STUDY ON FIELD WATER-SALT BALANCE SIMULATION USING SWAP MODEL: A CASE STUDY OF FARMLAND IN THE CENTRAL SHAANXI PLAIN
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基于 SWAP 的田间水盐平衡模拟研究——以关中农田为例

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Abstract: *To study the variation law of key components for water-salt balance of typical farmland in the central Shaanxi Plain, this paper calibrated and verified the SWAP model based on a field trial of summer maize growing season from 2013 to 2014. Variations of different components during different summer maize growth stages were analyzed and discussed according to the calculated results of water-salt balance by the verified SWAP model. Results showed that the calibrated and verified SWAP model could well simulate dynamic variation laws of water-salt content of different soil layers in the study area. Within the study period, transpiration of maize in 2013 and 2014 was restricted by water content in the surface layer. The accumulative actual transpiration accounted for 57.6% and 64.9% of potential transpiration, respectively. Soil water supply from underground water was mainly in the vigorous growth of maize. The accumulative underground water supplies in 2013 and 2014 were 10.3cm and 7.4cm, respectively. Water flux at bottom soil was highly sensitive to rainfall and irrigation, presenting the obvious deep leakage. The soil salinity changes at 0~120cm layer in 2013 and 2014 were -72.87 mg/cm^2 and -81.32mg/cm^2, respectively. Great desalination was observed in the rainy season of maize growth.*

Keywords: *Soil moisture; Salinity; SWAP model; Water balance; Salt balance*

INTRODUCTION

Salinization is a universal soil character in arid and semi-arid regions in China [8]. Soil salinization and soil secondary salinization caused by irrigation are main constraints against local agricultural development and the main influencing factors of local ecological environmental stability [2]. The Lubotan at the junction of Pucheng County and Fuping County lies in the central Shaanxi Plain where it has the richest agriculture in arid and semi-arid regions. The local groove terrain of low-in-middle but high-in-surroundings, diversion irrigation in the Luoxi irrigation area and common flood irrigation implemented in Lubotan have caused drainage silting, groundwater level rise and intensifying salinization of soil, thus influencing local food production and sustainable agricultural development significantly[5]. Through a series of farmland ameliorative measures like perfecting the irrigation and drainage system, no large-scale salinization of soil has occurred and crop output has recovered to the normal level. However, local crop growth is still influenced by different degrees of salt stress.

The SWAP (Soil-Water-Atmosphere-Plant) model developed by Wageningen University (Netherlands) calculates water movement and solute transport in soils by using the one-dimensional Richards equation and the convection-dispersion equation. With consideration to

摘要: *为了研究关中平原典型农田水盐平衡关键组分的变化规律，本文基于 2013～2014 年夏玉米生长季的田间试验，对 SWAP 模型进行了率定和验证，并根据验证后模型的水盐平衡计算结果，对其各分量在夏玉米不同生长阶段的变化过程进行了分析与讨论。研究结果表明：经过率定和验证后的 SWAP 模型较好地模拟了研究区田间土壤各层水盐含量的动态变化规律。模拟期内，2013 与 2014 年季玉米的蒸腾量受到了表层含水量的制约，累积实际蒸腾量占潜在蒸腾量的比值分别为 57.6%和 64.9%；地下水对于土壤水的上升补给主要出现在玉米生长的旺盛阶段，累积地下水上升补给量分别为 10.3cm 和 7.4cm；土壤底部水分通量变化对降雨和灌溉的响应强烈，并表现为明显的深层渗漏。2013 与 2014 年季田间 0～120cm 土壤盐分变化量分别为-72.87 mg/cm^2 和-81.32mg/cm^2，主要在玉米生长的雨季脱盐明显。*

关键词: *土壤水分; 盐分; SWAP 模型; 水量平衡; 盐分平衡*

引言

盐渍化是我国干旱、半干旱地区土壤的一个普遍特征[8]。土壤的盐渍化和灌溉引起的土壤次生盐渍化问题是制约该地区农业发展的主要障碍，也是影响该区生态环境稳定的重要因素[2]。陕西省富平县与蒲城县交界的卤泊滩地区位于干旱、半干旱区农业最富庶的“关中平原”地带，滩区四周高中间低的槽形地势特点，加之洛西灌区引水灌溉及当地常年实施的漫灌方式，造成滩区内排水沟道淤积，地下水位上升，土壤盐碱化逐渐加剧，严重影响了当地的粮食生产及农业的可持续发展[5]。通过一系列健全灌排系统等土地改良措施，滩区内整治后的地块没有再发生大面积的盐渍化，且作物产量接近正常，但当地农作物的生长，仍会受到不同程度上的盐分胁迫影响。

由荷兰 Wageningen 大学研制的 SWAP（Soil-Water-Atmosphere-Plant）模型，利用一维 Richards 方程和对流-弥散方程分别计算土壤的水分运动以及溶质运移过程，同时考虑了水盐等逆境胁迫对于作物生长的影响[7]，使得该

effect of adversity stresses like water and salt on crop growth [7], the SWAP model is more applicable to simulation study on water-salt movement and balance in salinization farmland soils. The SWAP model has been widely used in both China and foreign countries for its perfect physical mechanism. However, few researches on its applicability in the central Shaanxi Plain have been reported yet. Based on field trial data of summer maize in 2013 and 2014, the SWAP model was calibrated. It was confirmed feasible to describe component variation law of water-salt balance in the study area. Dynamic changes of different components of water-salt balance at different summer maize growth stages were analyzed and discussed, aiming to provide theoretical basis for soil secondary salinization control in the agricultural irrigation area in the central Shaanxi Plain.

MATERIAL AND METHOD

Field test

One improved typical salinization farmland in the midwest of Lubotan was chosen as the study area. It belongs to semi-arid continental climate, with extremely uneven precipitation distribution in one year. Most precipitations are received from July to September, accounting for 49% precipitation of the whole year. It is dry in rest time of the year. The groundwater depth is about 2m throughout the year. There're distinct dry and wet seasons. The dry season is longer than the wet season. Particularly, it is windy but has less rainfall in spring, accompanied with great evaporation. The annual sunshine duration is 2349.5~2472.0 h. The 0 ℃ accumulated temperature is 4906.5～5022℃ and the ≥10℃ accumulated temperature is 4276.3～4477.3℃, basically satisfying growth demands of wheat, maize and cotton . Physical and chemical parameters of soil in the study area are listed in Table 1 .

The State Key Laboratory of Ecohydraulic Engineering for Northwest Arid Regions, Xi'an University of Technology established a field observation station in the study area in 2013 in order to observe the water cycle elements and water-salt dynamics of typical farmlands in the Lubotan. Instruments in this station are mainly for conventional meteorological observation, soil water-salt observation and groundwater level observation. The observation items of conventional meteorological elements could be used to calculate evapotranspiration of reference crops. Soil water-salt observation is mainly accomplished by multiparameter sensors (Campbell-CS655) which are buried 2m deep in test pits. There are four small shafts surrounding the test pit, where water level sensors (Campbell-CS450) are buried in to observe groundwater level. Crop rotation of wheat in winter and maize in summer is adopted for farmlands surrounding the soil water-salt observation profile. The summer maize uses "Zhengdan 958" which is generally sowed in early June and harvested in middle October. According to farming habit of local peasants, since there are plentiful precipitation after the elongation stage of summer maize (July~September), two flood irrigation with subsiding water from the Yellow River will be implemented at trefoil stage and elongation stage of maize. To observe dynamic growth of maize in the observation stage, the 101m×105m study area was divided into 25 20m (L)×20m (W) blocks. Plant height, root depth, leaf area index and aboveground biomass were observed manually through regular uniform sampling of each block. The field test design and instrument layout in the observation station are displayed in Fig.1.

模型更可能适用于盐渍化农田土壤水盐运动及其平衡过程的模拟研究。SWAP 模型以其较为完善的物理机制在国内外各地区得到了广泛应用。但在关中平原地区的相关适用性研究还相对较少。本文利用 2013～2014 年两季夏玉米的田间试验观测资料，率定并验证了 SWAP 模型对于描述研究区田间水盐平衡分量变化规律的适用性，并对模型计算的两季夏玉米各生长阶段的水盐平衡各组分动态进行了分析与讨论，旨在为关中农灌区土壤次生盐渍化的防治提供理论基础。

材料与方法

田间观测实验

选取卤泊滩中西部(109°22′E、34°48′N)一处改良过后的典型盐渍化农田作为研究区域。研究区属半干旱大陆性气候，降雨年内分布极不均匀，多集中在 7 到 9 月份，占全年降雨量的 49%，其他季节较为干旱，常年地下水埋深约 2m 左右。干湿季节分明，干季长于湿季。尤其是春季多风少雨，蒸发量大。年日照时数 2349.5~2472.0h，0℃积温 4906.5～5022℃，≥10℃积温 4276.3～4477.3℃，基本上满足小麦、玉米、棉花等作物的生长需求。研究区土壤理化特性指标如表 1 所示。

西安理工大学西北旱区生态水利工程国家重点实验室于 2013 年在研究区建立了田间观测站，目的是为了对卤泊滩地区典型田间的水循环要素及水盐动态进行观测。站内布设的仪器主要用于常规气象观测、土壤水盐观测以及地下水位观测等。常规气象要素的观测项目可以满足参考作物腾发量的计算需要；土壤水盐观测主要由埋深 2m 的测坑当中所布设的多参数传感器（Campbell-CS655）完成；测坑附近打有 4 口小型竖井并分别埋设了水位传感器（Campbell-CS450）用于地下水位的观测。环绕土壤水盐观测剖面的农田，种植模式为冬小麦-夏玉米轮作。其中，夏玉米品种为“郑单 958”，大致在每年 6 月初播种至同年 10 月中旬收获。按照当地农民的耕作习惯，由于每年夏玉米拔节期后（7 月～9 月）的降水充沛，故基本在玉米的三叶期和拔节期前后进行两次淡水灌溉，方式为大水漫灌，所用灌溉淡水为黄河退水。为了对观测期内的玉米生长动态进行观测，将 101m×105m 的研究区域均匀划分为长宽约 20m×20m 的样方，共计 25 个。通过定期在每个样方当中进行的均匀采样来完成作物株高、根深、叶面积指数以及地上部生物量的人工观测。田间观测试验设计和站内仪器的布设概况如图 1 所示。

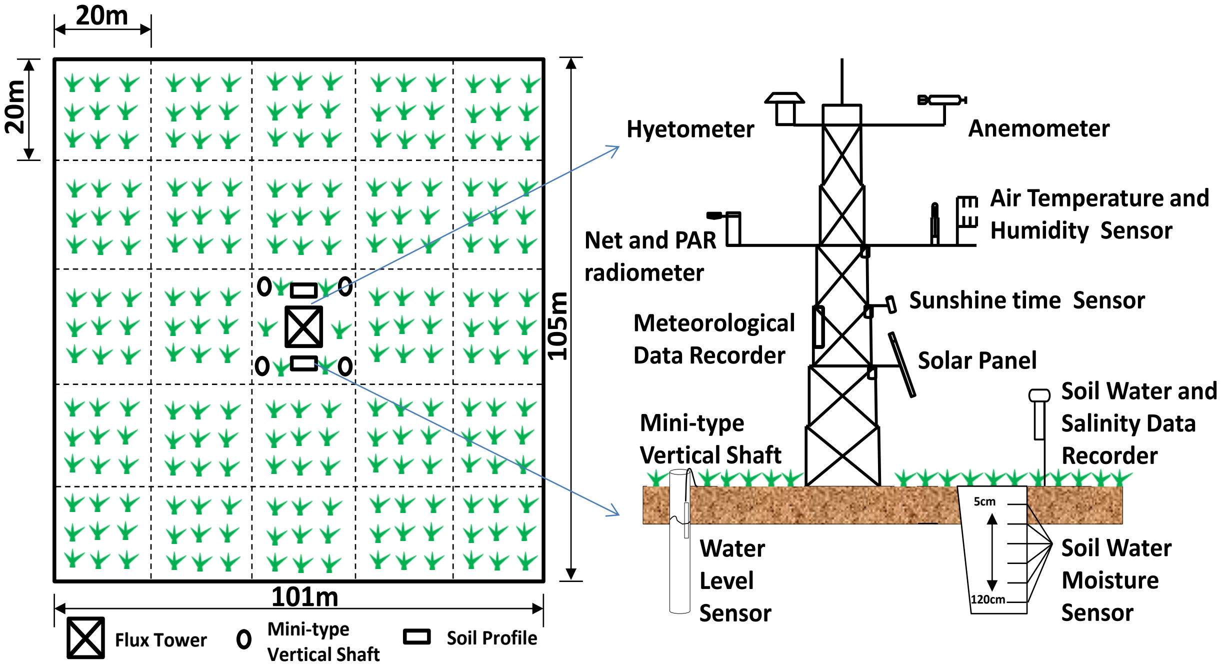

Fig. 1 - Schematic representation of the experimental design and instruments layout

Table 1

Physical and chemical properties in the soil profile of 0–100 cm

Depth (cm)	Soil particle size distribution (%) Sand (>0.05mm)	Silt (0.002-0.05mm)	Clay (<0.002mm)	Bulk density (g/cm^3)	pH (H_2O)	Organic C (%)
0-20	44.1	52.7	3.2	1.48	8.3	1.15
20-40	43.2	54.0	2.8	1.46	8.4	1.03
40-70	44.1	53.4	2.5	1.45	8.6	0.82
70-100	42.5	53.8	3.7	1.45	8.6	0.76

SWAP model

SWAP model is an open-source simulation model applicable for field macro quantitative analysis. It is developed by Wageningen University (Netherlands) on the basis of new research fruits concerning water dynamics and soil water movement of the current SPAC (Soil-Plant-Atmosphere Continuum) system. It is mainly used for simulation analysis on field soil water movement, solute transport and crop growth under different irrigation levels, and also could solve research and practice problems involving agriculture, water resources management and environmental protection . The SWAP model could be divided into three main parts: meteorology part, crop part and soil part. Each part could be further divided into several sub-modules (which are realized by different functions). It simplifies soil heat and water movement as well as solute transport into vertical one-dimensional movement and solves the partial differential equation by finite different method. Soil water movement is described by Richards equation and soil solute transport is described by traditional convection-dispersion equation. It reflects effect of water and salt stress on crop growth through water absorption rate of crop roots under different water potentials.

Considering practical soil texture in the study area and active layer depth of summer maize roots, the simulated soil depth in this paper was 0～120cm, which was divided into three layers: 0～30cm, 30～60cm and 60～120cm. When simulating water and salt contents in

模型介绍

SWAP 模型是荷兰 Wageningen 大学在充分吸取了当前 SPAC（Soil-Plant-Atmosphere Continuum） 系统水分动态以及非饱和土壤水分运动最新研究成果的基础上，研制开发的适用于田间宏观量化分析的开源模拟模型，主要用于田间尺度不同灌溉水平下的土壤水分运动、溶质运移及作物生长等过程的模拟分析，并能够解决农业、水资源管理和环境保护等几个领域的研究与实践问题 。模型分为 3 个主要部分，即气象部分、作物部分、土壤部分，每个部分又分为若干个子模块（由各个函数实现）。模型将土壤水热运动和溶质运移简化为垂向一维运动，并采用有限差分法求解偏微分方程。土壤水分运动利用 Richards 方程描述，土壤溶质运移过程采用传统的对流-弥散方程描述。模型通过分析作物根系吸水速率在不同水势下的削减情况来体现水盐胁迫对于作物生长的影响。

根据研究区土壤质地的实际情况以及夏玉米根系活动层深度，本文选择模拟的土层深度为 0～120cm，并将土柱划分为 0～30cm、30～60cm、60～120cm 三个层次。模拟土壤剖面各层次的水盐含量时，要求将每个土层再细分

different layers of the soil profile, each soil layer shall be further divided into several units. In this simulation, the soil depth 0～120cm was divided into 32 units. To simulate water dynamics in the upper soil layers precisely, units close to the earth surface were set at 0.5~1cm thick and those of the lower layer were set at 5~10cm thick. The upper boundary inputs of the model were parameters that determine water flux in surface soil layer, such as irrigation, rainfall and surface evaporation. Due to the shallow water table in the study area, variation of groundwater level with time was taken as the lower boundary condition of the model. Initial condition setting includes initial salinity of soil layer and pressure head which could be gained from observation data of instruments in the station.

为若干单元。本次模拟将 0～120cm 土柱共划分为 32 个单元。为了能精确模拟土柱上层的水分动态，将接近土表的单元格设定为 0.5～1 cm 厚度，下层设为 5～10 cm 厚度。模型上边界条件输入为灌溉、降雨以及土面蒸发等决定土壤表层水分通量状况的有关参数。考虑到研究区地下水位常年为浅埋深状态，故以地下水位随时间的变化过程作为模型的下边界条件。初始条件设定包括各土层初始时刻的含盐量及压力水头等，均可从站内仪器的观测资料当中获得。

RESULTS AND DISCUSSIONS

Model calibration and verification

Measured data of meteorology and soil water and salt content from 2013 to 2014 in the observation station were collected for model parameter calibration and verification. Field observation data in 2013 were used to calibrate model parameters and those in 2014 were used to verify the model. In this paper, international universal root-mean-square error (RMSE) and mean relative error (MRE) were used as the evaluation indexes of model simulation effect.

结果与分析

模型率定与验证

收集并整理观测站 2013～2014 年的气象和土壤水盐含量等实测数据作为模型参数率定与验证的数据资料。其中，2013 年的田间观测数据用来率定模型参数，2014 年的数据用于模型验证。本文采用国际上较为通用的均方根误差（RMSE）和平均相对误差（MRE）作为模型模拟效果的评价指标。

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(P_i - O_i\right)^2} \tag{1}$$

$$\mathrm{MRE} = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{P_i - O_i}{O_i}\right| \times 100\% \tag{2}$$

Where N is number of measured data, O_i is the i^{th} measured data and P_i is the corresponding simulated value.

To simulate soil water content, hydraulic characteristic parameters of soil layers have to be determined. Soil samples of different layers were collected from the test pit profile in the study area, which were then carried back to the laboratory to get the soil water characteristic curve through “tensiometer weighing method”. Later, related test data were fitted using the RETC (retention curve program for unsaturated soils) software developed by USSL (US Salinity Laboratory) [4], thus getting the initial values of hydraulic characteristic parameters of soils. With reference to measured soil water of summer maize during the calibration period (2013), meteorological and irrigation system of the study area as well as initial values of soil hydraulic characteristic parameters gained from laboratory test were input into the SWAP model together until getting the optimum fitting result between the simulated results and measured results. In this way, calibration results of VG (Van Genuchten) model parameters of soil layers in the study area were gained (Table 2).

Limited by test conditions, this paper has not set parameters of solute adsorption and decomposition rate in the soil solute transport module of the model when simulating soil salinity. Dispersity and molecular diffusion coefficient are the main calibrating parameters in soil salinity simulation. The multi-parameter sensor CS655 in

上式中的 N 为实测值的个数，O_i表示第 i 个实测值，P_i表示对应的模拟值。

对于土壤含水量的模拟，需要确定土柱各层次的土壤水力特性参数。具体是通过在研究区测坑剖面各层采集土样并带回室内进行“张力计称重法”得到其对应的土壤水分特征曲线后，利用 USSL（美国盐改中心）开发的 RETC（retention curve program for unsaturated soils）软件对相关试验数据进行拟合[4]，从而得到土壤水力特性参数的初值。参考 2013 年率定期夏玉米整季的土壤含水量实测资料，并将研究区气象、灌溉制度以及室内试验得到的土壤水力特性参数初值一并输入 SWAP，以模拟值与实测值拟合度达到最优为止，从而得到了研究区土壤各层 VG（Van Genuchten）模型参数的率定结果，如表 2 所示。

针对土壤含盐量的模拟，鉴于试验条件的限制，本文省略了模型土壤溶质运移模块里的溶质吸附及其分解速率等细节问题的参数设定。因此，进行含盐量模拟时率定的参数主要是弥散度和分子扩散系数。站内的多参数传感器

the station couldn't output soil salinity directly. Laboratory "conductometry" is needed to further determine the transformational relation between soil bulk electrical conductivity (EC_b, dS/m) measured by the multi-parameter sensor in the station and the salinity (S, g/kg). The goal is to get the optimum fitting between measured salinity and simulated result. The calibration results of dispersity and molecular diffusion coefficient are 13cm and 0.4cm^2/d, respectively.

Maize growth dynamics in the study area within the observation period were simulated by the simple crop module in the SWAP model. Based on regular manual observation of maize growth in the study area, plant height, leaf area index and root depth of different stages that have to be input in the module, could be determined. Additionally, initial values of parameters difficult to be measured, such as extinction coefficient of canopy, critical pressure head that causes water stress and critical soil conductivity that causes salt stress, are all determined through literature review [1,9]. Calibration results of main input parameters of this module are shown in Table 3.

CS655 并不能直接输出土壤的含盐量结果，需要借助室内“电导法”试验来进一步确定站内多参数传感器测量的土壤电导率值 EC_b（bulk electrical conductivity , dS/m）与全盐量 S（salinity，g/kg）之间的转换关系。以含盐量实测值与模型模拟值的吻合度达到最优为目的，弥散度和分子扩散系数的率定结果分别为 13cm 和 0.4cm^2/d。

对于观测期内研究区玉米生长动态的模拟，本文采用了 SWAP 模型当中的简单作物模块。基于对研究区玉米生长定期的人工观测，能够确定该模块所需要输入的各阶段株高、叶面积指数以及根系深度三方面的生长动态。另外，冠层消光系数、引起水分胁迫的临界压力水头值和引起盐分胁迫的土壤临界电导率值等不易测量的参数，均是通过查阅相关文献来确定其初始值[1,9]。经过反复调参，该模块的主要输入参数率定值如表 3 所示。

Table 2

VG model parameters calibrated values of soil moisture characteristic curve

Soil Depth (cm)	Saturated water content θ_s (cm^3/cm^3)	Residual water content θ_r (cm^3/cm^3)	Saturated hydraulic conductivity Ks (cm/d)	Shape factor		
				α	n	λ
0～30	0.37	0.0885	11.4	0.017	1.26	0.5
30～60	0.41	0.0936	10.7	0.011	1.48	0.5
60～120	0.40	0.1031	10.2	0.010	1.66	0.5

Table 3

Calibrated values of primary crop biological parameters in simple crop growth module

Parameters	Selected values (summer maize)
Extinction coefficient for diffuse visible light (-)	0.53
Extinction coefficient for direct visible light (-)	0.75
Press head (cm) below which roots: h1, h2, $h3_{high}$, $h3_{low}$, h4 $^{\#}$	-15, -30, -325, -600, -15000
ECsat level below which no salt stress (dS/m)	1.5
Decline root water uptake above this level (%/dS/m)	8.5
Minimum canopy resistance (s/m)	70.0
Precipitation interception coefficient (-)	0.25

Note: #. Parameters of water stress response function adjusted as per value suggested by Veenhof and McBride (1994).

Analysis on simulation results of soil water and salt contents

Calibrated parameters for simulating soil water content (SWC) were input into the SWAP model to simulate SWC of summer maize in 2013 and 2014. Results are shown in Fig.2. Meanwhile, a statistical test on the fitting degree between measured and simulated SWC was made (Table 3). Overall, RMSE of soil layers during the calibration period and verification period was smaller than 0.03cm^3/cm^3, and MRE was lower than 10%, indicating that calibrated and verified SWAP model could well simulate SWC dynamics in the study area. However, water content in the surface layer (0～30cm) fluctuates more violently than that in deeper layers (>30cm). Moreover, the simulation precision of surface soil volumetric moisture content is lower than that of deep

土壤水盐含量模拟结果分析

将用于土壤含水量模拟的相关参数率定值输入到模型当中，并分别对 2013 与 2014 年两季夏玉米田间土壤各层的含水量（SWC）状况进行了模拟，结果如图 2 所示。同时，对土壤含水量各层实测与模拟结果的吻合程度进行了统计检验，如表 3 所示。总体来看，率定期与验证期各层的 RMSE 值不超过 0.03cm^3/cm^3，且各层的 MRE 值均低于 10%，说明经过率定和验证后的 SWAP 模型能够较好地模拟研究区土壤剖面各层的水分动态。然而，表层 0～30cm 含水量的波动要明显高于埋深 30cm 以下土层，且表层土壤体积含水量的模拟精度要低于深层的模拟精度，

soil layer. This is mainly because organic content, macro pores and other soil properties often have high spatial temporal variability in upper layer, thus making surface SWC dynamics more complicated than deeper layers [3]. When simulating SWC dynamics under crop influence by uploading crop files, some parameters, especially those related with water absorption of roots, were set as theoretical values provided by associated references. This will bring great error in describing transpiration of crop root zone in the study area.

Soil salt content (SSC) of summer maize in 2013 and 2014 were simulated based on calibrated relative parameters. Results are shown in Fig.2. A statistical test on measured and simulated SSC was made (Table 3). RMSE during the calibration period and verification period was smaller than 1.5mg/cm^3, and MRE was lower than 15%, indicating that the calibrated and verified SWAP model could reflect general variation law of SSC in the study area within the observation period. However, the statistical test reported that the SSC simulation of the SWAP model is poorer than the SWC simulation. It has great simulation errors to surface soil layer (0~30cm). This is mainly because when adjusting parameters of the solute transport module, no targeted laboratory soil column test was conducted except for neglecting solute adsorption and decomposition rate. Therefore, the limited parameter calibration results are inadequate to describe dynamic changes of SSC in the crop root zone in the study area. Meanwhile, SSC in surface layer (0～30cm) changes more violently than that in deeper layers (>30cm) and surface SSC simulation precision is lower than the deeper layer. This is similar with SWC simulation results, indicating that SWC simulation influences SSC simulation precision significantly.

这主要是由于有机质含量、大孔隙和其它土壤属性通常在上层具有较高的时空变异性，使得表层土壤水分的动态比深层土壤复杂得多[3]；而且通过加载作物文件来模拟作物影响下的土壤水分动态时，个别参数的设置主要来源于相关文献提供的理论值，尤其是与根系吸水有关的参数设置，这在一定程度上会对研究区作物根系层蒸腾耗水过程的描述带来较大偏差。

基于率定后的相关参数分别对 2013 与 2014 年两季夏玉米田间土壤各层含盐量（SSC）状况进行了模拟，结果如图 2 所示。对各层含盐量的实测和模拟值进行了统计校验，见表 3。率定期和验证期的 RMSE 值不超过 1.5mg/cm^3，且各层的 MRE 值均低于 15%，说明经过率定和验证后的 SWAP 模型较好地反映了观测期内研究区土壤剖面各层含盐量的大致变化趋势。但从统计校验结果来看，模型对于土壤含盐量的模拟效果并没有土壤含水量的模拟效果好，尤其是表层 0～30cm 含盐量的模拟偏差较大。这主要是因为在对溶质运移模块进行调参的过程当中，除了未考虑溶质吸附及其分解速率等细节问题以外，未开展针对性较强的室内土柱试验，使得有限的参数率定值不足以描述研究区作物根系层土壤盐分的动态变化。同时，表层 0～30cm 含盐量变化较 30cm 以下土层剧烈，且表层含盐量的模拟精度要低于深层，这与含水量的模拟结果类似，说明对于土壤含水量的模拟在很大程度上影响了土壤含盐量的模拟精度。

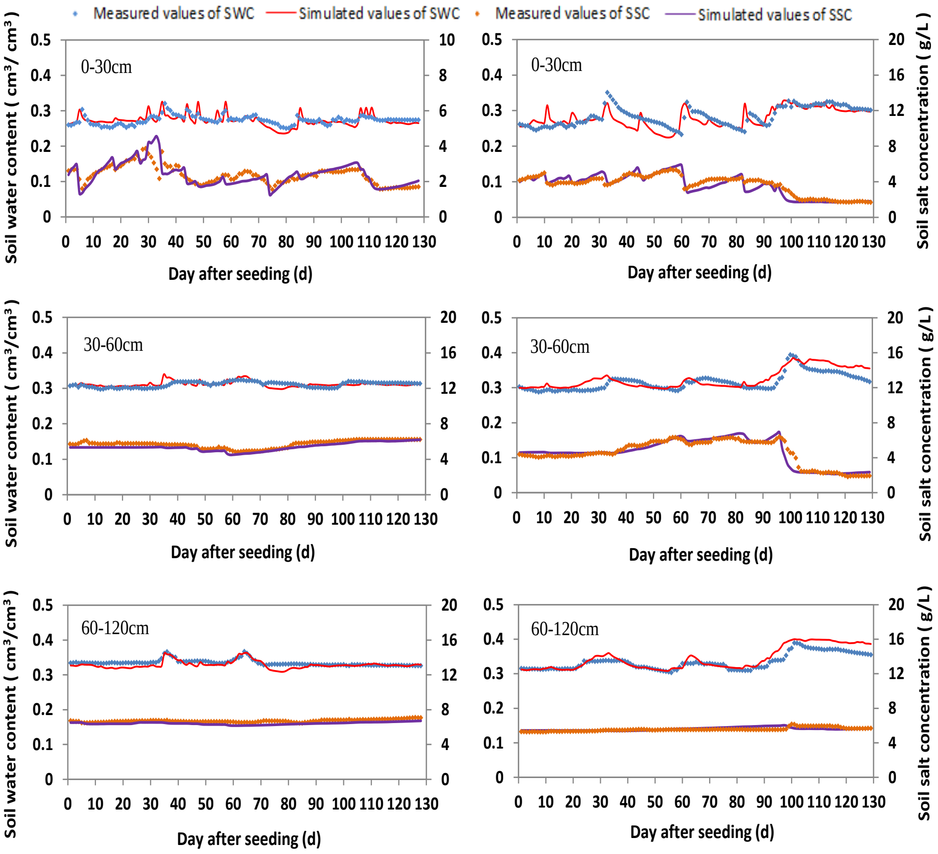

Fig.2- Simulated versus measured water and salt content of the soil solution in different soil layers during model calibration (left) and verification (right)

Table 4

Goodness-of-fit test indicators relative to SWAP model calibration and verification

Growing season	Soil depth（cm）	Soil water content（cm^3/cm^3）		Soil salt content（mg/cm^3）	
		RMSE（cm^3/cm^3）	MRE（%）	RMSE（mg/cm^3）	MRE（%）
Calibration (2013)	0-30	0.014	4.2	1.392	13.8
	30-60	0.008	2.2	0.827	8.2
	60-120	0.009	2.0	0.490	4.1
Verification (2014)	0-30	0.022	5.9	1.268	11.1
	30-60	0.018	3.8	0.922	9.3
	60-120	0.016	3.4	0.424	3.2

Analysis on calculated results of water-salt balance

The calibrated and verified SWAP model maintains high simulation precision of SWC, implying that this model could simulate soil water movement and solute transport in the study area and the simulated results of field water-salt balance components are reliable.

Calculated results of water balance

Daily results of precipitation, irrigation (IRR) and groundwater level (GWL) during the summer maize growth period from 2013~2014 as well as main water balance components output by the model are exhibited in Fig.3. Main water balance components include crop transpiration, surface evaporation, bottom water flux (QBOT) and water storage changes in 0～120cm soil layers (DSTOR). No independent observation data of surface evaporation and crop transpiration were available in the station. However, it can be seen from Fig.3 that simulated results of the SWAP model basically conform to different forms of evapotranspiration change features of maize in different growth stages and under different surface coverage. In the study area, field evapotranspiration during seedling stage of summer maize (about 30d from emergence stage to seven leaves stage) is dominated by surface evaporation because of the slow growth of aboveground parts and low field coverage. The summer maize achieves the most vigorous growth of nutritive organs like leaves and stems during the heading stage (about 50d from the elongation stage to tasseling stage). During this stage, leaf area index and crop transpiration increase significantly compared to the early period, but surface evaporation reduces because of the high canopy density. Reproductive growth takes the dominant role during the anthesis maturity period (about 45d from milk-ripe stage to maturity stage), while vegetative growth stops basically. With the gradually aging of nutritive organs, crop transpiration declines. In the model output results, the accumulative actual transpiration in 2013 and 2014 accounted for 57.6% and 64.9% of potential transpiration, respectively. This symbolizes crop transpiration in the simulation period is influenced by surface soil water content to a certain extent.

Viewed from dynamic changes of water flux on the soil water-groundwater interface during maize growth period in 2013 and 2014, groundwater level in the study area was mainly influenced by precipitation and irrigation. The simulated soil water storage changes are consistent with observed groundwater level changes. The bottom flux changes were less influenced by crop factors, and made strong responses to only rainfall and irrigation. The accumulative soil water supplies from groundwater in 2013 and 2014 were 10.3cm and 7.4cm, respectively.

水盐平衡计算结果分析

经过率定和验证后的 SWAP 模型对土壤水盐含量的模拟保证了较高的精度，说明该模型能够进行研究区土壤水分运动及溶质运移的模拟，且模拟得到的田间水盐平衡分量的计算结果是可靠的。

水量平衡计算结果分析

图 3 所示为 2013～2014 年两季夏玉米生长期内降雨、灌溉（IRR）、观测地下水位（GWL）以及模型输出的田间水量平衡主要分量的逐日计算结果，包括作物蒸腾量、土面蒸发量、底部水分通量（QBOT）和 0～120cm 土壤储水变化量（DSTOR）。试验站缺乏对土面蒸发和作物蒸腾的分别观测，但由图 3 可以看出，模型对于两个分量的模拟，基本符合玉米在各生育期内不同形态及地表覆被情境下的蒸散变化特征。其中，研究区夏玉米由于苗期（出苗期至七叶期，约 30 天左右）地上部茎叶生长缓慢，农田覆被率较低，因而田间蒸散发以土面蒸发为主。穗期阶段（拔节期至抽穗期，约 50 天左右），玉米叶片及茎节等营养器官的生长是整个生育期内最为旺盛的阶段，所以叶面积指数及作物蒸腾量相比初期显著增加，但此时较高的冠层郁闭度使得土面蒸发呈现低值。夏玉米到了花粒期（乳熟期至成熟期，约 45 天左右），生殖生长占据主导，而营养生长已基本停止，伴随着营养器官的逐渐老化，作物蒸腾量亦呈现衰减趋势。模型输出的计算结果当中，2013～2014 年两季玉米生育期内累积实际蒸腾量占潜在蒸腾量的比值分别为 57.6%和 64.9%，说明模拟期内的作物蒸腾量在一定程度上受到了表层土壤含水量的影响。

从两季玉米各生育期土壤水-地下水界面水分通量的动态变化来看，研究区地下水位主要受降雨和灌溉的影响，且模拟得到的土壤储水变化量与观测地下水位的波动较为一致。两季的底部通量变化受作物因素影响较小，仅在降雨和灌溉时响应强烈。2013 年与 2014 年两季玉米田间的地

The water storage in 0~120cm layers reduced by 5.52cm in 2013 and increased by 1.58cm in 2014. Specifically, the negative soil water supply from groundwater mainly occurred after the elongation stage when maize grows vigorously. With the growth of leaves, field evapotranspiration intensified gradually, so that soil water in saturated zone flows to the unsaturated zone through capillary action, thus resulting in the positive bottom flux and upward supply. Increase of soil water storage and deep leakage of soil water mainly occurred after irrigation and heavy rainfall. For example, twice irrigation at the 30th day and 58th day after summer maize sowing in 2013 as well as the twice irrigation at the 28th day and 59th day after summer maize sowing in 2014 accumulated 6.7cm and 7.2cm deep leakage, respectively. The highest accumulative deep leakage was in the lasting heavy rainfall at late maize growth period in 2014, reaching 4.86cm. Deep leakage of soil water is a kind of waste of farmland water resources. In particular, plentiful deep leakage after irrigation lowers utilization of irrigation water. It is strongly suggested to adopt corresponding measures to relieve deep leakage of irrigation water [6].

下水累积入渗补给量分别为 10.3cm 和 7.4cm，0～120cm 土壤储水变化量分别为-5.52cm 和 1.58cm。具体来看，地下水给予土壤水方向向上的负补给主要出现在拔节期以后，该阶段玉米生长发育旺盛，随着叶片的增大增多，田间蒸散日趋强烈，使得饱和带土壤水经由毛细作用补给至非饱和带，底部通量为正值，方向向上。土壤储水量的增大及土壤水的深层渗漏主要发生在灌溉和强降雨过后。例如，2013 年夏玉米播种后第 30 天和第 58 天的两次灌溉，2014 年夏玉米播种后第 28 天和第 58 天的两次灌溉，分别累计产生了 6.9cm、7.2cm 的深层渗漏量；2014 年夏玉米生长后期发生的长历时强降雨期间产生的累计深层渗漏量最高达 4.86cm。土壤水的深层入渗属于农田水资源的无效损耗，尤其是灌溉后的大量深层入渗降低了灌溉水的利用效率，应采取相应的措施用以缓解灌水所造成的深层入渗[6]。

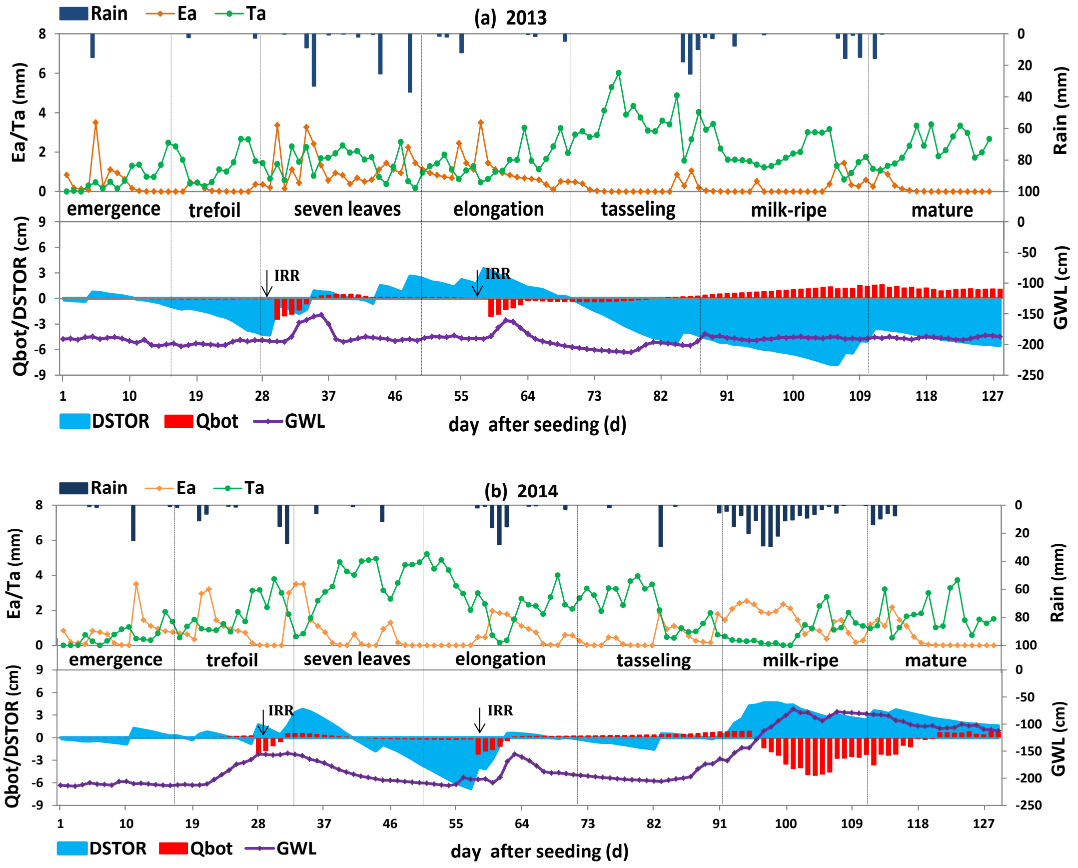

Fig.3- Actual evaporation (Ea), actual transpiration (Ta), vertical bottom flux (Qbot) and change water storage (DSTOR) at 120 cm soil profile versus rainfall (Rain), irrigation (IRR) and groundwater level (GWL) changes during summer maize's growth seasons of 2013 (a) and 2014 (b).

Calculated results of salt balance

Fig.4 shows simulated results of salt balance components at different maize growth stages from 2013~2014, including solute flux at soil surface (SQTOP), solute flux at soil bottom (SQBOT) and solute storage of 0~120cm soil layers (SAMPRO). In Fig.4, SAMPRO at maize harvest in 2013 and 2014 decreased by 72.87 mg/cm^2 and 81.32mg/ cm^2 compared to that at early

盐分平衡计算结果分析

图 4 所示为 2013～2014 两季夏玉米各生长阶段田间盐分平衡组分的模拟结果，包括土壤表层盐分通量（SQTOP）、底部盐分通量（SQBOT）和 0～120cm 土壤盐分储量（SAMPRO）。由图 4 可以看出，两季玉米收获时的土壤盐分储量相比初期均有不同程度上的削减，表

period, indicating the desalinization of 0~120cm soil layers after maize plant. The most distinct desalinization was in the mid and late growth periods of summer maize. SQBOT presented evident downward leaching states at the same periods. Due to the lasting heavy rainfall during the milk-ripe stage of maize in 2014, both salt reduction and downward SQBOT reached the maximum of the simulation period. This is mainly caused by the frequent heavy rainfalls in the study area if neglecting lateral drainage. However, this paper set few parameters for the solute transport module and neglected salt storage in macro pores and absorbed salt by root system . Therefore, the simulated salt balance result is still one-sided and needs further deep researches.

明每经过一季玉米种植后，0～120cm 土壤将处于脱盐状态。2013 与 2014 年季的盐分储量分别减少了 72.87 mg/cm^2 和 81.32mg/ cm^2，主要是在夏玉米生长的中后期脱盐明显，而且两季的底部盐分通量变化，亦在该时段表现为明显的向下淋洗状态，尤其是发生在 2014 年玉米乳熟期的长历时强降雨事件，使得盐分削减量与向下的底部盐分通量均达到了模拟期内的最大值。究其原因主要是该生长时段正值当地的雨季，本研究在不考虑侧向排水的情况下，该阶段频繁发生的强降雨事件是导致研究区土壤盐分向下淋洗的主要因素。然而，本文针对溶质运移模块所设定的参数较少，未考虑到大孔隙盐分储量和根系吸盐量等盐分平衡输出项，因此模型计算得到的盐分平衡结果仍较为片面，有待后续对此进行深入研究。

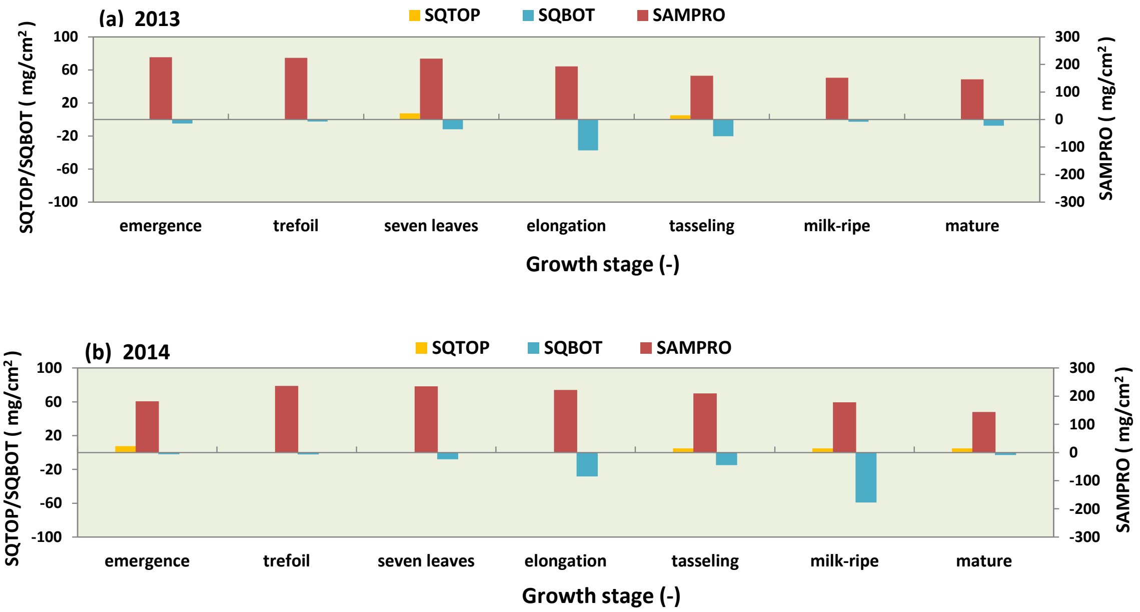

Fig.4- Solute flux at soil surface (SQTOP), solute flux at soil bottom (SQBOT) and solute amount at 120cm soil profile (SAMPRO) in different summer maize's growth stages during seasons of 2013 (up) and 2014 (down)

CONCLUSIONS

Field applicability of SWAP model is tested by the observation data during summer maize growth period from 2013~2014 in typical farmland in the irrigation area of the central Shaanxi Plain. Meanwhile, water-salt balance results simulated by the verified SWAP model are analyzed and discussed. It concludes that:

(1) During model calibration and verification, simulated soil water and salt contents reflect the general variation trend of measured values. During the calibration (2013) and verification (2014), RMSE of SWC is smaller than 0.03cm3/cm3 and MRE is lower than 10%. RMSE of SSC is smaller than 1.5mg/cm3 and MRE is lower than 15%. This means that the calibrated and verified SWAP model is applicable for simulation study on water-salt dynamic changes of the soil profile in the study area. The simulated water-salt balance components are reliable.

(2) According to SWAP results on field water balance components during summer maize growth periods in 2013 and 2014, the accumulative actual transpiration accounts for 57.6% and 64.9% of potential transpiration, indicating that crop transpiration is restricted by surface soil water content. DSTOR reduced by 5.52cm in 2013 and increased by 1.58cm in 2014. Soil water supply from groundwater mainly is mainly achieved in vigorous

结论

本文利用关中灌区典型农田 2013～2014 年夏玉米生长季的观测数据，对 SWAP 模型进行了田间适用性检验。同时，对验证后的模型所模拟的水盐平衡结果进行了分析与讨论。得到主要结论如下：

（1）模型率定和验证的过程中，土壤水盐含量的模拟值均较好的反映了实测值的大致变化趋势。其中，率定期与验证期各层含水量的 RMSE 值不超过 0.03cm^3/cm^3，且各层的 MRE 值均低于 10%；率定期和验证期各层含盐量的 RMSE 值不超过 1.5mg/cm^3，且各层的 MRE 值均低于 15%，说明经过率定和验证后的 SWAP 模型适用于模拟研究区土壤剖面各层的水盐动态变化，且模拟得到的水盐平衡分量结果是可靠的。

（2）根据 SWAP 对研究区两季夏玉米田间水量平衡各分量的计算结果：2013 与 2014 年季夏玉米生育期内累积实际蒸腾量占潜在蒸腾量的比值分别为 57.6%和 64.9%，说明作物蒸腾受到了表层土壤含水量的制约。2013 与 2014 年季 0～120cm 土壤储水变化量分别为-5.52cm 和

growth of maize. The accumulative soil water supply from groundwater in 2013 and 2014 was 10.3cm and 7.4cm, respectively. In the study area, QBOT is highly sensitive to rainfall and irrigation, mainly manifested by great deep leakage. The accumulative deep leakages after irrigation in 2013 and 2014 reached 6.9cm and 7.2cm.

(3) According to SWAP results on field salt balance components during summer maize growth periods in 2013 and 2014, SAMPRO at the harvest reduced by 72.87 mg/cm2 and 81.32mg/ cm2 compared to that at early stage, indicating the desalinization of 0~120cm soil layers after maize plant. The most distinct desalinization is observed in the mid and late growth periods of summer maize. Neglecting lateral drainage, heavy rainfalls are the main cause of overall desalinization of 0～120cm soil layers in the study area.

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1.58cm，地下水给予土壤水的上升补给主要出现在作物生长旺盛阶段，地下水累积上升补给量分别为 10.3cm 和 7.4cm；研究区土壤底部水分通量变化对降雨和灌溉的响应强烈，主要表现为明显的深层渗漏，2013 与 2014 年季灌水后的累计深层入渗量分别为 6.9cm 和 7.2cm。

（3）根据 SWAP 对研究区两季夏玉米田间盐分平衡各分量的计算结果：2013 与 2014 年季玉米收获时的土壤盐分储量相比初期的盐分储量分别减少了 72.87 mg/cm^{2} 和 81.32mg/ cm^{2}，表明经过一季的玉米种植后，研究区 0～120cm 土壤处于脱盐状态，并且两季玉米普遍在生长的中后期脱盐明显。在不考虑侧向排水的条件下，强降雨事件是造成研究区 0～120cm 土层整体脱盐的主要因素。

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