Estimating Net Groundwater Depletion in Well Irrigation Areas with Long Short-term Memory Networks

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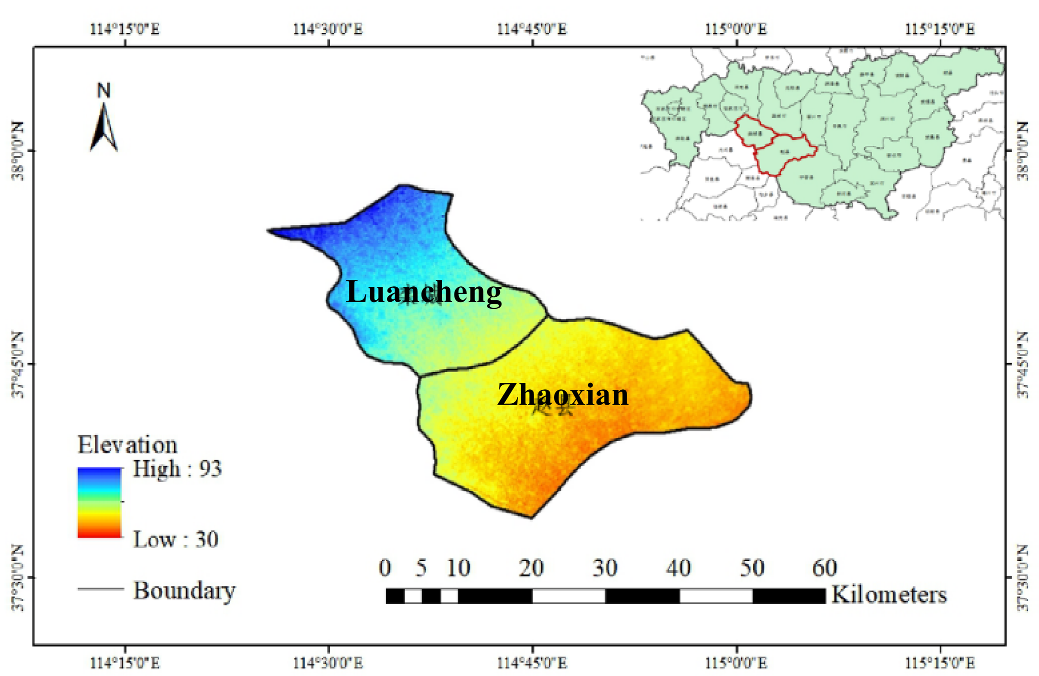
1. Introduction

In China, the agricultural water use accounts for 60% in total water consumption and over 90% in agricultural irrigation. Because of the uneven distribution of water resources in time and space and the lack of surface water resources, most of the northern China heavily relies on groundwater as the main water supply to develop well-channel or well irrigation modes. However, without scientific management and measurement of agricultural water, the overexploitation of groundwater in the past years has resulted in massive impact on the environment, like groundwater depression core and land subsidence. Among many groundwater relative variables, net groundwater depletion means the actual groundwater consumption for human activity, which would not return back to subsurface aquifer. Therefore, estimating the net groundwater depletion is quite significant to develop water-saving agriculture and exploit groundwater resources rationally.

In the field of groundwater depletion research, there are mainly four methods, including surveys and statistics, water balance models, numerical simulation and remote sensing data. Among them, based on the distributed farmland hydrological model and saturated zone water balance equations, net groundwater depletion can be directly calculated. Ge et al. [1] combined Soil-Water-Atmosphere-Plant (SWAP) model with groundwater balance equations to calculate the net groundwater depletion in five typical counties of Hebei Plain. However, the traditional methods are too complex, fortunately the machine learning methods [2] provide a new research insight for constructing scientific and simple calculation methods of net groundwater depletion.

Considering the scale of study areas, data acquisition and method simplicity, this paper intends to build an estimation model of net groundwater depletion with LSTM neural network in the well irrigation area, so as to provide scientific guidance for agricultural irrigation and production.

2. Study area and data

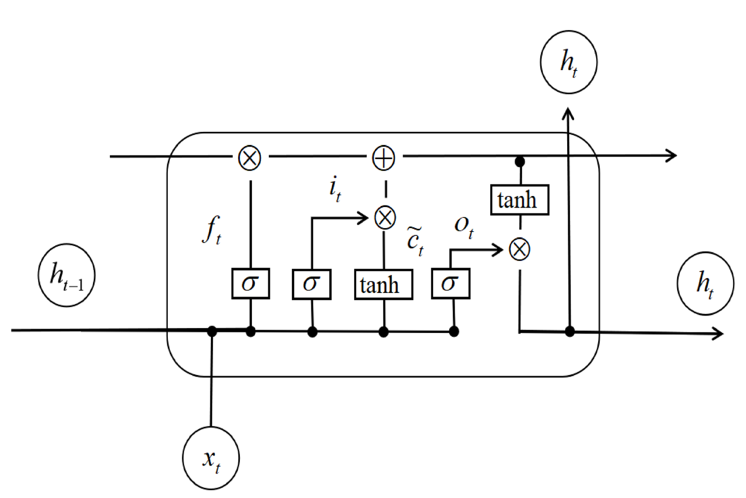


Luancheng and Zhaoxian are two typical counties in Shijin irrigation area, Hebei province. Luancheng covers 354 km^2 and Zhaoxian covers 675 km^2 with flat terrain, whose elevation is around 50-100m. The two counties belong to north temperate zone continental monsoon climate. The annual average temperature is 12.2 ~ 12.6 ℃, and the annual average rainfall decreases from west to east, respectively 504 mm and 460 mm for Luancheng and Zhaoxian. Both counties are **well irrigation areas** and the main crop is wheat in winter and corn in summer.

- Meteorological data: daily precipitation, daily maximum temperature, daily minimum temperature, daily mean relative humidity, daily mean wind speed and daily sunshine duration.
- Flux station data: observed ET, observed soil moisture contents, observed groundwater level.
- Agricultural station data: date of crop sowing and harvest.
- Grid datasets: soil parameter, landuse, DEM and remote sensing ET.
- Statistical data: water resources bulletin.

3. Methods

3.1 LSTM Model



Long short-term memory neural network (LSTM) was proposed by Hochreiter and Schmidhuber, is an adapted version of RNN networks. An LSTM cell contains contains input gate, output gate and forget gate They can control how the information flows in the different layers so as to address problems of exploding or vanishing gradient and later were refined or simplified. Therefore, LSTM network is widely used in the classification, processing and prediction of long time series data.

3.2 Net groundwater use calculation model

The unsaturated-saturated zone water balance model can be used to calculate the net groundwater consumption based on the water exchange between unsaturated zone and saturated zone.

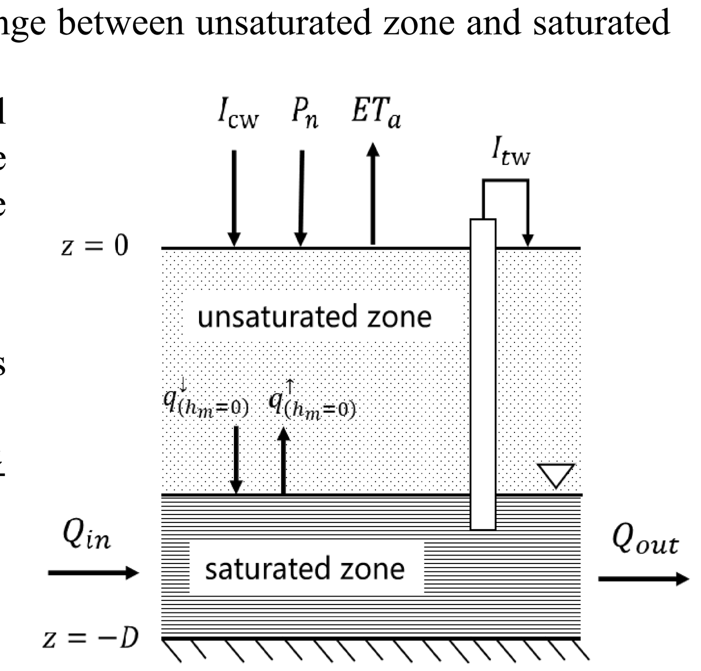
In this paper, the difference between tubewell extractions I_{tw} and net recharge rate q_{nr} to the saturated zone is defined as net groundwater use I_{ngw}, being mathematically expressed as:

$$I_{ngw} = I_{tw} - q_{nr}$$

The water balance equation in unsaturated zone is as follows:

$$P_n + I_{cw} + I_{tw} - ET_a + q^{\downarrow}_{(h_m=0)} - q^{\uparrow}_{(h_m=0)} = \frac{dW_u}{dt}$$

Where, P_n is net precipitation, ET_a is actual evapotranspiration, I_{cw} is canal water irrigation, I_{tw} is tubewell irrigation, $\frac{dW_u}{dt}$ means the soil moisture storage W_u changeover time t, which can be calculated by Van Genuchten-Mualem function.

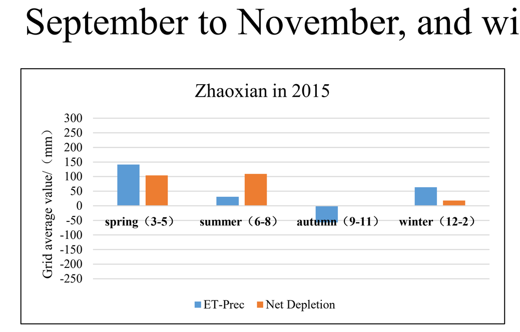


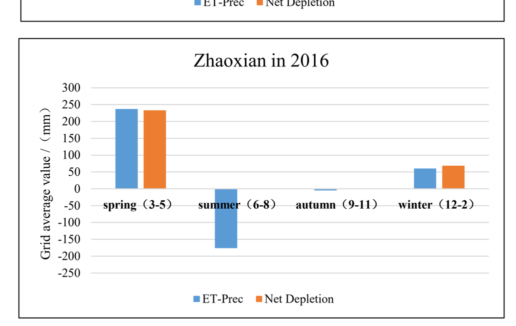
4. Result

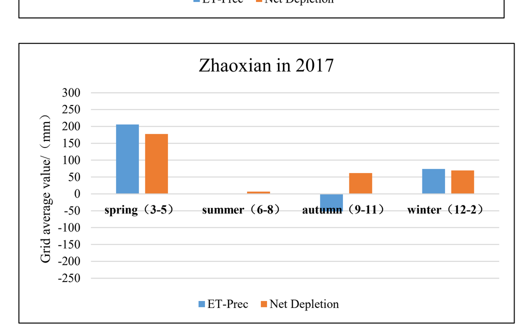
4.1 The variation law of net groundwater depletion

According to the SWAP model with PEST optimization method constructed by Ge et al, the monthly actual irrigation water, evaporation, runoff and bottom leakage in Luancheng and Zhaoxian from 2006-2017 were simulated based on 1 km × 1 km grid in the study areas. Combing with the water resources bulletin, the total amount of everything for irrigation in these two counties both exceeded 70%, so the difference between the net groundwater depletion for agricultural irrigation and the actual total net groundwater extraction amount can be negligible. Given that the actual irrigation water simulated by the SWAP model is the net groundwater depletion for agricultural irrigation, the simulated actual irrigation water was regarded the total net groundwater depletion in this study.

Given that the main crop is wheat in winter and corn in summer, the variation law was analyzed on seasonal scale in each year. In this paper, spring is from March to May, summer is from June to August, autumn is from September to November, and winter is from December to February in the next year.

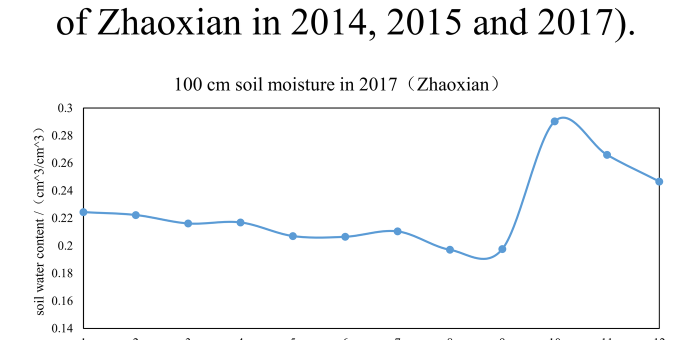






From the histogram of net groundwater depletion in Luancheng and Zhaoxian from 2006 to 2017 on seasonal scale, it can be found that the depletion activity presented the seasonal law. Among them, the groundwater depletion activity mainly took place in spring and winter, and the amount of net groundwater depletion in spring was larger than that in winter. Further analyzing the influences in spring and winter, the groundwater depletion mainly affected by the freshwater budget (the difference between evaporation and rainfall). To some extent, the larger the freshwater budget was, the greater the net groundwater depletion was, which showed the positive correlation.

Besides, it also occasionally appeared in summer and autumn (i.e. the groundwater depletion activity of Luancheng in 2014 and 2015 and that of Zhaoxian in 2014, 2015 and 2017).



In addition to the freshwater budget, it was also found that the soil water content also affected the depletion activity based on the simulation results of SWAP model soil water (100cm).

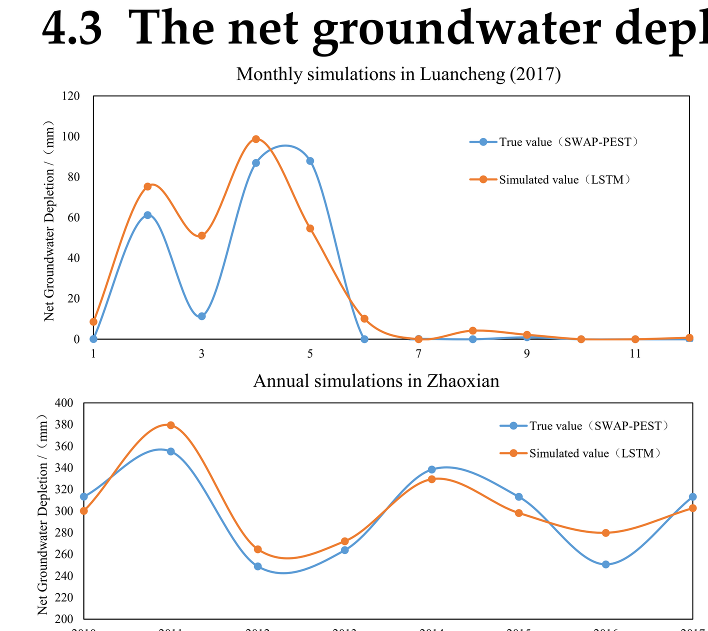
4.2 The cross correlation analysis of net groundwater depletion relevant variables

This paper selects the annual and monthly dataset of Luancheng from 2006 to 2017 as examples to carry out cross correlation analysis between the relevant variables and the net groundwater depletion.

Relative variables	Annual Lag	Monthly Lag
Freshwater budget	0 (+ 0.578)	0(+ 0.396)
Change of groundwater level	-1 (+ 0.596)	-14 (+ 0.261)
Net groundwater use	0 (+ 0.410)	0 (+ 0.317)

There is no significant time difference between the freshwater budget and net groundwater depletion on the annual scale and monthly scale, which is the same with the result of the analysis between net groundwater use and net groundwater depletion. While the variation of the change of groundwater level is one year later than that of net groundwater depletion on the annual scale, and 14 months later than that on the monthly scale.

4.3 The net groundwater depletion estimation model with LSTM networks



The annual and monthly estimation model on groundwater depletion with LSTM networks was established based on the training samples of Luancheng from 2006 to 2016 and verified with the dataset of Zhaoxian.

Based on the annual and monthly estimation models with LSTM networks, the annual and monthly net groundwater depeltion of Zhaoxian also are calculated. The annual estimation accuracy of Zhaoxian is good with NSE = 0.80 and R = 0.90, and the simulation result of the monthly model in Zhaoxian also is generally good (R = 0.91, NSE = 0.82). Besides, the simulated results of the monthly model Luancheng is also satisfying with NSE=0.77 and R=0.89.

In conclusion, the annual and monthly estimation models on groundwater depletion with LSTM networks have good simulation performance and also can be apply in other well irrigation areas with similar groundwater depletion laws.

Annual Scale	Monthly Scale	
Zhaoxian	Luancheng	Zhaoxian
NSE=0.80，R=0.90	NSE=0.77，R=0.89	NSE=0.82，R=0.91

5. Conclusion

In this paper, the net groundwater depletion models is carried out in two well irrigation areas (Luancheng and Zhaoxian). Firstly, calculating the net groundwater depletion in study areas from 2006 to 2017 based on SWAP model with PEST optimization method, then analyzing the spatial and temporal variation rules and influences of the net groundwater depletion, and finally, the annual and monthly estimation models of net groundwater depletion with LSTM networks is constructed and verified. The main conclusions are as follows:

(1) The variation law and influences of net groundwater depletion in well irrigation areas

Groundwater depletion mainly occurs in winter and spring, and the depletion amount in spring is greater than that in winter, which is mainly affected by evaporation and precipitation. There are also some special years when the depletion activity occurred in summer and autumn，which are also affected by the soil water content.

(2) The selection and cross correlation analysis of net groundwater depletion relevant variables

Based on the analysis of net groundwater depletion influences, the freshwater budget, the difference between evaporation and precipitation, is used to reflect the effects of evaporation and precipitation. Besides, the net groundwater use refers to the soil water content and the change of groundwater level directly reflect the influence of depletion activity on groundwater depth. The result of cross-correlation analysis between input variables and net groundwater depletion in Luancheng shows that there is no significant time difference between the freshwater budget, net groundwater use with net groundwater depletion respectively, but the response time between the change of groundwater level and the net groundwater depletion is one year later on the annual scale, and 14 months later on the monthly scale.

(3) The estimation models of net groundwater depletion with LSTM networks

The annual and monthly models were constructed in Luancheng and verified in Luangcheng and Zhaoxian, and the simulated result of SWAP model were regarded as true value. The monthly estimation models performed well both in Luangcheng (NSE-0.77) and Zhaoxian (NSE=0.82). Besides, the performance of annual model was also satisfying in Zhaoxian with NSE of 0.80. The result also indicates that the models are applicable in the well irrigation areas with similar groundwater depletion laws.

Reference

[1] GE Yuqi. Impacts of crop production on groundwater depletion in the Hebei Plain [D]; Tsinghua University, 2017. （in Chinese）

[2] Benjamin D. Bowes,Jeffrey M. Sadler,Mohamed M. Morsy,Madhur Behl,Jonathan L. Goodall. Forecasting Groundwater Table in a Flood Prone Coastal City with Long Short-term Memory and Recurrent Neural Networks[J]. Water,2019,11(5)..

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