Abstract

Based on field experiments of the water irrigation which have been conducted in the LuanCheng Agriculture Experimental Station of Chinese Academy of Sciences, SWAP (Soil-Water-Atmosphere-Plant) model developed by Wageningen Agricultural College was used as an analysis tool. The parameters in the model were calibrated with the data of irrigation experiment. Some kinds of irrigation schedules in different flow years and certain irrigation quotas in this region were developed. The different irrigation quotas based on different irrigation schedules were simulated with SWAP model. The guidance irrigation schedule was put forward as five irrigation times in winter-wheat field and one irrigation time in the summer-corn field in median flow year. The optimal irrigation schedule would be useful for reference of water use of the farmland in this region.

Keywords: SWAP model ; Farmland ; Soil water ; Irrigation model ; Numerical simulation

1. Introduction

The Piedmont of Mountain Taihang is high grain production zone in North China Plain. With society advancement and economy development, water resource scarcity has been one of the key factors retarding the local agriculture development. Therefore, in order to achieve sustainable development, it is
strategically important for strengthening the adjustment and management of farmland moisture content regulation and framing scientific irrigation regime.

At the present time, A great deal of research has been done on regulation of the soil moisture change in field. A good many factors that cause soil water changing and irrigation water quota are analyzed and discussed. Such as soil types, soil texture, crop trials and climatic conditions [1]-[4]. Many mathematical models have been developed for predicting soil water movement processes. The simulation technology appearance has provided a powerful tool and method to understand the soil water transfer rules and assess irrigation water use efficiency.

In this paper, basing on the field experiment works previously, the author has simulated the processes of soil water migration and soil water distribution for different typical hydrologic years by use of “Soil-Water-Atmosphere-Plant” Model in LuanCheng County, Hebei Province which is a representative zone of the Piedmont of Mountain Taihang. It has provided the theory basis for formulating scientific water saving irrigation regime.

2. Study area

This study was conducted at the LuanCheng Agro-Eco Experimental Station of the Chinese Academy of Sciences, which is located at the base of Mt. Taihang (37.53°N, 114.40°E, and 50m above sea level). The average annual precipitation is 482mm with 70% falling in summer (from June to September). In winter wheat growing season (October to May of the next year), the precipitation is about 130mm. The silty loam soil at the experimental site is primitive type and has a deep unsaturated zone, the groundwater is 26-30 meters deep. The agriculture depends on the groundwater irrigation. The winter wheat and summer corn double cropping system is the main cropping pattern in this region.

3. Methods

3.1. Data source

The soil water content data come from observed value by TDR 300 in LuanCheng Agro-Eco Experimental Station from October in 1998 to September in 2000. The meteorological data come from the observations of automatic weather stations (AWS) in LuanCheng County.

3.2. Introduction of SWAP

The Soil–Water–Atmosphere–Plant (SWAP) relationship is a one-dimensional, physical model for water, heat and solute transport in saturated and unsaturated zones [5]. The program is designed for an integrated modeling of the Soil-Atmosphere-Plant System. Transport processes at field scale level and the whole growing season is considered. System boundaries at the top are defined by the soil surface with or without crop and the atmospheric conditions. The lateral boundaries simulate the interaction with surface water systems. The bottom boundary is located in the unsaturated zone or in the upper part of the groundwater and describes the interaction with regional groundwater.

3.2.1 Meteorological data

It has collected that precipitation, air humidity, daily irradiance, maximum temperature, minimum temperature and wind speed by the meteorological station of LuanCheng County from 1998 to 2000,
potential and even actual evapotranspiration estimates are possible with the Penman-Monteith equation [6].

3.2.2 Crop factors

Crop factors depend on the crop type. It is taken to be variable from crop emergence to maturity. Table 1 has listed crop factors for winter wheat and summer corn. Evapotranspiration can be calculated at different stages by P-M equation[7].

Table 1 Crop parameters of winter-wheat and summer-corn

| Stage of Plant Development (Ds) | Winter-wheat | Summer-corn |
|-------------------------------|--------------|-------------|
| Leaf area index | Plant height(cm) | Depth of plant roots(cm) | Leaf area index | Plant height(cm) | Depth of plant roots(cm) |
| 0.50 | 0.91 | 30.0 | 65 | 0.20 | 10.5 | 26 |
| 1.01 | 1.18 | 30.0 | 65 | 2.54 | 80.3 | 48 |
| 1.35 | - | - | - | 4.50 | 200.8 | 60 |
| 1.49 | 1.45 | 30.0 | 65 | - | - | - |
| 1.64 | - | - | - | 4.19 | 210.8 | 64 |
| 1.73 | 4.75 | 63.3 | 70 | - | - | - |
| 1.85 | 5.00 | 70.0 | 93 | - | - | - |
| 2.00 | 4.25 | 90.0 | 105 | 3.00 | 220.0 | 65 |

Note: Ds is 0.00 means seedling, 1.00 means flowering; 2.00 means mature.

3.2.3 Soil hydraulic data

The relationships between the water content and hydraulic conductivity function can be calculated by Van-Genuchten equation [8-9]. Table 2 has listed soil parameter of each distinct soil layer in test zone[10]. Saturated water content and saturated hydraulic conductivity values were applied with Table 2, other parameters were adopted after calibrated with the data.

Table 2 Characteristics of soil in study area. [11]

| Depth(cm) | Texture | Effective porosity (%) | Field capacity(%) | Wilting point(%) | Saturated hydraulic conductivity(m.d⁻¹) |
|-----------|---------|------------------------|------------------|----------------|---------------------------------------|
| 0-25      | Loam    | 49                     | 36               | 9.6            | 1.1                                   |
| 25-40     | Loam    | 46                     | 35               | 11.4           | 0.43                                  |
| 40-60     | Loam    | 46                     | 33               | 13.9           | 0.73                                  |
| 60-85     | Loam    | 46                     | 34               | 13.9           | 0.71                                  |
| 85-120    | Clay loam | 46                  | 34               | 12.9           | 0.02                                  |
| 120-165   | Silt loam | 42                   | 39               | 13.9           | 0.003                                 |
| 165-210   | Clay loam | 44                   | 38               | 16.4           | 0.46                                  |
3.2.4 Irrigation data

In winter wheat growing period and summer corn growing period, the precipitation is 117.65mm and 353.36mm in test zone from 1998 to 2000, respectively. The irrigation requirement of the winter wheat and summer corn double cropping system in a whole duration is about 1000mm precipitation [12]. To meet the needs of water requirement of winter wheat has arranged five times irrigation and 50mm quota each time. In contrast, summer corn has not been irrigated, but rainfall are very unevenly distributed and soil moisture are insufficient at seedling and filling stage. So it has been arranged one times irrigation and 90mm quota each time.

3.3 Model calibration

A model was set up to simulate 6 soil layers, with each layer corresponding to a measured soil-moisture internals. Two of the 6 neutron-probe sites were selected for model calibration; data from the remaining 24 months were used to test the performance of the calibrated model. Model calibration was accomplished primarily by trial-and-error adjustment of $\alpha$ and $\lambda$ to minimize root mean-squared error (RMSE) and optimize graphical fit between model-calculated and measured soil moisture content of 30cm and 100cm soil layer (Figure 1). After calibration, all parameter values of VG equation has listed in Table 3.

Table 3 Soil parameters of VG model after calibrated.

| Depth(cm) | $\theta_{m}(cm^3.cm^{-3})$ | $\theta_{sat}(cm^3.cm^{-3})$ | $K_{sat}(cm.d^{-1})$ | $\alpha(cm^{-1})$ | $\lambda$ | n   |
|-----------|-----------------|-----------------|-----------------|---------------|-------|-----|
| 0-20      | 0.01            | 0.43            | 100.00          | 0.05          | -0.80 | 1.18|
| 20-40     | 0.02            | 0.46            | 43.00           | 0.02          | -2.00 | 1.24|
| 40-80     | 0.02            | 0.47            | 73.00           | 0.03          | -2.50 | 1.16|
| 80-120    | 0.02            | 0.50            | 2.00            | 0.02          | -3.00 | 1.14|
| 120-160   | 0.03            | 0.52            | 0.30            | 0.03          | -3.50 | 1.15|
| 160-200   | 0.01            | 0.49            | 1.60            | 0.02          | -2.00 | 1.08|

Fig. 1 Comparison between measured and model-calculated volumetric soil-moisture content of 30cm (a) soil layer and 100cm (b) soil layer
3.4 Irrigation requirement design

It was insufficient in long-series of precipitation data on experimental station. So the different frequency rainfall conditions has calculated according to precipitation data of experimental station since twenty-seven year from 1974 to 2000 by means of the method of Pearson Type III distribution curve. The result is that the precipitation of high flow year is 575.5mm, precipitation of normal flow year is 452.3mm and precipitation of low flow year is 362.5mm.

Based on the formers’ study results, the control methods of irrigation quota were used in this simulation. We have broken irrigation quota up into three categories. Firstly, high irrigation is actual irrigation regime in local crop growing stage. Secondly, normal irrigation has cut two time irrigations in setting and jointing stage of winter wheat and two time irrigations in jointing and earing stage of summer corn on the basis of high irrigation quota. Lastly, the low irrigation has reduced the most irrigation but the most necessary irrigation with sowing and wintering. Each irrigation quota is by local actual irrigation quantity. It is simulated by SWAP model the treatment combination of three levels of precipitation and three levels of irrigation.

Table 4 The simulate schedule of crop irrigation patterns

| Plant          | Irrigation times | Growth period | Irrigation quota(mm) |
|----------------|------------------|---------------|----------------------|
|                |                  |               | High | Normal | Low  |
| Winter-wheat   | Oct 15           | Sowing        | 40   | 40     | 40   |
|                | Dec 5            | Winter-irrigating | 80  | 80     | 80   |
|                | Mar 25           | Setting       | 50   | -      | -    |
|                | Apr 15           | Jointing      | 70   | -      | -    |
|                | Mar 5            | Earing        | 80   | 80     | -    |
|                | Mar 25           | Grouting      | 50   | 50     | -    |
|                | Jun 15           | Sowing        | 70   | 70     | 70   |
| Summer-corn    | Jul 15           | Jointing      | 30   | -      | -    |
|                | Aug 15           | Earing        | 60   | -      | -    |
|                | Sep 25           | Grouting      | 40   | 40     | -    |

“-” means missing value;

4. Results and analysis

4.1 Dynamic changes of soil moisture on the different treatment

Figure 2 show the process of soil water content changing on 30cm soil layer and 100cm soil layer in low flow year. There is a close relation between soil water content change and irrigation or evaporation. Because the hysteresis has existed in evaporation from soil and it has been as a reservoir of soil water content by itself. The similar result turns up in the variation of the soil water content between 100cm layer and 30cm layer, but the variation scope is smaller than that of the 30cm layer.

The results indicated that mean moisture content in 30cm and 100cm soil layer of summer corn is 0.23 and 0.31, which is 75% and 90% of field capacity under high irrigation quota, respectively. This phenomenon describes that sufficient soil water is adaptable to the growth of corn. Under normal and low
irrigation condition, moisture content in 30cm soil layer of wheat’s wintering stage has been decreasing, the lowest is 0.13 and only 35% of field capacity, which shows it is too much exhaustion of precancerous soil water content because of crop growth in low rainfall. Soil with a serious water deficit must be irrigated twice timely in setting and jointing stage after crop wintering to ensure good crop-growth.

4.2 Crops evapotranspiration under different precipitation patterns

Figure 3 gives the crop cumulative evapotranspiration contrast diagram under different rainfall levels years at medium irrigation treatment. As can be seen from the graph, during the period of winter wheat growth, the year cumulative evapotranspiration have not obvious difference, the total is about 250 mm in different rainfall levels. At the late growth period of summer corn, the crop cumulative evapotranspiration in wet year increases is much more than normal and low flow year, which reveals, the precipitation in normal and low flow year is inadequate and cannot meet the requirement of late period growth of summer corn and crop growth is restricted at a certain degree at later rainy season, but the precipitation in wet year is adequate, which has relieved the contradictions of the water insufficient contradiction at the crop’s later growth period in certain extent.

4.3 Leakage water under precipitation and irrigation patterns

It shows the results of simulation with different patterns in Table 5. There are always the phenomenon of emigration deep leakage water under different patterns. Their amounts were generally 3%-5% of water infiltration. When amount of precipitation and irrigation came up 700mm, soil moisture of 0-2m layer could balance in the growing stage. In winter-wheat growing stage with little rainfall, crop growing needs to use up a large number of water, which had led to the decay of soil moisture. In summer-corn growing stage, soil moisture increased comparing with various irrigation patterns by the rainfall. Rainfall amount with an increase rate of 40% than that of low flow year. It can meet the requirements of crop growing and recharge for groundwater. Therefore it is an effective measure utilizing excessive rainfall and surface runoff to recharge groundwater.

![Fig 2](image-url) Soil-moisture content of 30cm soil layer (a) and 100cm soil layer (b) of different irrigation quotas in low flow year.
Fig. 3 Crop cumulative evapotranspiration in different flow year

| Effective Rainfall (mm) | Irrigation Quantity (mm) | Actual Evaporation (mm) | Actual Transpiration (mm) | Charge of 0-2m soil layer water (mm) | Seepage amount (mm) |
|------------------------|--------------------------|-------------------------|---------------------------|-------------------------------------|---------------------|
| Winter-wheat           | Summer-corn              | Winter-wheat            | Summer-corn               | Winter-wheat                        | Summer-corn         |
| 536.1                  | 570                      | 97.5                    | 84.1                      | 359.4                               | 337.2               | 536.1                  | 570                              | 97.5                              |
| 536.1                  | 360                      | 83.1                    | 81.1                      | 263.7                               | 343.1               | 536.1                  | 360                              | 83.1                              |
| 536.1                  | 190                      | 86.0                    | 76.2                      | 209.4                               | 333.8               | 536.1                  | 190                              | 86.0                              |
| 415.3                  | 570                      | 94.8                    | 86.3                      | 352.3                               | 318.2               | 415.3                  | 570                              | 94.8                              |
| 415.3                  | 360                      | 82.4                    | 84.2                      | 259.1                               | 267.6               | 415.3                  | 360                              | 82.4                              |
| 415.3                  | 190                      | 81.4                    | 82.7                      | 215.8                               | 164.7               | 415.3                  | 190                              | 81.4                              |
| 318.2                  | 570                      | 104.1                   | 97.6                      | 325.6                               | 306.7               | 318.2                  | 570                              | 104.1                             |
| 318.2                  | 360                      | 99.8                    | 96.5                      | 271.9                               | 207.6               | 318.2                  | 360                              | 99.8                              |
| 318.2                  | 190                      | 91.3                    | 91.2                      | 203.2                               | 153.8               | 318.2                  | 190                              | 91.3                              |

5. Conclusion

The numerical simulation model presented in this paper can be a useful tool for describing soil moisture migration under a wide variety of circumstances. The approach involved a scenario analysis with SWAP model is used for three precipitation and irrigation patterns for winter-wheat and summer-corn system. The result shows that the calibrated model represents preferably the field soil water migration. In normal year, it need to be irrigated twice after overwintering for winter-wheat but it can supply the water needed with precipitation for summer corn, It is necessary that take reasonable land and
water management measures to make the rainfall stored in soil and infiltrate to recharge groundwater and improve the utilization efficiency of rainfall resource.

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