}(\bar{\ } D_{yy}\frac{\partial c_i}{\partial y} + \bar{\ } D_{ry}\frac{\partial c_i}{\partial r}) - \frac{\partial q_r c_i}{\partial r} - \frac{q_r c_i}{r} - \frac{\partial q_y c_i}{\partial y} + Q_i + H_i \quad (4)$$

where:

$c$is the soil volumetric quality;

j -nitrogen element,

q_r and$q_y$are soil moisture flux in the r-direction and soil moisture flux in the y-direction;

Q -source term of the transformation between nitrogen forms;

H -reminiscence of the transformation between nitrogen forms;

D_{rr} - the effect coefficients of the concentration gradient in the r-direction on the diffusion flux of the solute in the r-direction;

D_{ry}-the effect coefficients of the concentration-gradient in the y-direction on the diffusion flux in the r-direction solute.

EXPERIMENT DESIGN

Water and Nitrogen Experiments at Different Temperatures

The soil bulk density was 1.51 g/cm^3, and the following experiments were carried out in the environments of 5^{o}C, 10^{o}C, 15^{o}C, 20^{o}C, 25^{o}C, 30^{o}C and 35^{o}C, respectively:

(1) The orifice plate and the copper mesh are installed on one end of the plexiglass soil column, and the pressure in the semi-infinite soil column is pushed in line with the external pressure.

(2) The experiment was air-dried, blended with 2mm sieve, mixed and layered, and packed into plexiglass soil column according to the standard of 5cm per layer. Then, copper mesh and supportable porous plate are installed, covered with bottom plate to prevent the collapse of the soil edge.

(3) Preparation of 100mgN / L potassium nitrate solution, poured into the bottle. The temperature of the incubator was adjusted to 5°C, 10°C, 15°C, 20°C, 25°C, 30°C and 35°C, respectively, and the plexiglass soil column was placed in an incubator.

(4) The Markov bottle is made the constant water head for infiltration and the water level and the lower edge of the soil column is maintained in a balance.

(5) When the wet front is 2/3 that of the length of the soil column, the water supply is stopped. At the end of the experiment, the soil water content and the concentration of nitrate were determined by taking 5 g of soil in each layer. The soil water content was measured by oven-weighing method. The soil water content was measured by oven at 105°C, and the concentration of nitrate nitrogen was detected by flow analyzer.

Experiments on Different Irrigation Quantity

(1) On the first day after irrigation, soil samples were extracted with a 2 cm diameter, 1 m long soil drill. The soil samples were taken in plastic bags and aluminium boxes, and well marked for use in soil moisture and nitrogen measurements.

(2) Soil extraction was carried out along a same radial section every day. Sampling points are taken at the points where r is 20, 25, 30 and 35cm in the radial direction. For the vertical direction, sampling points are chosen at the points where y is 10, 25 and 30cm. The upper limit depends on the wet range.

(3) The soil moisture content was determined by dry weighing method. The oven temperature is adjusted to 105°C to bake the soil for 6-8 hours, and the soil is then removed and put into the desiccators for weighing after cooling. Finally, $(X-Y)/(Y-Q)$ is used for water content determination. In the equation, X is the container + wet soil weight and Y is the container + dry soil weight; Q is the container weight.

(4) According to the above steps, the water content and NO3-N of the 3rd, 5th and 7th day of irrigation were measured.

RESULTS

Water and nitrogen transport at different temperatures

Water content

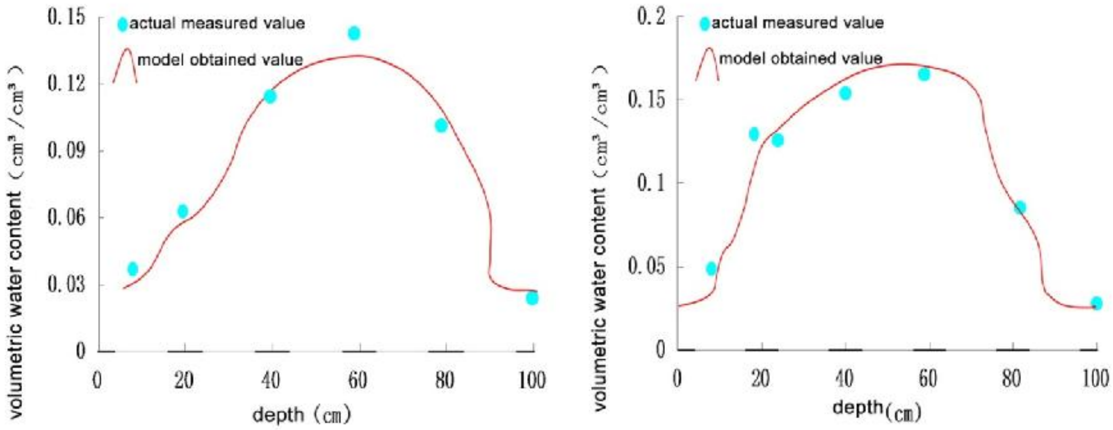

Fig.3 –The measured and model values of soil water content at different temperatures

As shown in figure 2, the left figure is the comparison of the measured value and the model value of soil volumetric moisture content, changing with the vertical depth changes at 35^{o}C system temperature, on the 15th day,when the radius is 45cm.

The right figure is the comparison of the measured value and the model value of soil volumetric moisture content, changing with the vertical depth changes at 25^{o}C system temperature, on the 5th day,when the radius is 25cm.

The left and right graphs show that the values obtained by the model agree well with the actual measured values. At the edge of the moist soil, the model value is slightly larger than the measured value, because the reduction rate of the volume of soil moisture around the wetting front of the moisture is faster than other regions. At the same time there is the possibility of human influence, that is, the operation of mixing with dry soil can lead to the result that the model value is greater than the measured value.

On the whole, the error range between the model value and the measured value is small and the error is within the allowable range. Therefore, the model can effectively verify that the water content determination model with constant volume head water infiltration is correct.

Nitric nitrogen

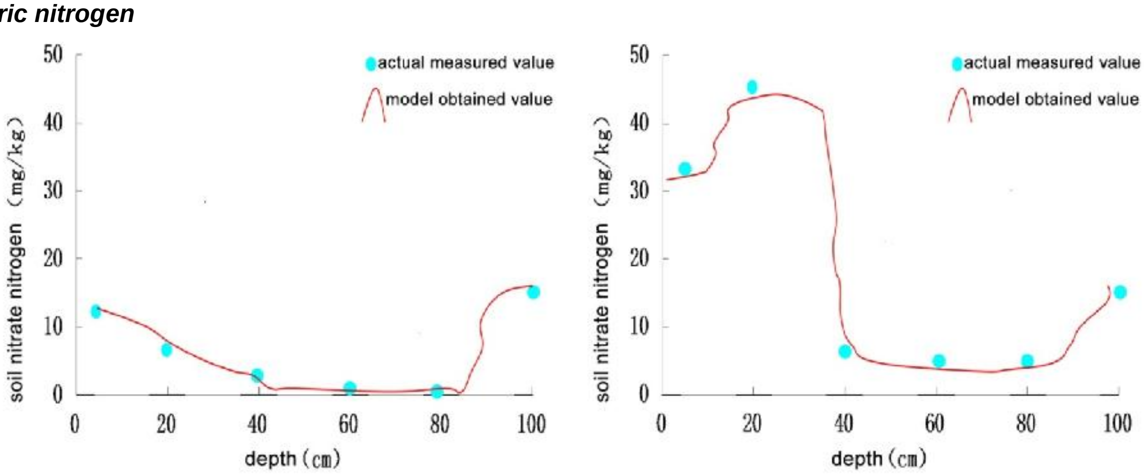

Fig.4 – The measured and model values of soil nitric nitrogen at different temperatures

As shown in figure 3, the left graph shows the comparison chart of the simulated and measured values of vertical nitrate nitrogen distribution at 35^{o}C, on the 5th day, when the radius is 25cm; the right graph shows the comparison chart at 25^{o}C, on the 10th day, when the radius is 45cm.

From the figure, we can see that the content of NO3-N in the more humid edge soil is higher, and in the middle part is smaller, with the model values close to the actual ones.

The average error is small, within the allowable range, so the model can effectively detect the situation of nitrogen in soil.

Water and nitrogen transport of different irrigation
Water content

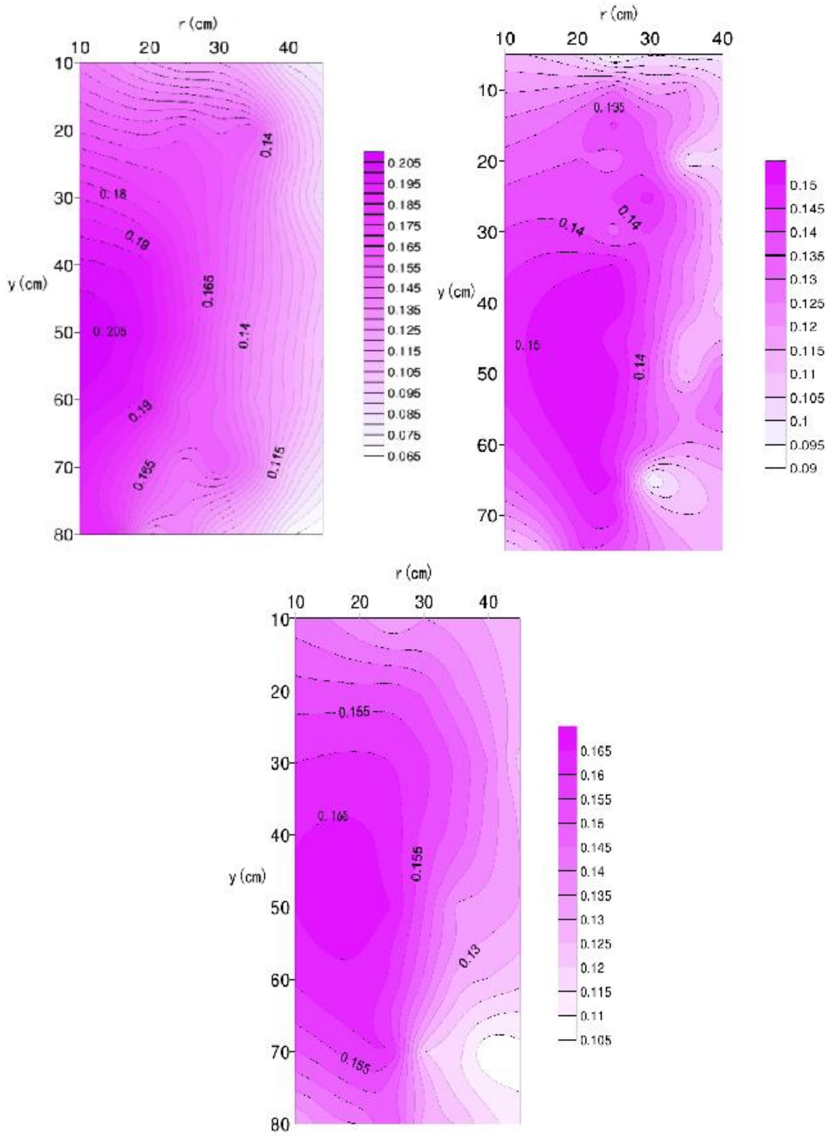

Fig.5– The contour map of soil water content under different irrigation water amount

As shown in Fig. 4, the distribution characteristics of the contours of the three water-cut maps are the same, representing the maps when the irrigation water amount is 6L, 8L and 10L. When the irrigation amount is 6L, the soil surface water content is low. With the increase of depth, water content begins to rise and is about 0.165 at 20cm depth and 0.175 at 30 cm depth and reaches the maximum value at 50cm depth. The depth area of the increase in water content is 40-60cm, which is the same case when the irrigation water amount is 8L and 10L. It shows that in the water storage pit, the deep water content is larger and the water content in the middle and deep layers also increases with the increase in irrigation.

Nitrate nitrogen

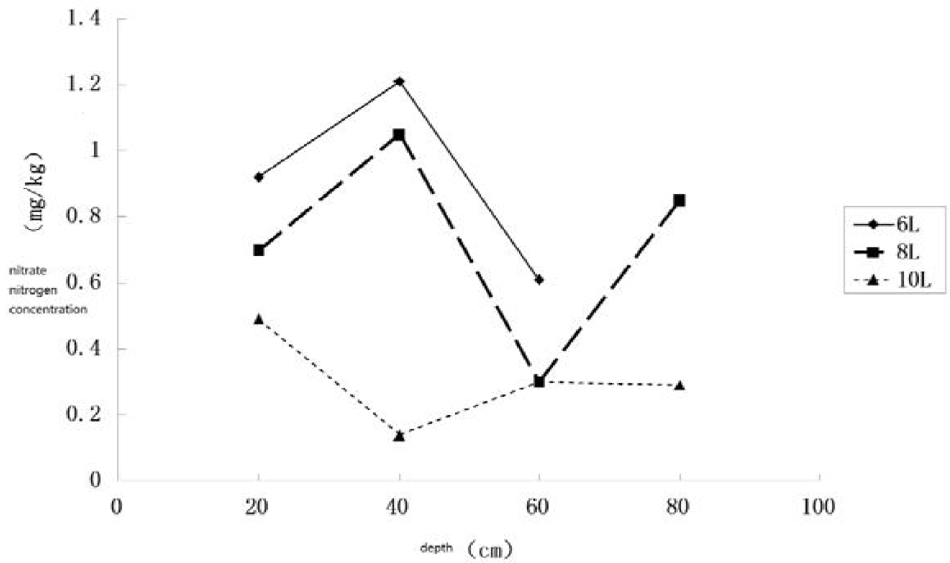

Fig.6 – The nitrate content at different irrigation water amount

As shown in Fig. 5, when the irrigation amount was 8 L, the concentration of nitrate nitrogen increased first and then decreased. The soil NO3 - N concentration increased at the depth of 20-40cm, and reached the maximum at 40cm depth. The concentration of NO3-N decreased in the depth of 40-60cm and gradually increased after 60cm. The middle and deep level irrigation of the puddle has good water retention feature and soil water can be considered as an important carrier of soil nutrient cycling and flow. From figure 5 and figure 6, we can see that the soil water content began to increase at 30-60 cm depth and peaked at about 50 cm. For NO3-N, it dissolves in the soil solution and migrates soil colloid along the soil gap, so the adsorption capacity of soil on it is weak. The nitrate nitrogen in the soil below 40cm depth presents a decreasing trend. With the increase of soil depth, the nitrification was weakened, and the denitrification was gradually enhanced. Denitrification requires denitrifying bacteria, while most of denitrifying bacteria are isoxic bacteria and only a small part of denitrifying bacteria are good bacteria. At the depth of 70-80cm, the nitrate content increased due to the accumulation of NO3-N in the edge of the wetted soil. The other irrigation water had the similar characteristics. It should be pointed out that when the irrigation amount is 10L, the concentration of NO3-N in the soil is obviously smaller than 1, indicating that the nitrate infiltration is more obvious in the lower soil layer.

CONCLUSION

The development of agriculture is inseparable from water, soil and fertilizer. To make the relationship among the three more clear, in this paper, water and nitrogen contents in soil under different temperature and different irrigation water conditions were studied.

The water and nitrogen values of the model were in good agreement with the measured values. With the increase in irrigation volume, the water content in the deep layer also increased. Besides, large irrigation volume led to the more obvious infiltration of nitrate nitrogen in the lower soil layer. The moisture movement model and the nitrogen transport model established in this experiment had certain accuracy and feasibility, and should be popularized and used.

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