SIMULATING ENERGY BALANCE AND HYDROLOGIC CYCLE IN A DESERT-OASIS TRANSITIONAL ZONE USING RZWQM2

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ABSTRACT

The simulation of energy balance is essential to define soil water and heat flux, and quantifying crop water demand and optimizing irrigation management practices are critical to water resource management in extremely arid desert oases. The objectives of this study were (i) to evaluate the performance of RZWQM2 in simulating energy balance in bare soil ground in the desert-oasis transitional zone thus evaluate the relationship between precipitation and groundwater recharge; (ii) to develop an optimal irrigation scheme for cotton planted in this area using the RZWQM2 model being calibrated against soil moisture content, cotton growth stage, and cotton yield. This study took an irrigated agricultural field in an extremely arid oasis transition zone in Cele, Xinjiang, northwest of China as a research site, and the revised hybrid RZWQM2 model was evaluated in simulating energy balance components, soil water content in different soil layers, crop growth stages and yield under desert climate. The energy balance components were measured on a bare soil near the cotton planting field. The model performed well in simulating total shortwave radiation (T_s) and net radiation (R_n), with coefficient of determination (R^2) > 0.93, model efficiency (ME) > 0.80 and percent bias (PBIAS) < ± 20%, while the simulation for ground heat flux (G) was unacceptable, with R^2 = 0.818, ME = -0.160 and PBIAS = -102.8%. Although the model failed to satisfactorily simulate ground heat flux, the simulation in surface energy balance was in general acceptable compared with other literatures. The simulated annual average actual ET (42.5mm) is generally lower than precipitation (43.2mm), and the excess water infiltrated into the ground and stored in various depths of the soil profile.

In the irrigated cotton field, the model simulation in soil water is comparable with other research, with evaluation parameters R^2 ranging from 0.198 to 0.538, ME from -0.368 to 0.374, PBIAS < ±20% for different layers. The simulation in cotton yield is also satisfactory with (R^2) = 0.8, ME=0.75, root mean squared error (RMSE) =415.0kg/ha and relative RMSE (RRMSE)=12.5% for cotton yield. Although

model simulated plant emergence dates were generally 6 days late because the model is lack of plastic mulching component after seeding, simulated flowering and bolls cracked dates matched well with those of observed, with the difference around ±4 days. From the simulated water balance data, the annual crop water consumption (actual evapotranspiration, AET) was 52.2cm and 10.1 cm deep percolation, while the simulated annual crop water requirement was 61.3 cm, suggesting a water stress under current irrigation practices and water wasted through deep seepage. A water stress-based irrigation decision support tool was applied to develop an optimal irrigation scheme for the cotton field using the RZWQM2 model, and it could save irrigation water by 4.7% (4.3cm per year) and increase the production by 15.8% (451kg ha^{-1} per year). It indicated that without canopy on the surface, groundwater would generally be recharged from precipitation though the precipitation is very low and this recharge is very trivial; RZWQM2 was applicable in simulating energy balance components, soil water content and crop production in extremely arid district. Rescheduling of irrigation using a water stress-based method can be used to optimize irrigation water use and cotton production.

RÉSUMÉ

Permettant de définir les flux de chaleur et d'humidité du sol, de quantifier la demande en eau des cultures, et de mettre en place des pratiques de gestion optimales en matière d'irrigation, une simulation précise du bilan énergétique et du cycle hydrologique d'un oasis situé dans un désert extrêmement aride, s'est avéré essentiel à la gestion de ses ressources hydriques. La présente étude eut pour objectifs : (i) d'évaluer la capacité du modèle RZWQM2 à simuler le bilan énergétique d'un sol nu dans une zone de transition desert-oasis, élucidant ainsi la relation existante entre le taux de précipitation and la recharge des eaux souterraines, (ii) d'utiliser le modèle RZWQM2 — étalonné avec des données locales [Cele, Xinjiang (Chine)] d'humidité du sol (θ), d'étapes phénologiques et de rendement de la culture — afin de développer un régime d'irrigation optimal pour le coton (*Gossypium hirsutum* L.) dans une zone de transition oasis-désert hyperaride. Le modèle étalonné fut évalué quant à sa capacité à simuler avec précision les éléments du bilan énergétique, θ des différentes couches du sol, ainsi que les étapes phénologiques et le rendement de la culture, sous un climat désertique. Certains éléments du bilan énergétique furent quantifiés sur un terrain dénudé près du champ de coton. Le modèle se montra précis en simulant le rayonnement solaire à ondes courtes (T_s) et le rayonnement net (R_n), présentant un coefficient de détermination (R^2) > 0.93, coefficient d'efficacité Nash-Sutcliffe (NSE) > 0.80 et pourcentage de biais (PBIAS) inférieur à ± 20%. Cependant, sa simulation du flux de chaleur dans le sol (G) fut inacceptable (R^2 = 0.818, NSE = -0.160, PBIAS = -102.8%). Quoique le modèle fut incapable de correctement simuler la valeur de G, dans l'ensemble sa simulation du bilan énergétique en surface s'avéra acceptable par rapport aux simulations rapportés dans d'autres études. Sur une base annuelle, l'évapotranspiration (ET) réelle moyenne (ET_r = 42.5 mm) fut généralement inférieure à la précipitation moyenne (43.2 mm); l'excès d'eau s'infiltrant dans le sol y étant entreposée à divers niveaux du profil du sol. Pour le coton irrigué, la précision du modèle quant au θ des différentes couches du sol (0.198 ≤

$R^2 \leq 0.538$; $-0.368 \leq ME \leq 0.374$; $|PBIAS| < 20\%$) fut comparable à celle rapportée ailleurs. Également, la simulation du rendement du coton s'avéra satisfaisante [$R^2 = 0.8$; ME = 0.75; racine carrée de l'erreur quadratique (RMSEP) = 415.0 kg ha^{-1} et RMSEP relative (RRMSEP) = 12.5%]. Le modèle n'étant pas équipé d'un dispositif permettant de simuler le paillage plastique, ses estimations de la levée des cultures furent généralement 6 jours en retard. Par contre, les dates de floraison et de fendaison des capsules correspondirent de près aux dates observes au champ, avec une différence maximale de ±4 jours. A partir du bilan hydrique, la consommation d'eau annuelle de la culture (ET_a), la percolation profonde, et le besoin en eau de la culture furent estimés à 522 mm, 101 mm et 613 mm, respectivement, laissant entrevoir qu'un certain stress hydrique avait eu lieu sous le présent régime d'irrigation et qu'une certaine quantité d'eau fut gaspillé par percolation profonde. Par l'entremise du modèle RZWQM2, un outil d'aide à la décision s'appuyant sur le stress hydrique et servant à gérer l'irrigation fut développé, et permît la préparation d'un régime d'irrigation optimal pour le champ de coton. Ce nouveau régime d'irrigation permît une économie de 4.7% en eau d'irrigation (43 mm y^{-1}) et une hausse de production de 15.8% (+451 kg ha^{-1} y^{-1}). Pour cette zone de transition oasis-désert hyperaride, la présente étude démontra qu'en l'absence d'un couvert végétale couvrant la surface du sol, la recharge des eaux souterraines provint de la précipitation, quoique celle-ci fut faible et la recharge minimale. Capable d'offrir une simulation précise du bilan énergétique, du niveau de θ, et du rendement de la culture pour une région hyperaride, le modèle RZWQM2 offrît l'occasion de diriger le rééchelonnement de l'irrigation selon le niveau de stress hydrique, et d'optimiser ainsi l'efficacité d'utilisation de l'eau d'irrigation et le rendement du coton.

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Preface and Contribution of Authors

This thesis contains title page, abstract in both English and French, acknowledgement, table of contents, list of tables, figures, abbreviations and symbols, major content, and references. The major content includes four chapters, respectively, Chapter 1: introduction; Chapter 2: Energy Partition and Groundwater Recharge in a Desert-oasis Transition Zone as simulated using RZ-SHAW; Chapter 3: Optimizing Irrigation Rates for Cotton Production in an Extremely Arid Area using RZWQM2 simulated Water Stress and Chapter 4: Summary and Conclusion. There are connecting statements before Chapter 2 and Chapter 3.

Chapter 3 is a manuscript under review in the Transactions of the ASABE. The manuscript is co-authored by my supervisor Dr. Zhiming Qi, and also Zhe Gu, Dr. Dongwei Gui, Professor Fanjiang Zeng.

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LIST OF ABBREVIATIONS AND SYMBOLS

AET	Actual Evapotranspiration (mm)
α_s	Albedo for bare soil
α_{sp}	Albedo for snowpack
Cv	Empirical Extinction Coefficient (-)
CWR	Crop Water Requirement (cm)
DSSAT	Decision Support System for Agrotechnology Transfer model
Ds	Deep Seepage
ET	Evapotranspiration
FC	Field Capacity
FC10	Soil Water Content at 10kPa (cm^3 cm^{-3})
FC33	Soil Water Content at 10kPa (cm^3 cm^{-3})
FC1500	Soil Water Content at 10kPa (cm^3 cm^{-3})
G	Ground Heat Flux (W m^{-2})
H	Sensible Heat (W m^{-2})
IWUE	Irrigation Water Use Efficiency
L	Longwave radiation (W m^{-2})
LE	Latent Heat (W m^{-2})
PET	Potential Evapotranspiration (mm)
R_n	Net Radiation
RWU	Root Water Uptake
RZWQM	Root Zone Water Quality Model

SWC	Soil Water Content (cm^3 cm^{-3})
SHAW	Simultaneous Heat and Water model
T_s	Total Shortwave Radiation (W m^{-2})
TURFAC	Turgor Factor for Water Stress Index

CHAPTER 1 INTRODUCTION

1.1 GENERAL INTRODUCTION

Surface energy balance and hydrologic cycle interact with each other and affect the physical, chemical and biological processes in agricultural systems. Soil water content influence the water distribution in the ecosystem and participate in the segmentation of net radiation through determine the available water for evapotranspiration (ET) (Western et al., 1999). Energy balance determines the surface energy flux and also plays an important role in water transfer within soil-atmosphere interface by affecting evapotranspiration (Maruyama and Kuwagata, 2010). These processes subsequently influence nutrient cycling and control the development of plants. Therefore, understanding the energy and water transfer characteristics under different climate conditions is critical to arrange agricultural practices and provide guidance to field management.

Cele oasis transition zone located in Hotan, Xinjiang, northwest of China, with annual average precipitation 37mm, annual solar radiation > 1800 (kw h/m^2). Agriculture is the dominant industry in Xinjiang district, consuming more than 90% of total regional freshwater (Karthe et al., 2015). With the expanding of agriculture and increase of water consumption in recent decades, water resource encounters serious problems that become the primary restriction of agricultural production (Yang et al., 2006). Thus, developing optimal irrigation management practices to realize sustainable agriculture is of great significance, and a preferable approach to achieve this goal is the interactive application of field results of experiments and simulating scenarios with appropriate models.

The Root Zone Water Quality Model (RZWQM) is an integrated physical, bio-chemical process model to study crop production and non-point source contaminants for water quality and can be applied in simulating water utilization and plant phenology, infiltration and water redistribution differences between atmospheric precipitation and irrigation, subsurface drainage, organic matter and nitrogen (N) transfer and effective utilization ratio and pesticide movement (Ahuja et al., 2000). RZWQM2 adopted the energy balance component from the Simultaneous Heat and Water (SHAW) model, which enables RZWQM to simulate energy components in various field conditions with long-term crop rotations and multiple management (Flerchinger, 2000). The hybrid RZ-SHAW model applied modified S-W approach (Shuttleworth and Wallace, 1985) to calculate surface energy balance and describe ET, and include explicit provisions of energy and water transfer through bare soil, canopy, snowpack and residue (Flerchinger et al., 2003; Flerchinger, 2000). Kozak et al. (2007) evaluated three RZ-SHAW submodules in simulating under two field conditions in Colorado, and obtained comparably good results with another energy model. Some research have been conducted in China north plain, applying RZ-SHAW model to simulate energy balance components, soil water content and evapotranspiration under varying meteorology conditions and canopies, manifested that the revised RZ-SHAW model were reasonable in simulating energy balance, soil hydrology, crop growth and had potential to make predictions and guide management schedule (Fang et al., 2014a; Li et al., 2012; Yu et al., 2007). The crop growth module in RZWQM2 is supported by crop growing components from Decision Support System for Agrotechnology Transfer (DSSAT) model, and has been extensively explored and widely applied, proved to be comprehensive in relative agricultural scope (Ma et al., 2012a; Ma et al., 2007). Saseendran et al. (2013) employed RZWQM2 model to simulate the long-term yield response of several plants at various soil available water conditions at planting, and then used the results to assess the potential of crop in increasing cropping frequency in wheat-fallow rotation system. His research verified that calibrated RZWQM2 (RZ-DSSAT) could be applied in managing crop system in dryland. Throp et al. (2007), Qi et al. (2011) and Wang et al. (2016) demonstrated the good performance of RZWQM2 in simulating soil hydrology, nitrogen dynamics and crop yield, and then applied the model to predict long-term influence of fertilizer application on crop yield and nitrogen dynamics. This model has also been applied in simulating energy balance, soil hydraulic cycle, crop development under varying irrigation conditions and predicting the yield response according to simulated water stress ((Fang et al., 2014b; Qi et al., 2016).

1.2 Objectives

Limited researches have been conducted on the simulation of cotton production, energy and water cycle in desert climate zone, and there are few studies on developing optimal irrigation practices based on the simulation results of RZWQM2. Therefore, the objective of this study was to

i) evaluate model performance in simulating energy balance components, soil moisture and cotton production against observed data in Cele oasis-desert transition zone in northwest of China and analyze the characteristics of energy balance and water water balance

ii) compare the values of annual evapotranspiration and precipitation under natural conditions, and analyze the regional change in groundwater storage.

iii) analyze the crop water requirement and apply WS-based method to develop practical and optimal irrigation scheme using simulated water stress.

CONNECTING STATEMENT TO CHAPTER 2

Chapter 2 is about the analysis of energy balance and water cycle characteristics on a bare surface near cotton field under natural condition. Hybrid RZ-SHAW model was applied in simulating energy balance components, which include total shortwave radiation, net radiation and ground heat flux, and generally used evaluation parameters were applied to evaluate the model performance. The feature of energy cycle was subsequently discussed based on the simulated data.

The model simulated actual evapotranspiration data was compared with local annual precipitation to determine the amount of water that seep into soil. The distribution of water storage has been analyzed within 21m soil depth (the depth of the impermeable layer) to understand the loss or recharge condition of groundwater.

Chapter 2 Energy Partition and Groundwater Recharge in a Desert-Oasis Transition Zone as Simulated using RZ-SHAW

2.1 Abstract

The simulation of energy balance is essential to the determination of soil water and heat flux and hydrologic cycle particularly in an extremely arid zone. The objective of this study were (1) to evaluate the performance of hybrid RZ-SHAW model in simulating energy balance in a desert-oasis transitional zone in northwestern China, and to partition the net radiation to sensible heat, latent heat, and ground heat fluxes; (2) to quantitatively compare soil evaporation and precipitation in this region, as well as the effect of water balance on groundwater resources using the RZ-SHAW model. The RZ-SHAW model was calibrated and validated using total shortwave radiation (T_s), net radiation (R_n) and ground heat flux (G) on an hourly scale from 2007 to 2014 in a bare ground in a desert-oasis transitional zone near the Cele oasis in China. The simulated values for these three components were 128.4 W m^{-2}, 38.63 W m^{-2} and -0.054 W m^{-2} respectively. The evaluation statistics indicated a good model performance in simulating T_s and R_n, with the values for percent bias (PBIAS), coefficient of determination (R^2), and model efficiency (ME) for the whole period equal to 1.53%, 0.984, 0.983 for T_s and 17.6%, 0.932, 0.821 for R_n. However, the simulation in ground heat flux (G) was less satisfactory, with PBIAS, R^2 and ME equal to -102.8%, 0.818 and -0.160. Since the total annual G was less than 0.05% of the total annual T_s, the inaccuracy simulation which contributes a small portion of the entire system is not a concern. These results suggest that RZ-SHAW model is capable of simulating energy balance in a desert-oasis area while the simulation in ground heat flux needed further improvement. For the simulation in energy balance, the sensible heat was 35.29 W m^2, accounting for 91.2% of the value of (R_n-G), while latent heat was 3.39 W m^{-2}. The model estimated annual actual evapotranspiration (AET) was 42.5mm, less

than the averaged annual precipitation 43.4mm. The soil water storage within 21 m-depth soil profile increased by 0.48cm and the water table rose by 10.32 cm during the whole research period (2007-2014). It indicated that the groundwater generally could be recharged from precipitation in this district over a long-term, while the soil stored water would also deplete through loss in the form of evapotranspiration (ET) when there is insufficient precipitation.

Key Words: RZ-SHAW model, energy balance, water cycle, ET, groundwater

2.2 Introduction

Approximately 41% of the total continental area is covered by arid and semi-arid regions where the precipitation and water resources are scarce and the ecosystem is fragile. In such regions, oasis and desert are two independent ecosystems but interact in terms of energy exchange and hydraulic cycle (Li et al., 2016). The oasis expansion and desertification are two co-existing geographical processes, and it is indicated in previous research that both of these two processes showed an accelerating trend (Gui et al., 2009). These two processes have close connection with water balance and energy transfer. Therefore, exploring the characteristics of energy and hydrology balance in an extremely arid region has profound significance for studying the interaction of oasis and desert, supporting the sustainable development of oasis ecosystem.

Cele oasis is located in the south edge of Taklimakan Desert, central Eurasia Continent under desert climate, with annual precipitation less than 50 mm. Under natural conditions, the water cycle in such an extremely arid district is mainly composed of three main processes (i) precipitation; (ii) the surface water loss through evapotranspiration, (iii) deep percolation of soil water. Evapotranspiration (ET) is the main form of water loss in such a water-limited region, which accounts for more than 95% of precipitation input (Wilcox and Thurow, 2006). ET affects the groundwater recharge by determining the amount of soil water stored in the soil profile, and groundwater influences ET through the capillary rise of groundwater to root zone. The accumulation and loss of groundwater under natural conditions determine the trend of water table fluctuation, and indirectly influence on the oasis expansion and desertification processes. Quantifying the relationship between evapotranspiration and precipitation contributes to the understanding of the dynamics of water cycle in the extremely arid region in northwest of China. However, limited research has been conducted to study the long-term trend of groundwater storage as affected by the precipitation and evapotranspiration in such extremely arid regions.

Several methods for ET measurement have been reported in previous research, such as Bowen ratio, eddy covariance, and weighing lysimeter (Meijninger et al., 2002; Nagler et al., 2005). However, these methods usually need costly equipment and are labor intensive, and the accuracy of some of these methods is probably unreliable due to the limitations of the instruments and restrictions of external factors, such as extreme weather (Elhaddad and Garcia, 2008; Fisher et al., 2007). Energy balance model is a good tool to estimate ET based on simulated latent heat, especially when the field data is not available, while the model needs to be calibrated against observed energy balance components. Senay et al. (2014) applied SSEBop model to simulate ET based on thermal data and compared ET with precipitation data to determine spatial variability of hydrologic sources and sinks in the Nile Basin, revealing the major source basins (Lake Victoria) and sink areas (South Sudan) of Nile River. Sun et al. (2008) used measured data to evaluate the simulated ET by MIKE SHE model in northern Wisconsin, USA, and proved the possibility of using model to study the effects of forest cover change on landscape water balance in multiple ecosystems. A complementary relationship method based GG model (Granger and Gray Model) has also been applied to estimate actual ET against multi-site observed data across north China, which circumvent the difficulties in validating site-specific model parameters (Zhu et al., 2016). The results indicated that the GG model was applicable in simulating daily ET in most ecosystem.

RZ-SHAW model is a hybrid model, which adopted the energy balance module from SHAW (Simultaneous Heat and Water) model to improve the simulation in energy and water transfer with different canopy and residue types (Flerchinger et al., 2009). Previous studies have been conducted to evaluate RZ-SHAW model performance in simulating energy balance components, water cycle, soil temperature in various places, and concluded that the model was qualified to simulate energy and water cycle under different meteorological conditions (Yu et al., 2007; Ma et al., 2012a; Kozak et al., 2007; Li et al., 2012; Qi et al., 2016; Fang et al., 2014a). These researches demonstrated the feasibility of utilizing RZ-SHAW model to study the characteristics of energy balance in agricultural systems, while this model has not been applied to simulate energy and water balance in an extremely arid oasis-desert transitional zone. Therefore, the objective of this study were i) to evaluate model performance in simulating surface energy balance components using hourly meteorology data in Cele oasis in the northwest of China; ii) to compare the modeled evapotranspiration with observed precipitation for the analysis in the regional change in groundwater storage.

2.3 MATERIAL AND METHODS

2.3.1 Site and experiment descriptions

This study was conducted at Cele National Station of Observation & Research for Desert Grassland Ecosystem in Xinjiang (36°59′ N, 80°48′ E). Cele oasis is a representative district in terms of the relationship between the ecological environment and water resources in arid areas. Cele oasis is located in the center of the Eurasian continent, far away from the ocean, which is under a warm temperate continental desert climate. The climate is extremely arid with an average annual precipitation 37 mm, and the groundwater table is around 15 meters. The solar radiation in Xinjiang district is abundant and the diurnal temperature range is great. The main type of the surface soil in the oasis farmland is aeolian sandy soil (Li et al., 2010) with high sand and low clay content.

Energy balance data includes total shortwave radiation, Ts, net radiation, R_n and soil heat flux, G were measured at the Cele National Station of Observation & Research for Desert Grassland Ecosystem (station number of CLDZH01ABC_01) from 2007 to 2014. Sensible heat and latent heat were not observed in this study. The energy balance data was collected over a bare soil ground. Meteorological data including air temperature, wind speed, relative humidity, solar radiation, pan-evapotranspiration, photosynthetically active radiation and rainfall were measured and recorded automatically on an hourly basis.

2.3.2 Description of RZ-SHAW model

In RZ-SHAW model, the potential evapotranspiration and soil heat flux are calculated using energy balance equation (Flerchinger, 2000):

$$R_n + H + LE + G = 0 \qquad (2.1)$$

where

R_n is net radiation (W m^{-2}),

H, LE are the sensible and latent heat flux respectively, and

G is ground heat flux (W m^{-2}).

Net solar radiation is calculated based on incoming and outgoing solar radiation, which is composed of direct and diffuse solar radiation. Net radiation is the sum of the total shortwave and total longwave radiation. Since the data was observed in bare ground, the net shortwave radiation is calculated by taking the energy reflection from the bare soil (Dingman, 2015):

$$Ts = K_{in} \cdot (1- a) \qquad (2.2)$$

where

K_{in} incident solar radiation (W m^{-2}), and

a is albedo,

The net longwave radiation is given based on the Stefan-Boltzman equation:

$$L = \varepsilon_s \cdot \varepsilon_{at} \cdot \sigma \cdot Ŧ_a^4 - \varepsilon_s \cdot \sigma \cdot Ŧ_s^4 \tag{2.3}$$

where

$\varepsilon_s, \varepsilon_{at}$	are integrated effective emissivity of surface and atmosphere respectively,
$Ŧ_a, Ŧ_S$	are air temperature and surface temperature (K), and
σ	is the Stefan-Boltzman constant (W m^{-2} K^4),

Then the net radiation is calculated by the sum of net shortwave and longwave radiation. Sensible heat flux is computed from temperature and vapor gradients between the exchange boundary, the equation suggested by Campbell (2012) as:

$$H = -\rho_a \, c_a \, \frac{(T - T_a)}{r_H} \tag{2.4}$$

where

ρ_a	is air density (kg m^{-3}),
c_a	is specific heat (J kg^{-1} C^{-1}), and
T, T_a	are the temperature for exchange surface and air (C),
r_H	is surface heat resistance ability (s m^{-1}),

Latent heat is related to water evaporation and transpiration, which is given by Flerchinger (2000):

$$LE = \frac{(\rho_{vs} - \rho_{va})}{r_H} \tag{2.5}$$

where

ρ_{vs}, ρ_{va}	are vapor density at the surface and at special height (kg m^{-3}),

Ground heat flux is solved by energy balance equation among the entire soil profile, which need interaction of heat and water flux equation for plant canopy, snow, residue and different soil layer.

2.3.3 Model calibration and validation

Data from 2007 to 2010 were chosen as calibration year and others as validation years. To meet the requirements of simulating groundwater storage, the soil depth applied in model simulation was set at 21 m, which is deeper than observed water table (15m). The hydraulic conductivity (K_{sat}) for the lowest layer was set at a very small value, assuming an aquiclude and almost no deep seepage beyond 21-meter depth of soil. The initial values for the soil hydraulic parameters were estimated based on soil texture and bulk density (Schaap and Leij, 1998). Subsequently those parameters were calibrated manually against observed soil water content in different layers (details listed in next chapter). All the initial values of soil hydraulic parameters and soil PET parameters are set as model original value based on the soil texture at research site, and the sensitivity of the parameter is given by Flerchinger (1991). These initial and adjusted soil PET parameters are listed in table 2-1.

Table 2-1 Initial soil PET parameter value, optimization range and adjusted values

Parameters	Initial	Range	Adjusted
α_d[1]	0.3	0.2~0.6	0.42
α_w[2]	0.2	0.1~0.6	0.38
r_H[3]	200	0~500	150

* Source of range value: Lee (1980), α_d = albedo for dry soil, α_w = albedo for wet soil, r_H = soil surface resistance (s m^{-1})

In the calibration procedure, albedo and canopy height were adjusted based on the reference range suggested by Lee (1980) and our field condition. The simulated soil energy components from optimizes parameters showed more consistency compared with measured data. In this study, percent bias (PBIAS), coefficient of determination (R^2), Nash-Sutcliffe model efficiency (ME) were applied to evaluate the performance of model simulation.

$$\mathrm{PBIAS} = \frac{\sum_{i=1}^{n}(S_i - O_i)}{\sum_{i=1}^{n} O_i} \quad (2.6)$$

$$R^2 = \frac{[\sum_{i=1}^{n}(O_i - \bar{O})(S_i - \bar{S})]^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2 \sum_{i=1}^{n}(S_i - \bar{S})^2} \quad (2.7)$$

$$ME = 1.0 - \frac{\sum_{i=1}^{n}(S_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \quad (2.8)$$

where

n is the total number of items in the data set,

$\bar{O}$ and $\bar{S}$ are the average measured and simulated values, respectively,

O_i is the i^{th} measured value, and

S_i is the i^{th} simulated value.

2.4 Results and discussion

2.4.1 Simulation results of energy balance component

The results diagram and evaluation statistics are showed in figure 2-1 to 2-3 and table 2-2. The results in day 21-23 in March, June, September and December was selected to present, and total shortwave radiation, net radiation and soil heat flux have been compared against with observed data.

Table 2-2 Evaluation statistics for energy balance components from 2007 to 2014

Energy balance components		Obs. ($W\ m^{-2}$)	Sim. ($W\ m^{-2}$)	R^2	ME	PBIAS
Ts[1]	Calibration	132.77	132.50	0.984	0.984	-0.20%
	Validation	120.2	124.3	0.984	0.982	3.43%
	Total	126.5	128.4	0.984	0.983	1.53%
Rn[2]	Calibration	37.69	40.55	0.944	0.847	7.60%
	Validation	28.02	36.73	0.920	0.790	31.1%
	Total	32.84	38.63	0.932	0.821	17.6%
G[3]	Calibration	2.804	-0.054	0.839	0.258	-101.9%
	Validation	1.033	-0.053	0.829	-0.896	-105.2%
	Total	1.917	-0.054	0.818	-0.160	-102.8%

*Latent heat (LE) and sensible heat (H) were not measured; simulated LE = 3.39 $W\ m^{-2}$, and H = 35.29 $W\ m^{-2}$. Ts is total shortwave radiation ($W\ m^{-2}$), Rn is net radiation ($W\ m^{-2}$), and G is soil heat flux ($W\ m^{-2}$)

The values of shortwave radiation and net radiation were higher from June to September than other period in the whole year, while the seasonal variation for heat flux was less evident. For the whole research period, the model performed well in simulating total shortwave radiation (Ts), with coefficient of determination (R^2) equal to 0.984, model efficiency (ME) equal to 0.983 and percent bias (PBIAS) equal to 1.53%. And simulated net radiation (Rn) was overestimated at night while underestimated at day time (Figure 2-2), with R^2 of 0.932, ME of 0.821 and PBIAS of 17.6%. These results are comparable to the research conducted in Colorado, where R^2 and ME were 0.98 and 0.96 for net radiation (Qi et al., 2016). However, the ground heat flux (G) was poorly estimated during the research period, where the R^2, ME and PBIAS are 0.818, -0.160 and 1.028 respectively. From Figure 2-3, the simulation for ground heat flux was much worse in summer period (June 21~23) than other period during the year, which can be explained by the meteorology and energy transfer characters during summer period. Most of the precipitation concentrated in this period, and energy transfer within the air-soil interface are more significant, which may lower the accuracy of field observation and then affect the simulation results. According to Hsieh et al. (2009), soil heat flux varies sinusoidally and theoretically, the mean of ground heat flux in a long-term observed period is equal to zero. The observed ground heat flux was 1.917 W m^{-2} much more than the simulated value of -0.054 W m^{-2}. However, compared to R_n and Ts, simulation in G is relatively difficult to reach to a high statistics value, because the low variance and mean value to close to zero. The observed annual Rn of this study was 38.63 W m^{-2}, while G was only 0.14% of Rn. Therefore, although the different between simulated and observed G was about 2.0 W m^{-2}, the effect on the total energy balance is minor.

In the energy partition, the net radiation accounted for only 26% of total shortwave radiation, which means that around 74% of energy was emitted into atmosphere. It is indicated that the energy utilization was low in this district, and most of energy was reflected back to the air through ground long-wave radiation, which caused the ground temperature rose rapidly during day time. The simulated sensible heat was 35.29 W m^2, accounting for 91.2% of the value of net radiation minus ground heat flux (R_n-G). The latent heat was 3.39 W m^2, and only accounted for 8.8% of (R_n-G). The simulation in Ts and Rn indicates that RZ-SHAW model is qualified to simulate energy balance components under extremely dry environmental system.

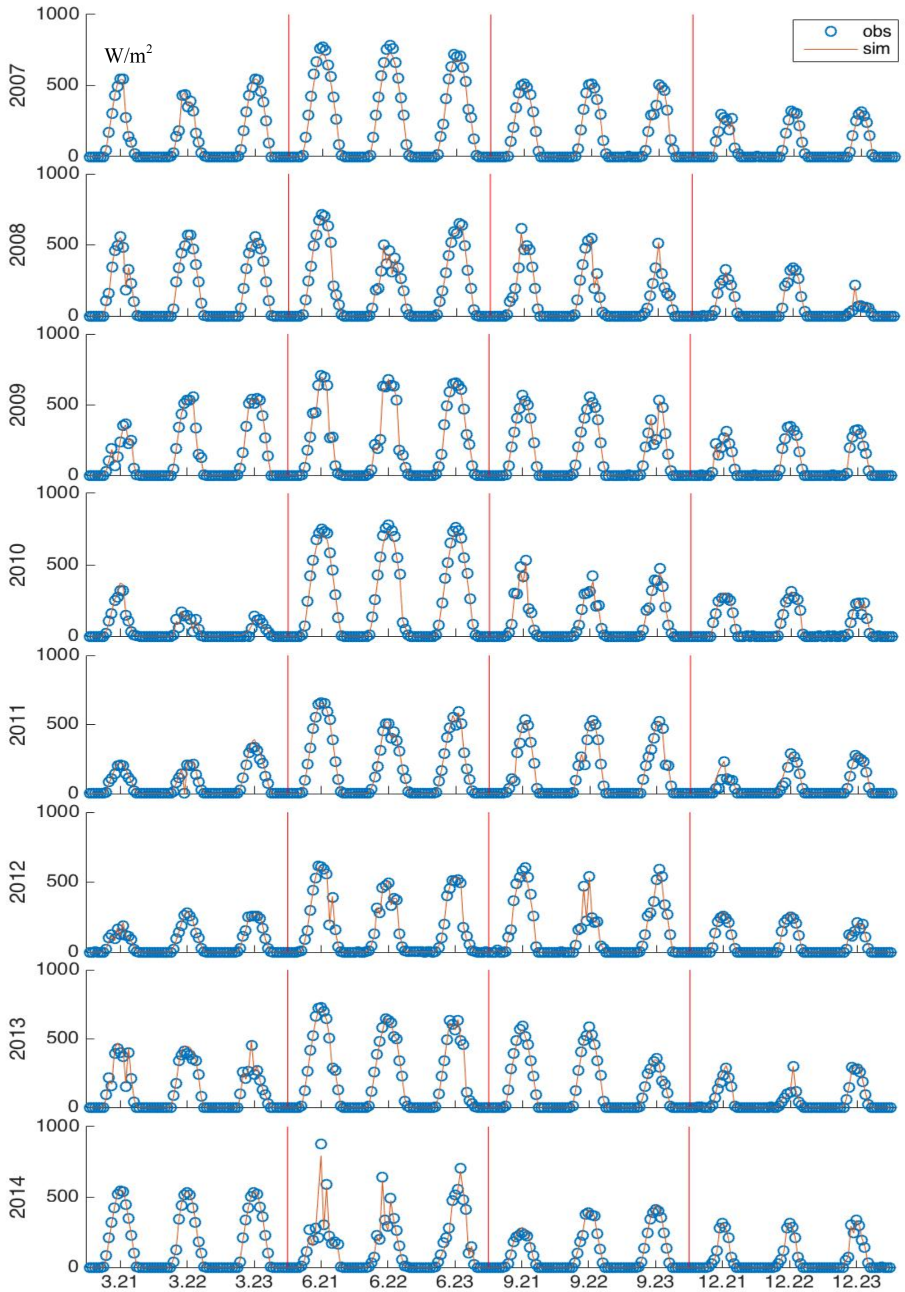
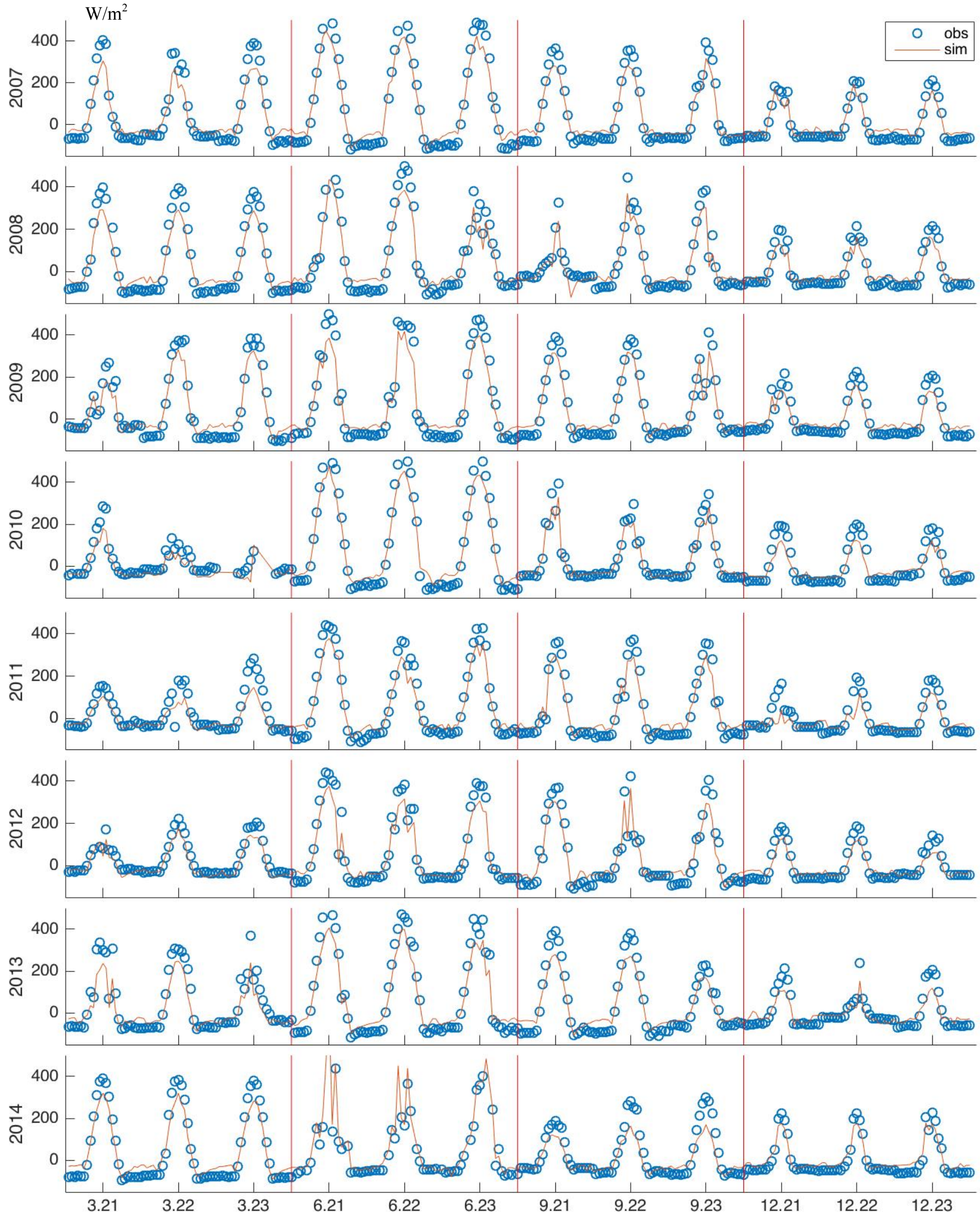


Figure 2-1 Simulated and observed hourly Total Shortwave Radiation (Ts) from 2007 to 2014



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462 Figure 2-2 Simulated and observed hourly Net radiation (Rn) from 2007 to 2014

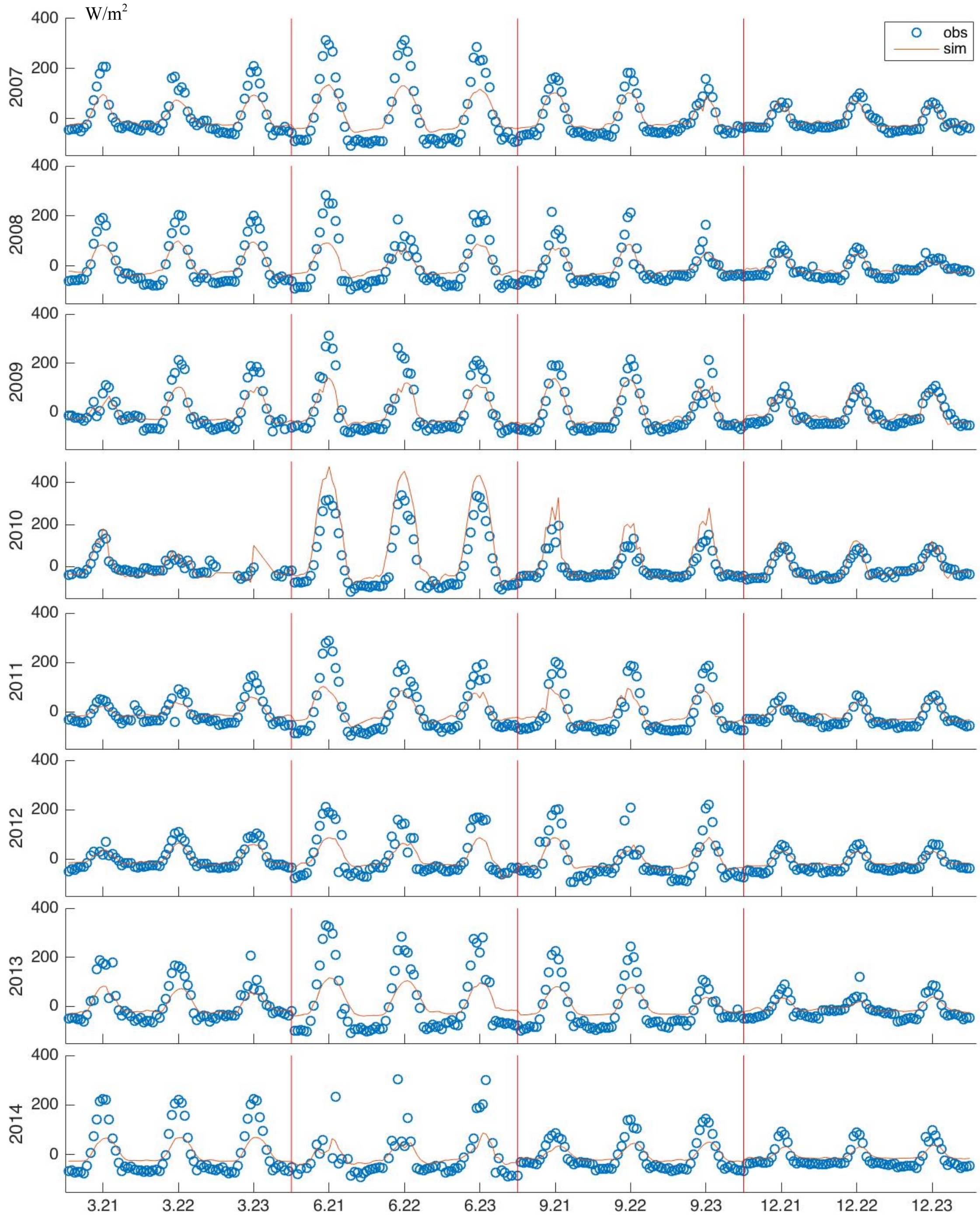

Figure 2-3 Simulated and observed hourly Ground Heat Flux (G) from 2007 to 2014

2.4.2 Analysis of supply condition of groundwater

Subsequently this study attempted to analyze the groundwater recharge or depleting using the simulated evaporation from the bare soil. Energy balance components were measured in bare surface without canopy and this place was not interfered by any agricultural management practices. The precipitation is the only water source of this field and evapotranspiration is regarded equal to evaporation. In this system, the majority of water input lost through evaporating from soil-atmosphere interface, and the water seepage into deep soil profile was very small amount. However, the long-term accumulation of this seepage is one of the main sources of groundwater in an extremely dry arid. Since sensible and latent heat fluxes were not observed in this study, the evapotranspiration (ET) was obtained from the RZ-SHAW model and compared with observed precipitation.

Table 2-3 Model simulated actual evapotranspiration (AET), potential evapotranspiration (PET), precipitation (P) and change of water storage in 20.98 meters soil profile (ΔS)

year	AET	PET	P	ΔS
		mm		
2007	30.1	926	34.0	11.6
2008	37.6	910	38.0	8.6
2009	34.5	940	43.0	23.8
2010	110.9	826	118.2	57.6
2011	14.4	870	5.6	-3.8
2012	58.0	815	61.6	26.2
2013	37.1	865	32.4	3.30
2014	17.6	826	13.4	-0.1
Average	42.5	872	43.2	0.06

As showed in Table 2-3, in this area, the estimated annual actual evapotranspiration (AET) on bare ground was 42.5mm, and potential evaporation (PET) significantly exceeded AET due to the strong radiation and scarce water supplies. The AET values also supported by the simulated partition of energy: since there was no sufficient water available for evapotranspiration, the energy consumed by latent heat was very little; and then most of net radiation contribute to increase the surface temperature and thereby is released into the atmosphere in terms of terrestrial radiation. During the research period, the annual precipitation was generally higher than that amount of actual evapotranspiration except for year 2011 and 2014, when there was extremely scarce precipitation. The water storage with 21-meter depth soil profile increased 0.06 mm per year on average from 2007 to 2014. And the difference between precipitation and actual evapotranspiration for each year was approximately equal to the change of soil water storage. Since in this scenario the simulated soil profile depth was set 21-meter and the water table depth was 15 m which was reported in field studies, the results indicated that there was certain amount of water accumulation in the soil during normal years while the soil water could be depleted through soil evaporation during extremely dry years.

Table 2-4 Summary of water balance components and the change of water table from 2007 to 2014 (cm)

Year	ΔS	P	AET	Ds	Td	Lf	WT_{ini}	WT_{fin}	ΔWT
2007	0.389	3.397	3.008	0	0	0	1528.59	1526.54	-2.05
2008	-0.059	3.799	3.758	0	0	0	1526.54	1524.92	-1.62
2009	0.853	4.303	3.451	0	0	0	1524.92	1523.76	-1.16
2010	0.815	11.817	11.094	0	0	0	1523.76	1522.89	-0.87
2011	-0.883	0.560	1.442	0	0	0	1522.89	1522.22	-0.67
2012	0.267	6.157	5.797	0	0	0	1522.22	1520.76	-1.46
2013	-0.472	3.329	3.711	0	0	0	1520.76	1519.42	-1.34
2014	-0.428	1.339	1.768	0	0	0	1519.42	1518.27	-1.15
Total	0.48	34.61	34.03	0	0	0	-	-	-10.31

ΔS is the change of soil stored water, P is the precipitation, AET is the actual evapotranspiration, Ds is the deep seepage, Td is the tile drainage, Lf is the lateral water flow, WT_{ini} is the depth of water table at first day of research period (1st JAN 2007), WT_{fin} is the depth of water table at last day of research period (31st DEC 2014), ΔWT is the change of water table (negative value means the rise of water table)

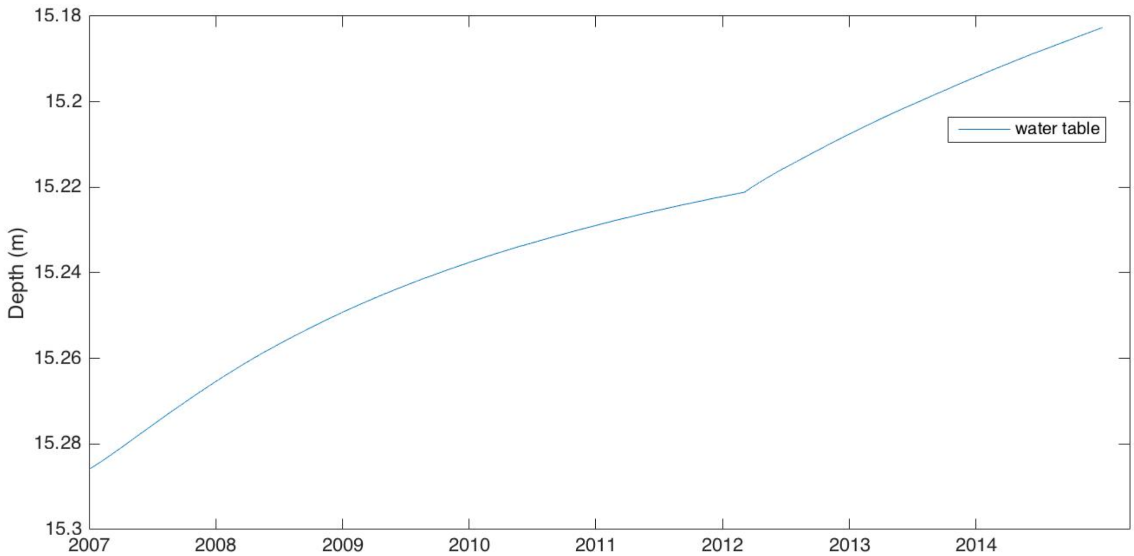

Figure 2-4 Change of water table depth (meter) from 1 JAN 2007 to 31 DEC 2014

Table 2-4 and Figure 2-4 show the water balance components and the change in water table during the whole research period. During the whole period, the precipitation was the only water source in this ecosystem, majority of water from precipitation was lost from evapotranspiration (98.3%), small part of incoming water infiltrated into deep soil layers, increasing the soil moisture and recharging ground water. There was almost no water loss through lateral water flow, tile drainage and runoff. The water storage in 21 m soil profile increased by 0.48cm from 2007 to 2014. Specifically, the values of actual evapotranspiration were larger than that of precipitation in 2008, 2011, 2013 and 2014, when the precipitations were relatively less compared to other years, and the soil water storage decreased correspondingly. However, in other years when the rainfall was relatively abundant, the AET was less than precipitation, and there was water accumulation in soil layers.

The initial water table depth was 15.29m, the final water depth was 15.18m, and the depth of water rose by 10.31cm during 8 years. In each year, the water table has risen in varying degrees, from 0.67 to 2.05cm. It indicated that the precipitation contributed to the groundwater accumulation and the increase of soil moisture.

2.5 Conclusion

In this study, the performance of RZ-SHAW model in simulating energy components was evaluated against observed data at the Cele station in an oasis-desert transitional zone from 2007 to 2014. Then simulated ET was compared with annual precipitation to analyze the dynamics of groundwater. The performance of RZ-SHAW model in simulating energy components was satisfactory though ground heat flux was not well simulated but it was minor in the energy balance components. The results also concluded that, on the bare soil in the desert-oasis transitional zone, the majority of incoming energy from solar radiation scattered into the atmosphere in form of short wave radiation. The simulated ET was in general slightly less than annual precipitation, and the analysis in soil water storage showed that there was a certain amount of water accumulation in deeper soil layers. Those indicated that the groundwater could be generally recharged by precipitation though with a very small amount and the groundwater resource will be enriched in this extremely arid desert-oasis transitional zone under natural conditions over the long-term.

CONNECTING STATEMENT TO CHAPTER 3

In this chapter, hybrid RZWQM2 was applied to study the water balance between soil-atmosphere interface and cotton production in an agricultural field in this desert-oasis transition zone in Cele, northwest of China. Firstly, the model was calibrated to simulate soil moisture, cotton phenology dates and cotton seed yield against field observed data. The simulated results were subsequently analyzed and simulated water balance was discussed to determine irrigation water use efficiency in the research field. Ultimately, water stress (WS) based regime was applied to develop an optimal irrigation scheme based on the simulated water stress, which indicated a potential feasibility of applying RZWQM2 for a better agricultural water management.

Chapter 3 is a manuscript prepared for publishing in the Journal of ASABE. The manuscript is co-authored by my supervisor Dr. Zhiming Qi, and also Zhe Gu, Dr. Dongwei Gui, Professor Fanjiang Zeng.

Chapter 3 Optimizing Irrigation Rates for Cotton Production in an Extremely Arid Area using RZWQM2 simulated Water Stress

3.1 Abstract

Quantifying crop water demand and optimizing irrigation management practices are essential to water resource management in arid desert oases. Agricultural systems modelling can serve to develop a better understanding of such growing conditions when field experiments conducted under conditions of water sufficiency are lacking. RZWQM2-simulated water stress can be used as an indicator for irrigation scheduling, but has not been applied to extremely arid zones. The objectives of this study were to (i) evaluate the performance of RZWQM2 in simulating soil moisture content and crop production in an extremely arid area; and (ii) to develop an optimal irrigation strategy using model-simulated crop water stress. In this study, RZWQM2 hybridized with DSSAT was calibrated and validated against soil moisture, cotton (Gossypium hirsutum L.) yield and development stage data collected from 2006 to 2013 in a flood-irrigated cotton field located in an extremely dry oasis in Cele, situated in Xinjiang, China (mean annual precipitation 37 mm). The simulated water balance was analyzed to determine the actual crop water consumption, crop water requirements, and seepage loss. Subsequently an optimal irrigation scheme was developed using RZWQM2 by averting crop water stress from planting to 90% boll open boll. In comparison to similar studies, the accuracy of soil moisture content simulations was deemed acceptable: percent bias < ± 15%, coefficient of determination (0.378 ≤ R2 ≤ 0.636), Nash-Sutcliffe model efficiency (0.130 ≤ ME≤ 0.557) and root mean squared error (0.022 m3 m 3 ≤ RMSE ≤ 0.031 m3 m 3). The model performed well in simulating cotton yield: (R2 = 0.80, ME = 0.750, RMSE = 415.0 kg ha-1 and relative RMSE (RRMSE) = 12.5%. Model-simulated plant emergence dates were generally 6 days late because of the model's lack of a mulching after seeding component, other phenological dates were closely matched, with a mean difference of ± 4 days. On average, over 8 years, the simulated growing season (planting to 90% boll open boll) water balance showed the cotton crop to consume 522 mm y-1 of water under current irrigation practice, indicating 101 m m of water to be lost through deep seepage. However, based on simulated PET, the crop water requirement was 613 mm y-1, suggesting a water stress under current irrigation practices. Under these conditions water stress occurred mainly during the late stages of the cotton growth. On average, the water stress-minimizing RZWQM2 irrigation schedule resulted in an apparent irrigation water savings of 43 mm y-1 (4.7%) and an annual yield increase of 451 kg ha-1 (15.8%) on average. RZWQM2 was shown to be suitable for simulating soil hydrology and crop development in an agricultural system implemented in an extremely dry climate. Rescheduling of irrigation using a water stress-based method can be used to optimize irrigation water use and cotton production.

Keywords.

Optimum irrigation, water stress, RZWQM2, soil water content, cotton production, WS-based regime

3.2 INTRODUCTION

Regions under a desert climate usually experience precipitation on the order of 25 to 200 mm y^{-1} (Laity, 2009), and are subject to significantly greater potential evaporation (E_p). Located in northwest China's desert climate zone, Xinjiang district produces almost two thirds (62.5% and 67.3% in 2015 and 2016, respectively) of China's total cotton production (China Agriculture, 2017), but at the cost of the agricultural sector accounting for 96.2% of the region's total water usage (Karthe et al., 2015). Given agricultural productivity's strong dependence on water availability, irrigation management is a critical agricultural practice under desert climate agroecosystems. Largely based on farmer's confidence and experience with traditional irrigation methods, approximately 40% of fields in the Xinjiang district receive flood irrigation (Zhou et al., 2013), potentially resulting in substantial deep seepage losses and inefficient use of water resources. It is therefore critical to optimize water resource use by improving the cotton production process in terms of water use efficiency (WUE).

An accurate assessment of crop water requirements is an indispensable component in developing irrigation schemes which optimize water use. Crop water requirements can be measured using weighing lysimeters and water balance methods, but such methods are laborious and time consuming. Liu et al. (2006) conducted a cotton irrigation experiment in Weili County, southern Xinjiang and reported cotton crop water requirement of 640 mm during the growing season, whereas Cai et al. (2002) found cotton water requirements to be about 380 mm in Shihez, northern Xinjiang. However, each of these measurements was based on a single cropping year. Another experiment on a cotton plantation was conducted in Cele (data used in this study) over a longer period (2006-2013); however, irrigation water requirement was not one of the factors investigated in this experiment where the cotton crop could have suffered from water stress.

Agricultural system models are promising tools for simulating water balance and can be used to estimate potential evapotranspiration (ET_p) , in other words, long term crop water requirements under no water stress conditions. The root zone water quality model 2 (RZWQM2), is a processing model, incorporating energy, water and nutrient equilibrium, plant growth, pesticide process and agricultural management components, which has performed well in simulating WUE and crop productivity (Ahuja et al., 2000). Using this model, Qi et al. (2013) estimated growing season ET_p for spring wheat (*Triticum æstivum* L.*)* grown in Sidney, MT to be 558 mm, and suggested that an additional 323 mm of irrigation water should be applied to meet the crop's water consumption in this region. Ma et al. (2012) applied parameterized RZWQM2 model to simulate maize responses to irrigation amounts representing specific percentages of estimated crop ET_p, and demonstrated the feasibility of using the model to schedule irrigation based on crop water requirements. Fang et al. (2010) evaluated RZWQM2 in simulating crop yield and soil water balance response to different irrigation treatments, and investigated irrigation strategies to reach high yield and WUE based on model simulation . This model has been well evaluated in terms of simulating water balance and crop production in many previous studies in many different field conditions. Used in simulating various variables (e.g., crop production, energy balance, water stress, crop response to climate change under full and deficit irrigation) for conditions prevailing in Colorado (Qi et al., 2016), the RZWQM2 model showed itself capable of estimating the effects of water stress on yield, water and energy balances. The model was also used to develop new crop cultivars (Ma et al., 2017). In the US Central Great Plains, Saseendran et al. (2013) employed RZWQM2 model to simulate the long-term yield response of several plants under various levels of soil available water at planting, and then used the results to assess the crops' potential to increase cropping frequency in a wheat-fallow rotation system. Their results showed RZWQM2 to be accurate in simulating soil moisture, crop production and water balance; however, it has never been evaluated under an extremely arid climate. Accordingly, in the present study, the model was evaluated against data collected from an extremely arid oasis in Xinjiang.

Water stress as simulated using RZWQM2 can be potentially used to trigger irrigation; thereby informing the development of an optimal irrigation schedule. Fang et al. (2007) demonstrated that wheat grain yield and WUE were significantly affected by crop water stress. Bausch et al. (2011) employed the ratio of stressed to non-stressed canopy temperature to quantify crop water stress. However, this method requires the co-existence of both full- and deficit-irrigation treatments. A recent study showed that water stress and crop yield response to water stress can be accurately simulated using a well-calibrated RZWQM2 model (Qi et al., 2016), and that these could, in turn, serve in irrigation scheduling, resulting in water savings for a corn field in Colorado (Gu et al., personal communication, 2017). As no well-defined irrigation scheme exists for cotton cultivation in Xinjiang, the present study was designed to (i) to evaluate the applicability of the RZWQM2 model in simulating soil moisture, cotton yield, phenology and water balance under extremely arid condition, and (ii) to develop an optimal irrigation strategy based on simulated crop water stress, using the calibrated RZWQM2 model.

3.3 Materials and Methods

3.3.1 Research site description and measurements

Located in a warm temperate continental desert climate district situated in the center of the Eurasian continent (36°59′ N, 80°48′ E), the Cele oasis constitutes an extremely arid environment, with sparse precipitation, adequate light, a large diurnal temperature range, but also a long frost-free period (210 days) conducive to the growth of various crops, and relatively abundant light and heat resources (Zeng, 1999). The long-term mean air temperature is 11.9 °C, and the percentage of available sunshine days exceeds 60%. The main type of the surface soil in the oasis farmland is sandy loam soil (classification standard defined by USDA) (Zeng et al., 2010). Cotton fields in the Cele district are irrigated with Cele river floodwaters or underground water (Li et al., 2011).

The long term (1960-2007) mean precipitation at the Cele oasis meteorological station is 37 mm y^{-1}, while E-pan is 2729 mm y^{-1}. The high potential evaporation capacity and limited precipitation often leads to low soil moisture (θ) conditions. Agriculture is the main economic driver in the Cele oasis ecosystem region, with the agriculture accounting for 65.63% of the output value of total economy in this area. Cotton is one of the most important cash crops in the Cele oasis.

The rectangular experimental plot measures 150 m (north-south) ×140 m (east-west) and was planted with cotton. Planting density was 23~45 plants per square meter with the maximum plant height approximately 75 cm and rooting depth of 100 cm. The experimental field was equipped with neutron probe (CNC100, Probe Science & Technology Ltd., Beijing, China, was previously calibrated for the studied soil) access tubes to measure volumetric θ. Two access tubes were installed in this field along the east-west center line. Each tube was about 35 m from the edge and the center of field, representing one side of the field. Volumetric water content (θ) was measured every 0.10 m to a depth of 0.60 m, and then every 0.20 m to a depth of 1.00 m every 5 days from 1 January 2007 to 31 December 2013. Measured θ from two tubes were averaged to represent the soil water regime in research field, where the water table depth exceeded 15 m, so groundwater had little if any impact on θ in the upper layers of the agricultural soil (Gui et al. 2009).

The timing of phenological stages of cotton and estimation of seed yield were conducted in this field during the growth period and after harvest, respectively, during every year from 2006 to 2013. The cultivars Ceke No.1 and Xinlu No.21 were grown in 2006-2011 and 2012-2013, respectively. Field management information such as planting and harvest dates, fertilization, irrigation data were also recorded. Flood irrigation was used in this field and ridges were made in this field for a more uniform application of flood irrigation. The timing and amount of irrigation are listed in Table 3-1. Meteorological data, including air temperature, wind speed, radiation, evaporation-pan, relative humidity, photosynthetically active radiation (PAR), and rainfall was collected hourly at a meteorological station situated 20 meters away from the research site. To determine yield, cotton in four randomly selected 1.0 m × 1.0 m squares was sampled. Total cotton, separated fiber and seed were dried at 60°C for 3 days prior to weighing. Only the seed's yield was used to calibrate and validate the model.

Table 3-1 Irrigation amount and frequency in the cotton field from 2006 to 2013

year	Irrigation practices	1	2	3	4	5	6	7	Total
2006	Date	01/Mar	01/Jun	14/Jun	30/Jun	17/Jul	02/Aug	25/Aug	7 times
	Irrigation Amount (cm)	15	12	12	12	12	12	12	87
2007	Date	01/Apr	08/Jun	27/Jun	15/Jul	05/Aug	25/Aug		6 times
	Irrigation Amount (cm)	15	9	9	9	9	9		60
2008	Date	02/Apr	14/Jun	27/Jun	28/Jul	07/Aug			5 times
	Irrigation Amount (cm)	15	9	9	9	9			51

2009	Date	03/Apr	29/May	14/Jun	27/Jun	28/Jul	21/Aug	6 times
	Irrigation Amount (cm)	15	12	12	12	12	12	75
2010	Date	07/Apr	14/Jun	03/Jul	15/Jul	13/Aug	04/Sep	6 times
	Irrigation Amount (cm)	15	10	10	10	10	10	65
2011	Date	15/Apr	08/Jun	26/Jun	18/Jul	17/Aug	13/Sep	6 times
	Irrigation Amount (cm)	15	10	10	10	10	10	65
2012	Date	11/Apr	03/Jun	26/Jun	12/Jul	03/Aug	23/Aug	6 times
	Irrigation Amount (cm)	15	10	10	10	10	10	65
2013	Date	16/Apr	19/Jun	02/Jul	20/Jul	16/Aug		5 times
	Irrigation Amount (cm)	15	10	10	12	12		59

3.3.2 RZWQM description

The Root Zone Water Quality Model 2 (RZWQM2), developed by USDA-Agricultural Research Service (ARS), is a one-dimensional model which includes modules for hydrology, energy balance, water quality, and crop growth. It has gained wide popularity in developing and evaluating management practices (Ma et al., 2012). The DSSAT crop models were incorporated into RZWQM2 to better simulate crop growth and development (Jones et al., 2003; Ma et al., 2006a; Ma et al., 2006b). More functions have been incorporated into RZWQM2 over the years, and the model can now be applied in simulating evapotranspiration, infiltration and soil water redistribution, subsurface drainage, organic matter and nutrient (N) cycling, as well as fate and transport of pesticides. Ma et al. (2012b) verified the feasibility of the application of RZWQM2 in simulating the response of maize growth to irrigation in Colorado, central great plain in America and conclude that the parameterized RZWQM2 was capable of emulating crop growth under different irrigation treatment and the results could be used to schedule irrigation. Sassendran et al. (2010) used RZWQM2 to simulate biomass and yield based on 14 years of data for 3 crops rotation, to predict the rotation effect on crop production under semiarid condition. Qi et al (2013) quantified the influences of management practices and tillage on soil moisture and crop production based on the simulated results of RZWQM2 and extended this results to different meteorology and management condition.

In order to simulate water transport in RZWQM2, water flow has been divided into two phases. The infiltration caused by rainfall or irrigation is modeled based on Green-Ampt approach (Ahuja et al., 1995).

$$V = \overline{K}_s \, \frac{\tau_c + H_0 + Z_{wf}}{Z_{wf}} \quad (1)$$

where

V is the infiltration rate (cm/hr),
$\overline{K}_s$ is the saturated hydraulic conductivity (cm/hr),
τ_c is capillary suction head (cm),
H_0 is depth of ponding (cm), and
Z_{wf} is depth of wetting front (cm)

The water redistribution in the soil profile after infiltration is calculated by Richard's equation (Celia et al., 1990).

$$\frac{\partial \theta}{\partial z} = \frac{\partial}{\partial z}\left[K(h,z)\frac{\partial h}{\partial z} - K(h,z)\right] - S(z,t) \quad (2)$$

where

θ is the volumetric soil water content (cm3/cm3),
z is soil depth (cm),
h is the matric water head (cm),
K is hydraulic conductivity (cm/hr), and
t is time (hr)

RZWQM utilizes ET modeling methodology to simulate potential evaporation on bare soil surface and transpiration if canopy using minimal surface resistances. Canopy and bare soil surface were divided into two layers in the ET model (Farahani and Ahuja, 1996), and the sum of latent heat for transpiration (λT) and evaporation (λE_s) is regarded as potential evapotranspiration, which is estimated by ET model using revised form of Penman-Monteith (P-M) ET equation (Shuttleworth and Wallace, 1985), written as:

$$\lambda ET = \lambda T + \lambda E_s \quad (3)$$

and in equation (4), λT and λE_s can be expressed as:

$$\lambda T = \frac{\Delta[(R_n - G) - R_{nsub}] + \rho c_p (VPD)/r_a}{\Delta + \gamma(1 + \frac{r_s}{r_a})} \quad (4)$$

and

$$\lambda E_s = \frac{\Delta(R_{ns} - G_s) + \rho c_p (VPD)/r_a}{\Delta + \gamma(1 + r_s/r_a)} \quad (5)$$

where

R_n, G are net radiation and soil heat flux respectively ($W\ m^{-2}$),
Δ is the rate of saturated vapor pressure change at certain temperature ($kPa\ °C^{-1}$),
R_{nsub} is net radiation below the canopy ($W\ m^{-2}$),
ρ is the air density ($kg\ m^{-3}$),
c_p is the specific heat of moist air ($J\ kg^{-1}\ °C^{-1}$),
VPD is the vapor pressure deficit measured at a reference level (kPa),
γ is the psychrometric constant ($kPa\ °C^{-1}$),
r_s, r_a are resistance from canopy and bulk boundary layers respectively ($s\ m^{-1}$), and
R_{ns}, G_s are net radiation and soil heat flux on bare soil surface respectively ($W\ m^{-2}$)

3.3.3 Model input, calibration and validation

RZWQM2 was executed using hourly meteorological data from 2007 to 2013. Other input data included soil property data (bulk density and soil particle distribution) and field management data (crop planting, irrigation, fertilization). The initial values for the soil hydraulic parameters were estimated based on soil texture and bulk density (Schaap and Leij, 1998) and the range for each parameters based on sandy loam is given by Rawls et al. (1982). Subsequently those parameters were calibrated manually against observed θ in different layers. The θ data for year 2009, 2010 and 2013 were used for calibration and the data for other years used for validation. The soil property information together with calibrated soil hydraulic parameters are listed in Table 3-2.

Crop growth and development parameters were manually calibrated against observed phenology dates and yield （2006 to 2013）following the protocol suggested by Ma et al. (2011). Data for 2009, 2010 and 2013 were chosen for calibration and the other years for validation. Available plant development-related data included planting date, flower emergence date, flowering date, boll cracking date and harvest date. The two cultivars planted, Ceke No.1 and Xinlu No. 21, were simulated using initial parameters of HO0001 ACALA SJ-2CDM and GA0002 Georgia King in the incorporated DSSAT crop models, respectively. The crop parameters were manually calibrated against observed phenological dates and yield. The calibrated crop parameters for the two cultivars are listed in Table 3-3.

Table 3-2 Observed soil properties and calibrated soil hydraulic parameters

Layer	ρ (Mg m^{-3})	Soil texture %			$ksat$ (mm d^{-1})	λ	p_b (cm)	Soil moisture (m^3 m^{-3}) at different matric potentials				
		sand	silt	clay				$\theta_{sat}, \psi_m = 0$	$\theta_{fc*}, \psi_m = -10$ kPa	$\theta_{fc}, \psi_m = -33$ kPa	$\theta_{pwp}, \psi_m = -1500$ kPa	$\theta_r, \psi_m = -\infty$
0-15	1.40	66.10	25.00	8.90	2.59	0.569	71.240	0.300	0.214	0.122	0.0387	0.028
15-30	1.45	65.35	27.70	6.95	2.59	0.472	36.529	0.353	0.257	0.161	0.0558	0.035
30-60	1.45	64.79	25.55	9.66	2.59	0.422	43.801	0.323	0.255	0.167	0.0643	0.041
60-90	1.48	67.60	24.54	7.86	2.59	0.578	67.722	0.403	0.331	0.188	0.0608	0.045
90-120	1.43	65.89	24.14	9.97	2.59	0.661	68.070	0.403	0.332	0.188	0.0577	0.041

ρ = bulk density; sand, silt, clay by USDA particle size range standard; k_{sat} = soil saturated hydraulic conductivity; λ = Brooks-Corey pore size distribution inde;. pb = bubbling pressure; θ_{sat} = saturated soil moisture content; θ_{fc*}= soil moisture at field capacity, sandy soil ($\psi_m = -10$ kPa); θ_{fc}= soil moisture at field capacity, standard soil; θ_{pwp}= soil moisture content at permanent wilting point; θ_r= residual water content.

Table 3-3 Calibrated crop development parameters for two cotton cultivars

Paramete	Description	Calibrated value	
		Ceke	Xinlu 21
EM-FL	Time between plant emergence and flower appearance (days)	36	35
FL-SH	Time between first flower and first pod (days)	5	11
FL-SD	Time between first flower and first seed (days)	10	17
SD-PM	Time between first seed and physiological maturity (days)	30	25
FL-LF	Time between first flower and end of leaf expansion (days)	47	51
LFMAX	Maximum leaf photosynthesis rate at 30 C, 350 vpm CO_2, and highlight (mg CO_2/m^2-s)	1.2	1.3
SLAVR	Specific leaf area of cultivar under standard growth conditions (cm^2/g)	200	220
SIZLF	Maximum size of full leaf (cm^2)	240	250
XFRT	Maximum fraction of daily growth that is partitioned to seed + shell	0.67	0.85
WTPSD	Maximum weight per seed (g)	0.2	0.2
SFDUR	Seed filling duration for pod cohort at standard growth conditions (days)	18	18
SDPDV	Average seed per pod under standard growing conditions (#/pod)	15	20
PODUR	Time required for cultivar to reach final pod load under optimal conditions (days)	8	8

Since there is no field observed cotton evapotranspiration to evaluate the model simulated actual ET, the cotton ET was estimated based on the neutron probe measured soil water depletion over effective root zone soil depth. The equation was applied to calculate cotton ET (mm) as follow (Jensen et al.,1990):

$$ET = \sum_{i=1}^{n}(\theta_1 - \theta_2)\Delta S_i + I + R \quad (6)$$

where,

n is the number of soil depth increments (mm),

θ_1 and θ_2 are the volumetric soil water content in two separate sampling dates at soil depth I (cm^3 cm^{-3}).

ΔS_i is the thickness of each depth increments (mm),
I is the depth of irrigation applied between the two sampling dates (mm), and
R is the depth of precipitation occurred between two sampling dates (mm)

The maximum effective root zone soil depth was assumed to be 1.8 m (Bucks et al., 1988), and we also assumed tht there was no deep seepage beyond 1.8m soil depth. Other details are described by Hunsaker et al. (1994).

In this study, percent bias (PBIAS), coefficient of determination (R2), Nash-Sutcliffe model efficiency (ME), root mean squared error (RMSE) were applied to evaluate the performance of model simulation for soil water content, while for cotton yield the relative error (RRMSE) was also used.

$$\mathrm{PBIAS} = \frac{\sum_{i=1}^{n}(S_i - O_i)}{\sum_{i=1}^{n} O_i} \tag{7}$$

$$R^2 = \frac{[\sum_{i=1}^{n}(O_i - \bar{O})(S_i - \bar{S})]^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2 \sum_{i=1}^{n}(S_i - \bar{S})^2} \tag{8}$$

$$\mathrm{ME} = 1.0 - \frac{\sum_{i=1}^{n}(S_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \tag{9}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - O_i)^2} \tag{10}$$

$$RRMSE = \frac{RMSE}{\bar{O}} \tag{11}$$

where,
n is the total number of items in the data set,
$\bar{O}$ and $\bar{S}$ are the average measured and simulated values, respectively,
O_i is the i^{th} measured value, and
S_i is the i^{th} simulated value.

Model performance is considered acceptable if -15% < PBIAS < 15%, R2 > 0.70, ME > 0.5, and RRMSE < 30% (Hanson et al., 1999; Ahuja et al., 2000; Moriasi et al., 2007) . For soil water content, the statistics above were compared with values in other similar studies. There was only one yield value for each year in the total 8 years, we choose year 2009, 2010 and 2013 with relatively high production to do calibration and other years to do validation. For the phenology dates, only difference between simulated and observed dates were compared.

3.3.4 crop water requirement

The PET simulated by the calibrated RZWQM2 model during the growing season (from planting to 90% boll open) was treated as the crop water requirement. The water balance components, including soil evaporation, plant transpiration, and deep seepage were analyzed to investigate soil water loss under flood irrigation.

3.3.5 Water stress (WS-) based irrigation scheduling method

The optimum irrigation schedule was generated using the calibrated RZWQM2 model through which the simulated water stress index was used to trigger irrigation. Namely, when the model predicted any water stress, irrigation would be applied to free the water stress, and the application rate was computed by the model to replenish the soil to θ_{fc}. The water stress index used is the turgor factor (*TURFAC*) which is generated by the DSSAT-CSM crop growth model embedded in RZWQM2. *TURFAC* describes the level of plant water stress and relates to the expansion of plant leaf cells. It is calculated as (Saseendran et al., 2015; Saseendran et al., 2014):

$$TURFAC = \frac{RWU}{RWUEP1 \cdot T_{\mathrm{p}}^{SW}} \tag{13}$$

where,

T_{p}^{SW}	is the potential transpiration computed using the Shuttleworth-Wallace method in the model (mm),
RWU	is the DSSAT potential root water uptake (mm), and
$RWUEP1$	is a species-specific parameter used for evaluating water stress impact on expansion growth of cells (set at 1.5 for cotton).

Water stress occurs when *RWU* (supply) is not sufficient for crop T_{p}^{SW} (demand) estimated by the Shuttleworth-Wallace model. The value of *TURFAC* ranges from 0.0 (zero) for a fully water stressed condition, to 1.0 for a water stress free condition. Once the water stress has occurred, the quantity of water to apply was calculated as:

$$IR_{t_0} = \left(\theta_{\mathrm{fc}} - \theta_{t_0}\right) \cdot RD_{t_0} \tag{14}$$

where,

θ_{fc} is the volumetric soil water content at field capacity across the full root zone (m^3 m^{-3}),

$\theta_{\mathrm{t_0}}$ is the volumetric soil water content across the root zone on the day of irrigation (m^3 m^{-3}),

$\mathrm{IR_{t_0}}$ is the required irrigation water supply required on the day of irrigation (t_0) (mm), and

$\mathrm{RD_{t_0}}$ is the simulated crop rooting depth on the day of irrigation (mm), and is retrieved from the model output.

The θ_{fc} and θ_{t_0} were calculated as weighted average:

$$\theta_{\mathrm{fc}} = \frac{\sum_{j=1}^{j=N}\left(\theta_{\mathrm{fc}}^{j} \cdot D_j\right)}{\sum_{j=1}^{j=N} D_j} \tag{15}$$

$$\theta_{t_0} = \frac{\sum_{j=1}^{j=N}\left(\theta_{\mathrm{sim}}^{j} \cdot D_j\right)}{\sum_{j=1}^{j=N} D_j} \tag{16}$$

where,

D_j is the depth of j^{th} layer of the root zone (mm),

N represents the number of layers in the root zone on the day of irrigation,

θ_{fc}^{j} is the soil water content at field capacity (m^3 m^{-3}) of the j^{th} layer, and

θ_{sim}^{j} is the simulated soil water content (m^3 m^{-3}) of the j^{th} layer on the day of when irrigation is required.

According to simulations run under irrigation treatments observed in the field, the growth of cotton almost ends after the growth stage “90% open boll” is reached. Under optimal irrigation scheduling, water application ends after the simulated “90% open boll” occurred. Irrigations applied prior to the planting date (pre-irrigations) were kept unchanged in the optimization. The minimum irrigation depth for each event was set to 50 mm, a practical number for flood irrigation in this sandy soil area.

Developed to facilitate the optimization process, a Java computer program package was designed to run the model automatically, then extract the simulated results and derive irrigation events before “90% open boll” in DSSAT using the method described. The Java program then wrote the derived irrigation event into the RZWQM2 input file automatically and run the model once again. This process was repeated until no water stress occurred before “90% open boll”.

Irrigation water use efficiency (IWUE), representing the effectiveness of irrigated water in generating yield was calculated as:

$$IWUE = \frac{Y - Y_o}{I_w} \quad (17)$$

where,

I_w	is the amount of irrigation water (mm).
IWUE	represents irrigation water use efficiency (kg ha^{-1} mm^{-1}), and
Y and Y_o	are the yield under irrigation management and under rain fed production, respectively (kg ha^{-1}).

The water savings ratio, yield increase and IWUE increase under irrigation management (*vs.* rain fed production) were calculated as follows:

$$\Delta I = (I_{FO} - I_{WS})/I_{FO} \quad (18)$$

$$\Delta Y = (Y_{WS} - Y_{FO})/Y_{FO} \quad (19)$$

$$\Delta IWUE = (IWUE_{WS} - IWUE_{FO})/IWUE_{FO} \quad (20)$$

where,

ΔI, ΔY, and $\Delta IWUE$	are irrigation water savings ratio (%), yield increase (%) and IWUE increase (%) respectively,
I_{FO}, Y_{FO}, $IWUE_{FO}$	are, respectively, irrigation water quantity (mm), yield (kg ha^{-1}) and IWUE (kg ha^{-1} mm^{-1}) measured under current irrigation management practices, and
I_{WS}, Y_{WS}, $IWUE_{WS}$	are irrigation water quantity (mm), yield (kg ha^{-1}) and IWUE (kg ha^{-1} mm^{-1}) simulated as occurring under the WS-based irrigation method, respectively.

Where, ΔI, ΔY, $\Delta IWUE$are irrigation water savings ratio (%), yield increase (%) and IWUE increase (%) respectively, I_{FO}, Y_{FO}, $IWUE_{FO}$ are irrigation water quantity (cm), yield (kg/ha) and IWUE (kg ha^{-1} cm^{-1}) under field observed irrigation managements respectively I_{WS}, Y_{WS}, $IWUE_{WS}$ are irrigation water quantity (cm), yield (kg ha^{-1}) and IWUE (kg ha^{-1} cm^{-1}) under the WS-based method, respectively.

3.4 RESULTS AND DISCUSSION

3.4.1 Soil water content and crop growth simulation

The statistical parameters to evaluate the model performance in simulating θ are presented in Table 3-4. For all soil layers, both calibration and validation phase simulated θ showed an acceptable level of agreement with observed data ($PBIAS < \pm 15\%$; $0.378 \leq R^2 \leq 0.615$; $0.314 \leq ME \leq 0.557$; $0.023 \leq RMSE \leq 0.033$ for calibration and $PBIAS < \pm 10\%$; $0.500 \leq R^2 \leq 0.636$; $0.130 \leq ME \leq 0.448$; $0.022 \leq RMSE \leq 0.026$ for validation). Although these statistics did not meet the satisfactorily criteria in particular for the top layers, but given the difficulty in simulating soil water content, our simulation is comparable to those obtained in research conducted on the north China plain (Fang et al., 2014a), where the ME was $-0.44 \leq ME \leq 0.25$ and $0.30 \leq R^2 \leq 0.66$ across different layers; and the results from Fang et al. (2014b), where ME vary from -2.263 to 0.203. The statistics of rRMSE for different soil layers are mostly with the criteria 'satisfactory', which vary from 0.183 to 0.525.

Table 3-4 Statistics for observed and simulated values of soil moisture and evaluation parameters

Depth	Calibration phase							Validation phase						
(m)	Obs.	Sim.	PBIAS	R^2	ME	RMSE	rRMSE	Obs.	Sim.	PBIAS	R^2	ME	RMSE	rRMSE
0.10	0.059	0.058	0.016	0.378	0.314	0.031	0.525	0.065	0.059	0.092	0.500	0.448	0.022	0.338
0.20	0.073	0.082	-0.123	0.538	0.330	0.025	0.342	0.081	0.087	-0.078	0.537	0.306	0.026	0.321
0.30	0.084	0.088	-0.046	0.602	0.433	0.023	0.274	0.089	0.093	-0.044	0.605	0.439	0.022	0.247
0.40	0.096	0.095	0.011	0.594	0.470	0.023	0.240	0.099	0.102	-0.034	0.597	0.413	0.023	0.232
0.50	0.106	0.099	0.067	0.615	0.510	0.024	0.226	0.108	0.106	0.016	0.513	0.310	0.025	0.231
0.60	0.111	0.100	0.093	0.594	0.453	0.024	0.216	0.116	0.107	0.072	0.636	0.412	0.022	0.190
0.80	0.126	0.121	0.042	0.451	0.349	0.033	0.262	0.126	0.121	0.016	0.612	0.340	0.023	0.183
1.00	0.121	0.127	-0.051	0.592	0.557	0.026	0.215	0.130	0.135	-0.039	0.594	0.130	0.024	0.185

Obs., observed mean (m^3 m^{-3}); Sim., simulated mean (m^3 m^{-3}); *PBIAS*, percent bias; R^2, coefficient of determination; *ME*, Nash-Sutcliffe model efficiency.

Since there was no recharge from groundwater, precipitation and irrigation were the main source of moisture in this district. For the upper soil layers, simulated θ values tend to have sharper peaks (Figure 3-1), which may because of a lower θ_{fc} (Table 3-2), and therefore lesser water storage. The θ showed a roughly increasing trend within each soil increment from the surface to a 1.00 m depth, indicating a better water retention capacity in the deeper soil profile. Such results have also been observed and explained in Li et al. (2010), whose study was conducted in neighboring farmland.

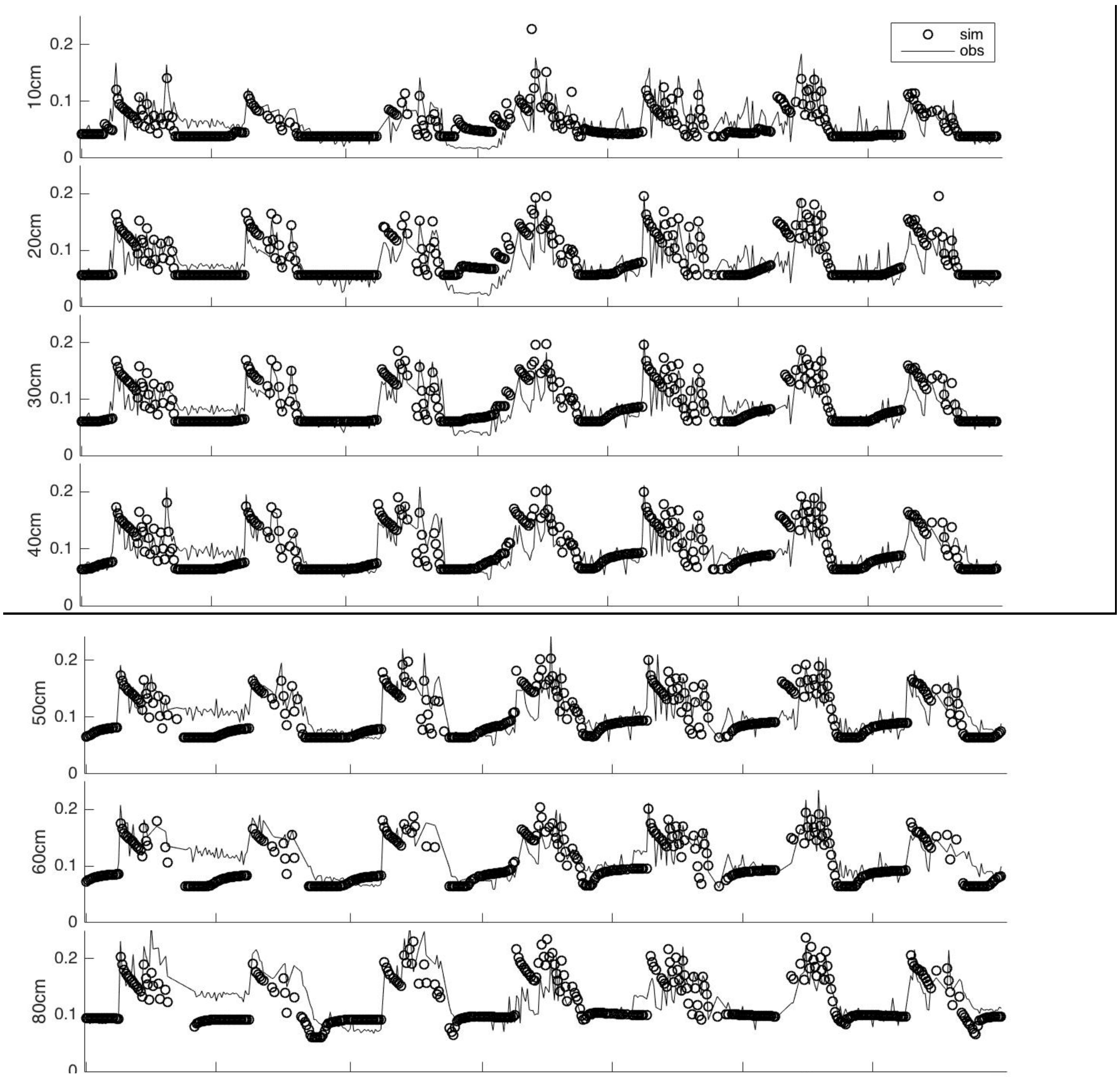

Figure 3-1 Simulated and observed soil water content within 0 to 1m soil depth, 2007 to 2013

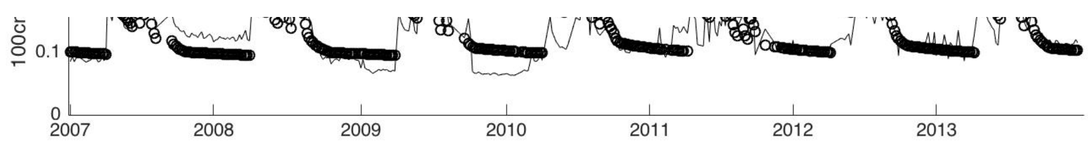

Figure 3-1 Simulated and observed soil moisture content within 0 to 100 cm soil depth from 2007 to 2013

Table 3-5 Simulated and observed plant development stages (unit: day of year)

Cultivar	Year	Planting	Plant development stage						
			Emergence		Flowering		Bolls cracked		Harvest
			obs	sim	obs	sim	obs	sim	
Ceke 1	2006	94	104	115	187	169	229	225	300
	2007	100	106	110	164	164	221	221	297
	2008	99	108	116	167	167	217	222	302
	2009	100	107	112	173	173	229	228	297
	2010	104	108	120	173	183	232	239	298
	2011	109	117	119	196	174	237	230	288
Xinlu 21	2012	106	118	122	176	179	241	241	310
	2013	110	118	126	187	183	239	246	314
Average		102.7	110.75	117.50	177.88	174.00	230.63	231.50	300.75

With the exception of the emergence dates, simulated dates for phenological stages (Table 3-5) were, in general, within 4 days of observed dates. The simulated results for ‘flowering’ and ‘bolls cracked’ dates were satisfactory, with average deviations of -3.9 day and 0.9 day, respectively. Simulated emergence dates were on average 6 days later than those of observed dates. This can be explained by the fact that through heat conservation plastic mulch accelerated germination, whereas RZWQM is as yet unable to simulated mulching. Notably, in 2006 and 2011, simulated flowering dates were significantly earlier than the observed dates, which may be the result of an inaccurate assessment of phenological stage in these years.

The cotton seed yield was in general adequately simulated (PBIAS = -0.0125; R^2 = 0.80; ME = 0.75) from 2006 to 2013. The RMSE and RRMSE values for yield simulation were 415.0 kg ha^{-1} and 12.5% respectively, values similar to those reported by Anapalli et al. (2016), where the RMSE and RRMSE were 333 kg ha^{-1} and 14%, respectively. Specifically, the results for calibration years (PBIAS = -0.0657; R^2 = 0.91; ME = 0.74; RMSE = 476.9 kg ha^{-1}, rRMSE = 11.8%) are better than those of validation years

(PBIAS = 0.0560; R^2 = 0.77; ME = 0.76; RMSE = 373.0 kg ha^{-1}, rRMSE = 12.9%. The significant overestimation (+37.6%) of yield in 2008 (Table 3-6), might be attributable to the milder weather conditions and relatively lower ET_p in 2008 (Table 3-7). Moreover, the total depth of irrigation in 2008 was 36 mm, much lower than other years. Although no observations of water stress were made, presumably a crop growing under a relatively high water stress would show a significant yield loss. The fact that simulated yield reduction in 2008 was not as great as that observed may suggest that the modeled response of cotton yield to high water stress needs further investigation. In general, the results indicated that RZWQM2 was capable of simulating crop phenology and yield under the extremely arid climate at the research site.

Table 3-6 Simulated and observed cotton seed yield and yield difference from 2006 to 2013

Cultivar	year	Yield（kg ha^{-1}）		Yield difference (%)
		Obs	Sim	
Ceke No. 1	2006	2857	3171	11.0
	2007	2716	2554	-5.8
	2008	1932	2659	37.6
	2009	3226	3495	8.3
	2010	4344	3953	-9.0
	2011	3067	2891	-5.7
Xinlu No. 21	2012	3880	3987	2.6
	2013	4570	3894	-14.8

3.4.2 Simulated crop water requirement

In order to understand irrigation efficiency and optimize irrigation practices, the distribution of water was analyzed. The soil water balance equation was applied as follow.

$$\Delta S = P + I - (R + AET + D_S + D_t) \quad (21)$$

where,

ΔS is the change of soil water storage in the soil profile (cm),

P is the cumulative precipitation (cm), I is the cumulative irrigation (cm),

R is the cumulative runoff (cm),

AET is cumulative actual evapotranspiration (cm),

D_S is cumulative deep seepage out of the soil profile (cm), and

D_t is the cumulative water loss to tile drain (cm).

The water flow within the macropore was negligible in this study. The changes of water storage in the soil profile and water distribution portions during cotton growing season (from plant to 90% bolls cracked) are showed in Table 3-7. The model-simulated water balance components (Table 3-7), excluding surface runoff which was zero for all the years due to the oasis soil's sandy texture and high k_{sat} (Table 3-2), show irrigation to be the main water input, a large portion of which is lost to *ET*. Crop water requirements, which are equivalent to ET_p, were 613 mm during the cotton growing season. Under crop management conditions based on farmer experience, about 496 mm of water were applied. Taking the mean growing season rainfall of 33.5 mm into account, an additional 83.5 mm water should be applied to meet the crop water requirements. According to the simulation, under current flood irrigation practices, a significant quantity of water — 100.9 mm y^{-1}, on average, 19.0% of the overall water supply was wasted through deep seepage.

The simulation showed a reasonable cotton water requirement compare to other studies. From the analysis of water supply, the simulated ET_a for the crop growing period represented from 69.7% to 98.6% of ET_p, with an average of 85% (ET_a = 522 mm). The ET_a values derived in the present study are similar to SWAT-simulated ET_a values (≈600 mm) obtained by Dourte et al. (2016) for a site in north Florida between 2002 to 2013.

Table 3-7 Portion of components in water balance equation during crop developing season (from planting to 90% bolls open) from 2006 to 2013.

Year	Water balance parameter* (mm)										
	ΔS	P	I	D_s	E_a	T_a	ET_a	E_p	T_p	ET_p	D
2006	-102.34	14.0	720	143.4	169	528	697	446	554	1001	304
2007	-66.03	14.0	450	22.8	78	430	509	173	483	656	147
2008	-114.76	34.6	360	24.6	74	412	486	125	462	587	101
2009	-40.63	37.4	600	146.7	85	447	532	116	493	609	76
2010	-78.38	78.6	500	156.9	84	416	501	94	421	515	14
2011	-133.36	3.0	400	56.4	67	414	481	93	439	532	51
2012	-70.76	58.0	500	142.5	69	418	487	76	418	493	7
2013	-124.60	28.6	440	113.8	64	417	480	77	431	509	29
Mean	-91.34	33.5	496	100.9	86	436	522	150	463	613	91

* D_S, cumulative deep seepage out of the soil profile; D, difference between ETp and ETa; D_t, cumulative water loss to tile drain; E_a, cumulative actual evaporation; E_p, cumulative potential evaporation; ET_a, cumulative actual evapotranspiration; ET_p, cumulative potential evapotranspiration; I, cumulative irrigation; P, cumulative precipitation; ΔS, change of soil water storage in the soil profile; Ta, cumulative actual transpiration; Tp, cumulative potential evaporation. The *I* in this table did not include the Pre-irrigation before plant (15cm for each year) and the irrigation after 90% open boll in 2011(10cm).

The model-simulated water balance components (Table 3-7), excluding surface runoff which was zero for all the years due to the oasis soil's sandy texture and high k_{sat} (Table 3-2), show irrigation to be the main water input, a large portion of which is lost to *ET*. Crop water requirements, which are equivalent to ET_p, were 613 mm during the cotton growing season. Although the field observed *ET* was not recorded to do the validation, this simulated cotton water requirement is very close to the results of the research conducted in south of Xinjiang, with water demand of cotton is 625mm (Liu et al., 2006). Under crop management conditions based on farmer experience, about 496 mm of water were applied. Taking the mean growing season rainfall of 33.5 mm into account, an additional 83.5 mm water should be applied to meet the crop water requirements. According to the simulation, under current flood irrigation practices, a substantial quantity of water — 100.9 mm y^{-1}, on average, 19.0% of the overall water supply was wasted through deep seepage.

The simulation showed a reasonable cotton water requirement compare to other studies. From the analysis of water supply, the simulated ET_a for the crop growing period represented from 69.7% to

98.6% of ET_p, with an average of 85% (ET_a = 522 mm).

In the present study, there were more substantial differences between ET_p and ET_a in the first three years (2006-2008) when water stress was suspected. The relatively lower observed yield and the simulated lower ET_a to ET_p ratio confirmed this suspicion. In contrast, the years with higher production had relatively lesser differences between ET_p and ET_a, suggesting that water applied may have closely meet the crop water requirement.

The simulation further suggests that, although rainfall was consistently low over all years, the variation in other climatic components (*e.g.*, solar radiation and relative humidity) may result in significantly different crop water requirements under an extremely arid climate. Using 2006 as an example, the irrigation depth was the greatest across all years, whereas yield was not correspondingly high, indicating that the quantity of irrigation alone did not meet crop water requirements, which were also greatest across all years. It also justifies the idea that if a long-term field experiment if not available, a long-term simulation is likely to be more reliable than one-year field study when determining irrigation water requirement for a crop.

3.4.4 optimum irrigation scheduling

A water stress-based irrigation scheduling method based on RZWQM2-simulated water stress was applied to optimize the irrigation schedule. The original field records and optimized data are presented in Table 3-8 and Figure 3-2. In general, this irrigation optimization approach suggests that applying 616 mm water to the cotton crop over the growing season, allowed the crop to achieve its highest yield potential (3.777 Mg ha^{-1}). The optimized irrigation treatment results in almost the same yield as the standard practice in 2006, 2010, 2012 and 2013, and provided 26.5% and 42.3% greater yields in 2011 and 2008, respectively. The quantity of model-suggested irrigation water applications was lower than the amount applied under standard practices in 2012 and 2013 (-22.9% and -2.6%, respectively), but higher in 2007 (+14.9%) and 2008 (+32.5%). Across all 8 years, the optimized irrigation resulted in an increase in IWUE ranging from 2.4% (2013) to 50.9% (2009), with a mean increase of 23.4%. Even for the years with no yield increase or water savings under the optimized irrigation scheduling, IWUE was also improved (Table 3-9), indicating that the traditional irrigation regime either applied insufficient water, resulting yield loss, or applied more water than the crop required to obtain a high yield. The water stress-based method proved to be an efficient way to schedule — based on a calibrated RZWQM2 model — a high-yield and water-saving irrigation regime.

Table 3-8 Comparison of the irrigation and yield response between FO and WS-based irrigation treatments

Year	Traditional irrigation regime			RZWQM2-derived water stress-based irrigation regime*		
	Irrigation (mm)	Seed Yield (Mg ha^{-1})	IWUE (kg ha^{-1} mm^{-1})	Irrigation / ΔI (mm / %)	Yield / ΔY (Mg ha^{-1} / %)	IWUE / $\Delta IWUE$ (kg ha^{-1} mm^{-1} / %)
2006	870	3.171	3.40	760 / 12.6	3.181 / 0.3	3.91 / 14.8
2007	600	2.554	4.25	689 / -14.9	3.310 / 29.6	4.80 / 12.9
2008	510	2.659	5.12	676 / -32.5	3.785 / 42.3	5.53 / 8.0
2009	750	3.495	4.65	636 / 15.2	4.471 / 27.9	7.03 / 50.9
2010	650	3.953	5.57	522 / 19.7	3.950 / -0.1	6.93 / 24.5
2011	650	2.891	4.45	570 / 12.4	3.656 / 26.5	6.42 / 44.3
2012	650	3.987	6.00	501 / 22.9	3.981 / -0.2	7.76 / 29.5
2013	590	3.894	6.58	574 / 2.6	3.882 / -0.3	6.74 / 2.4
Mean	659	3.326	5.00	616 / 4.7	3.777 / 15.8	6.14 / 23.4

* based on TURFAC, Eq. 7. $IWUE$, irrigation water use efficiency, Eq. 11; ΔI, ΔY and $\Delta IWUE$, percent irrigation water saving, percent yield increase, and percent $IWUE$ increase, Eqs. 12, 13, 14, respectively.

With 62 irrigation events under the water stress-based method (Figure 3-2), compared to 47 events under standard practices, water stress prior to crop stage “90% open boll” was eliminated in all 8 years. Although the irrigation frequency was higher under the water stress-based method, namely on average 8 extra irrigation events per year, water applied during each event was decreased to strictly the amount (> 50 mm) required to replenish the soil in the root zone to θ_{fc}. This amount ensured crop water requirements while minimizing deep seepage. Water quantity at each event under the standard irrigation operations was apparently greater than the capacity of the soil in the root zone; therefore, excessive applied irrigation water was wasted through deep seepage.

For the years 2006, 2010, 2012 and 2013, yield remained largely unchanged when shifting from a standard to a water stress-based irrigation regime (Table 3-8), In these years, crop water stress under standard irrigation practices occurred just before the “90% open boll” stage, so any yield change might be caused by the interactive effects of water and nitrogen stresses. Irrigation is required in extremely arid areas like Xinjiang, with a limited water supply, to avoid the occurrence of crop water stress. To derive an optimal irrigation management which both minimizes water consumption and allows an acceptable yield, one should be able to precisely estimate current θ and crop growth conditions, including whether the crop is under water stress or nitrogen stress, what the current growth stage is, etc. By applying the calibrated RZWQM2 model, crop water stress, soil moisture conditions and crop growth can be estimated accurately and this information subsequently applied to derive an optimum irrigation schedule in this area in the future.

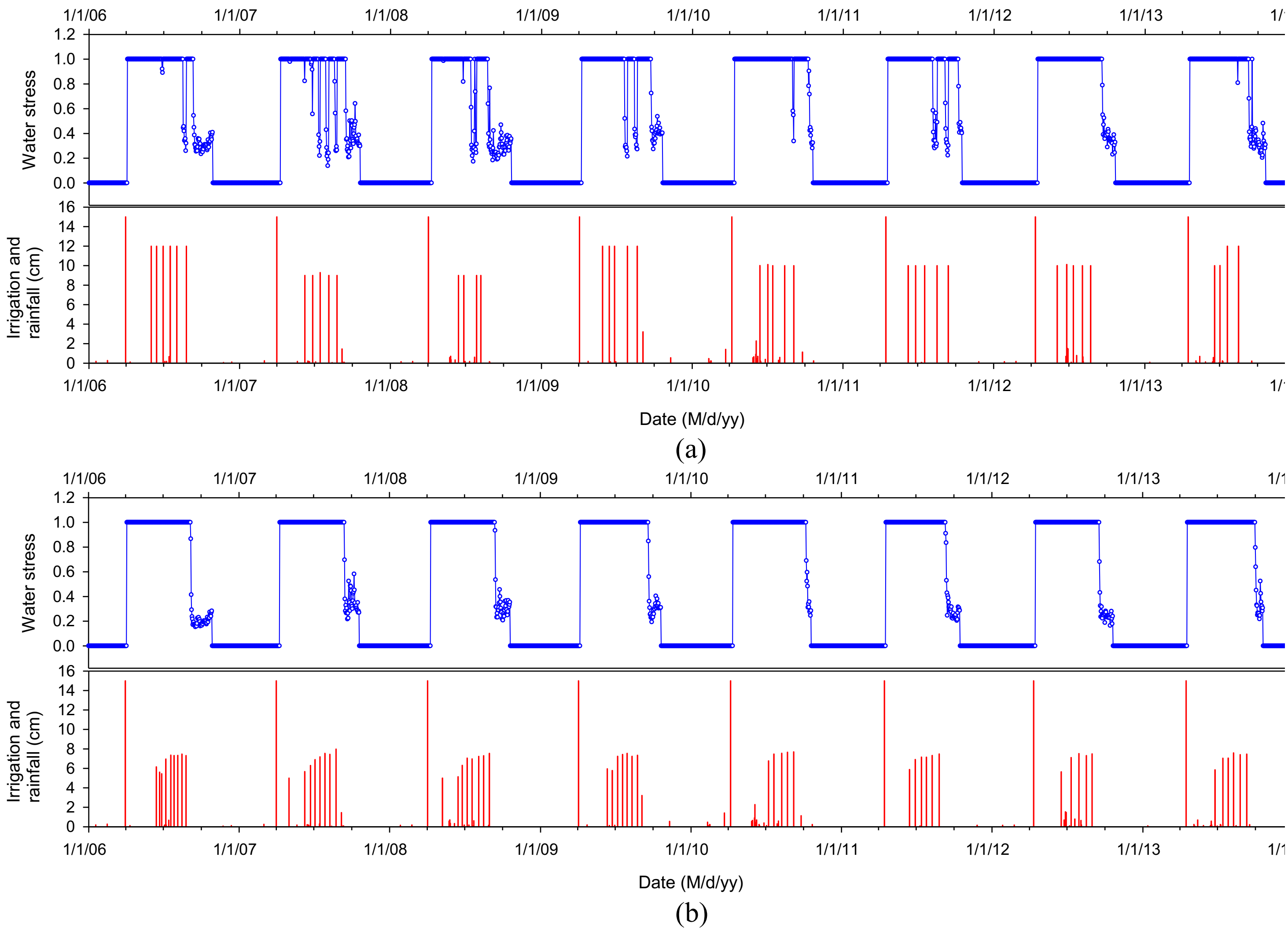

Figure 3-2 Water stress (TURFAC) response under (a) traditional irrigation regime and (b) water stress-based irrigation regime.

Table 3-9 Comparison of water balance within 2006 to 2013 during crop growing season (from planting to 90% boll open) between conditions under original irrigation practices and after WS-based regime optimal irrigation

Conditions	*Water balance parameters (mm)**						
	ΔS	P	I	D_s	E_a	T_a	ET_a
Original	-91.34	33.5	496	100.9	86	436	522
WS-based	-90.53	33.5	457	28.3	88	466	554

*D_s, cumulative deep seepage out of the soil profile; Ea, cumulative actual evaporation; ETa, cumulative actual evapotranspiration; I, cumulative irrigation; P, cumulative precipitation; ΔS, change of soil water storage in the soil profile; Ta, cumulative actual transpiration.

In the analysis of potential evapotranspiration, 83.5mm more irrigation was recommended to meet one hundred percent of crop water requirement, while WS-based regime saved irrigation by decreasing water waste through deep seepage from 100.9mm to 28.3mm (Table 3-9). The other parameters did not vary much before and after applying WS-regime to reschedule irrigation. On average, the water stress-minimizing RZWQM2 irrigation schedule resulted in an apparent irrigation water savings of 43 mm y^{-1} and an annual yield increase of 451 kg ha^{-1} on average. Rescheduling of irrigation using a water stress-based method can be used to optimize irrigation water use and cotton production.

3.5 Summary and Conclusion

To obtain an optimum irrigation schedule for cotton under an extremely arid desert oasis climate, the performance of RZWQM2 was evaluated in simulating soil water content, crop production and crop phenological stage against field observed data from the Cele oasis-desert transition zone in Xinjiang, China. The cotton yield and phenology dates were in general satisfactorily simulated by the RZWQM2 model. Although model accuracy statistics showed θ to be poorly simulated, the model performance under this climate can be deemed as acceptable when compared to studies conducted in other regions. The simulated water balance demonstrated that the cotton crop water requirement was 613 mm, and an additional application of 83.5 mm of irrigation water compared to present farmer-directed irrigation regimes providing 500 mm were needed to meet crop water requirement under an average rainfall of 33.5 mm y^{-1}. The simulation also suggested that current irrigation practices may result in a 100.9 mm loss of water through deep percolation. The irrigation schedule was optimized using model-simulated cotton crop water stress. The optimum irrigation schedule thereby derived could increase crop yield and irrigation water use efficiency by 15.8% and 23.4%, respectively, while reducing water application by 4.7%, compared to current irrigation regimes. This study demonstrated the model to be capable of simulating irrigated cotton production under an extremely arid desert oasis climate, and that model-simulated water stress could be used as a sufficient parameter for optimizing irrigation water use. It is further suggested that the RZWQM2 model could be used as a useful tool for regional water planning given its accurate simulation in crop water requirements.

CHAPTER 4 SUMMARY AND CONCLUSION

This study aims to study the energy transfer, water cycle, crop growth characteristics in a bare soil field and an agricultural field under extremely arid climate, and provide optimal management scheme for agricultural production. In Chapter 2, revised RZ-SHAW model was evaluated in simulating energy balance components in a bare soil field against observed hourly data, and the statistics demonstrated that the model simulation are satisfactory. Due to the insufficient external water supply in this district, little energy was consumed by evapotranspiration and majority of incoming energy was released into atmosphere in terms of surface heat radiation and reflection. Then the simulated evapotranspiration converted from simulated latent heat was compared with local annual precipitation, to quantify the amount of groundwater recharge or loss. The results showed that, in normal years, the local groundwater get recharged from precipitation, while in drier years with extremely scarce rainfall, the groundwater could be depleted due to strong soil evaporation and upward soil water flux.

In Chapter 3, soil water content, cotton yield and phenology dates were simulated using RZWQM2, and an optimal irrigation scheme was developed based on simulated crop water stress. The model performed satisfactorily in emulating cotton yield and developing stage, while the simulation for soil water content was acceptable. Simulated results also indicated that a certain amount of irrigation was wasted through deep seepage, and the existing irrigation scheme needed to be optimized. The simulated results indicated that modified RZWQM2 could adequately simulate energy balance, water cycle and crop production for desert-oasis agricultural system, although some of simulations need to be improved. The newly developed WS-based method presented a relative water saving and apparent yield increasing scheme, which provide a potential application of RZWQM2 into agricultural management practices.

Below are some deficiencies of this research and recommendations for future studies in relevant field:

i) To measure sensible and latent heat which were not observed in this study. It may improve the accuracy of the simulation in energy balance.

ii) Since the submodules of energy balance, hydraulic cycle and crop growth in RZWQM2 would interact with each other, the parameters for each submodule required repeat calculation to obtain more convinced results. However, this process was not conducted in this study.

iii) Under ideal condition, the simulated crop yield after optimizing irrigation using water stress based method is supposed to exceed the simulated yield under current irrigation scheme applied to the field. However, this was not the case in our simulation. Further investigation in improving this irrigation regime is recommended in future studies.

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