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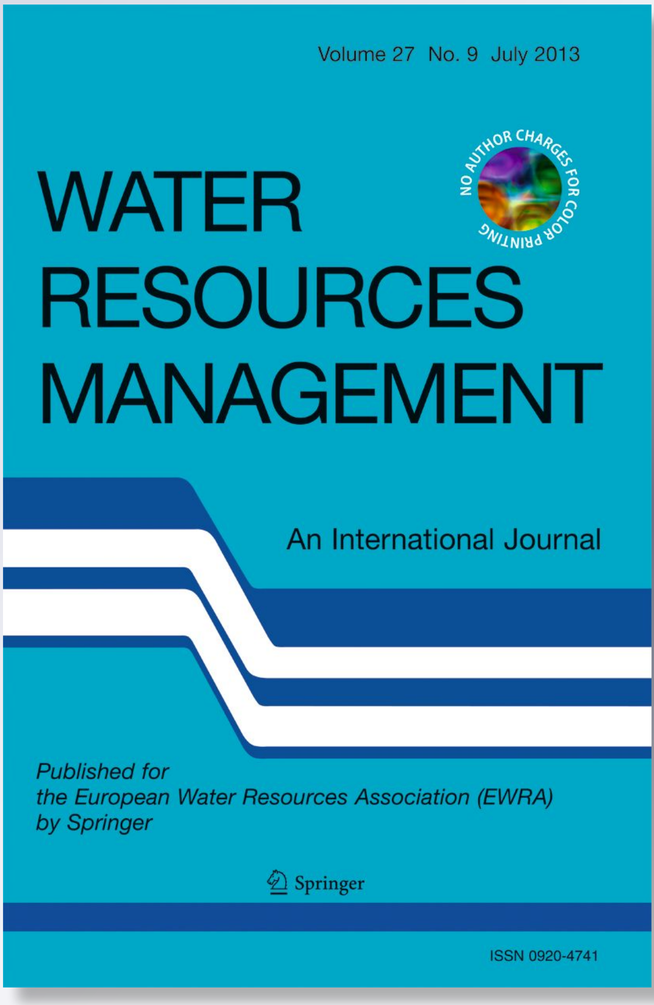
Water Resources Management
An International Journal - Published for the European Water Resources Association (EWRA)

ISSN 0920-4741
Volume 32
Number 9

Water Resour Manage (2018)
32:2969-2983
DOI 10.1007/s11269-018-1967-8



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Pond and Irrigation Model (PIM): a Tool for Simultaneously Evaluating Pond Water Availability and Crop Irrigation Demand

Ying Ouyang[1] **· Gary Feng**[2] **· Theodor D. Leininger**[3] **· John Read**[2] **· Johnie N. Jenkins**[2]

Received: 21 July 2017 / Accepted: 13 March 2018 /
Published online: 11 April 2018

Abstract Agricultural ponds are an important alternative source of water for crop irrigation to conserve surface and ground water resources. In recent years more such ponds have been constructed in Mississippi and around the world. There is currently, however, a lack of a tool to simultaneously estimate crop irrigation demand and pond water availability. In this study, a Pond-Irrigation Model (PIM) was developed to meet this need using STELLA (Structural Thinking, Experiential Learning Laboratory with Animation) software. PIM simulated crop land and agricultural pond hydrological processes such as surface runoff, soil drainage, and evapotranspiration as well as crop irrigation demand and pond water availability. More importantly, PIM was able to decide when to conduct crop irrigation based on management allowable depletion (MAD) root zone soil water content and to determine optimal ratios of agricultural pond size to crop land with sufficient pond water available for crop irrigation. As a case demonstration, the model was applied to concomitantly estimate row crops (i.e., corn, cotton, and soybeans) water irrigation demand and pond water availability in a farm located at East-central Mississippi. Simulations revealed that corn used more soil water for growth than soybeans, whereas soybeans needed more irrigation water than corn and occurred due to less rainwater available for soybeans growth. We also found that there was one time for corn, zero

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time for cotton, and two times for soybeans when the pond water level was drawn to near zero for irrigation from 2005 to 2014. PIM developed in this study is a useful tool for estimating crop irrigation demand and pond water availability simultaneously.

Keywords Crop irrigation demand · Mississippi · Pond-irrigation model · Pond water availability

1 Introduction

Agricultural ponds are gaining acceptance as a source of irrigation water to increase yields of row crops in addition to supply water for groundwater recharge and other environmental and ecological benefits. With a great need to save groundwater resources without reducing crop yield, more on farm water storage ponds have been constructed recently in Mississippi, parts of USA, and around the world (Carvajal et al. 2014; Ouyang et al. 2016). Mississippi is one of the major states for soybeans, corn and cotton productions in Southeast USA (MSU Extension Service 2014). To maximize crop yields, there was a 92% increase in irrigated crop land from 1998 to 2008 in Mississippi. This has resulted in an overdraft of groundwater resources in the region (Powers 2007; Konikow 2013; Vories and Evett 2014; YMD 2015; Ouyang et al. 2016).

In spite of more agricultural ponds have been constructed for crop irrigation, little effort has been made to estimate the ratio of pond size to irrigated crop land based on pond metric and its hydrological conditions. Recently, Ouyang et al. (2016 and 2017) developed a STELLA (Structural Thinking, Experiential Learning Laboratory with Animation (http://www.iseesystems.com)-based model (Pond Model) to meet this need. These authors found that a reasonable ratio of pond size to irrigated soybeans land is 1:18 if the irrigation rate is 2.54 cm d^{-1} and the low limit of the pond water level is drawn to near zero (8 cm). Their study suggests that the Pond Model developed is a useful tool for estimating the ratio of pond size to irrigated crop land.

While the crop irrigated land has increased 92% from 1998 to 2008 in Mississippi, our knowledge on crop water demand in this region is still fragmented. Feng et al. (2017) attempted to determine irrigation water demand for soybeans, corn and cotton in East-central Mississippi through the development and application of STELLA-based model (Irrigation Model) in conjunction with long-term weather data (1895–2014). Their study revealed that the average irrigation rate is about175 mm yr^{-1} for those tree crop species in Eastern Mississippi.

Since 1990s of last century, numerous crop growth, soil water balance, and crop irrigation models such as the Soil-Plant-Air-Water (SPAW) model (Saxton et al. 1992), Root Zone Water Quality Model (RZWQM2) (Ahuja et al. 2016) and Decision Support System for Agrotechnology Transfer (DSSAT) model (Jones et al. 2003) have been developed. These models and the aforementioned two STELLA-based models (*i.e.*, Pond Model and Irrigation model), developed by Ouyang et al. (2017) and Feng et al. (2017), have provided a very useful means for estimating pond water availability and crop irrigation demand. However, crop irrigation demand estimation and pond water supply assessment are an integrated part of agricultural water management practices. Crop irrigation demand and pond water supply must be estimated simultaneously to determine if there are sufficient pond water available for crop irrigation. This information is critical to decision makers like farmers and water resource managers. A thorough literature search, however, revealed that little to no effort has been devoted to tackling this issue.

Therefore, it is inevitably to couple the two models together for a user-friendly estimation of pond water availability and crop irrigation demand.

The goal of this study was, therefore, to develop a tool for simultaneously evaluating pond water availability and crop irrigation demand. Our specific objectives were to: (1) combine the Pond Model and Irrigation Model into one model or PIM (pond and irrigation model) with extensive modifications, (2) apply the PIM to estimate crop irrigation demand and pond water supply simultaneously using a farm site Eastern Mississippi as a case study; and (3) evaluate the feasibility of the PIM as a tool for simultaneously evaluating pond water availability and crop irrigation demand.

2 Materials and methods

2.1 Pond model description

Recently, we have developed a STELLA-based model to characterize pond water balance and hydrological processes such as rain water collection, runoff water gathering, reclaimed water recharge, surface water evaporation, pond discharge pipe release, pond spillway release, and soil seepage and drainage losses (Ouyang et al. 2017). The conceptual model and STELLA model to estimate pond water balance and hydrological processes are shown in Fig. 1. Although an elaborate description of the model (hereafter referred to as Pond Model) is beyond the scope of this study, a moderate description of major mathematical functions is given below for readers' conveniences.

For surface water runoff into a pond, the curve number method is used as follows (Rawls et al. 1992; Mullins et al. 1993):

$$R = \frac{(P - 0.2S)^2}{(P + 0.8S)} \tag{1}$$

where R is the surface runoff rate (cm h^{-1}), P is the rainfall rate (cm h^{-1}), and S is the watershed retention parameter. For pond water evaporation, the simple equation proposed by Abtew (1996 & 2005) is used as given below:

$$E = K_1 \frac{R_s}{\lambda} \tag{2}$$

where E is the evaporation from pond water (cm h^{-1}), K_1 is the coefficient (dimensionless), R_s is the solar radiation (kJ cm^{-2} h^{-1}), and λ is the latent heat of vaporization (kJ g^{-1}). The lateral seepage of water from saturated soil into pond or vice versa is estimated by Darcy Law:

$$D_{lateral} = AK \frac{h_{soil} - h_{pond}}{l} \tag{3}$$

where $D_{lateral}$ is the lateral seepage rate (cm^3 h^{-1}), A is the flow area perpendicular to l (cm), K is the saturated hydraulic conductivity (cm^3 h^{-1}), h is the hydraulic head (cm), and l is the flow path length (cm).

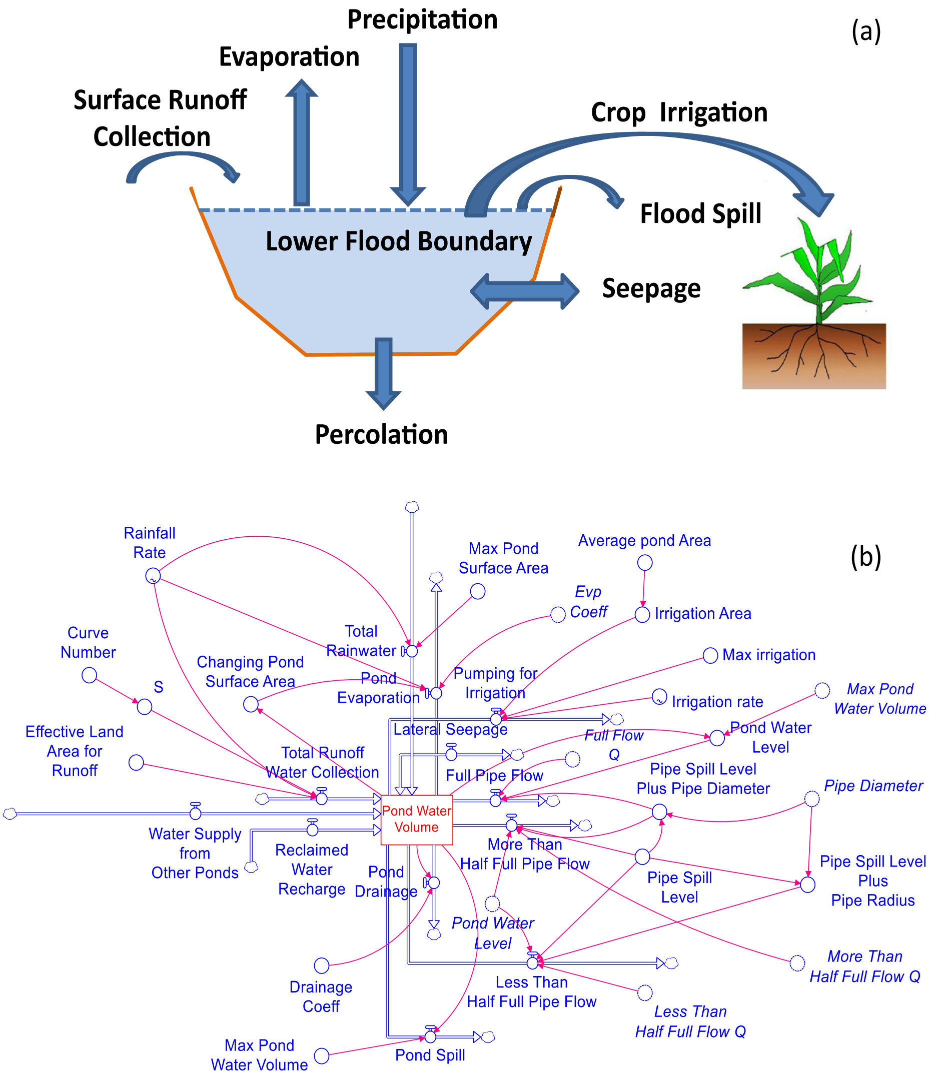

Fig. 1 Conceptual diagram of an agricultural pond hydrological processes (**a**) and a STELLA model to implement these hydrological processes (**b**)

Assuming that the pond is a trapezoidal trough, the volume of water in the pond is then calculated as (Ouyang et al. 2017):

$$V = \frac{h_p}{6}[WL + (W + a)(L + b) + ab] \tag{4}$$

where V is the volume of water in the pond (cm^3), h_p is the height of water in the trough (cm), W is the top width of the trough (cm), L is the top length of the trough (cm), *a* is the base width of the trough (cm), and *b* is the base length of the trough (cm).

When the pond water level reaches the discharge pipe level, water will leave the pond through the pipe outlet. In most case, the pipe is constructed using a polyvinyl chloride (PVC) or metal, which is considered as a uniform open channel flow. Therefore, the following Manning equation is used to calculate water discharge out of the pond from a pipe (Chow 1959):

$$Q = (1.49/n)A_p\left(R_h^{2/3}\right){S_b}^{1/2} \tag{5}$$

with

$$R_h = \frac{A_p}{P_{wp}} \tag{6}$$

where Q is the volumetric flow rate passing through the pipe (cm^3/h), n is the Manning roughness coefficient (dimensionless), A_p is the cross-sectional area of pipe flow normal to the flow direction (cm^2), R_h is the hydraulic radius (cm), S_b is the bottom slope of the pipe (dimensionless), and P_{wp} is the wetted perimeter of the cross-sectional area of flow (cm).

The Pond Model was calibrated, validated, and applied, as demonstrations, to estimate the diurnal and seasonal pond hydrological processes and water budget in Mississippi Delta (Ouyang et al. 2017) as well as to determine the ratio of pond size to irrigated soybean land in East Mississippi (Ouyang et al. 2016). Results suggest that Pond Model is a useful tool to estimate pond hydrological processes and water availability.

2.2 Irrigation model description

Crop irrigated land has increased 92% from 1998 to 2008 in Mississippi. However, our knowledge on rainwater surplus and deficit, crop water use, and irrigation demand are still fragmented in this region. Feng et al. (2017) attempted to determine rainwater deficit and irrigation demand for soybeans, corn and cotton in East-central Mississippi using trend analysis and a STELLA-based model. The STELLA model (hereafter referred to as Irrigation Model) simulates soil hydrological processes such as surface water runoff and soil water movement as affected by evapotranspiration (ET) and rainfall, and then determines soil water balance and timing for crop irrigation. The conceptual diagram and STELLA map of the Irrigation Model are given in Fig. 2. The surface water runoff and soil water percolation are calculated using Eqs. (1) and (3). Crop water use is equivalent to ET, which is the model input data. Root zone soil water content is calculated by dividing soil water storage with soil volume at root zone for each time step, which can be easily accomplished in STELLA. The irrigation decision is made when the root zone water content is less than or equal to the management allowable depletion (MAD) root zone soil water content. The root length changes with time according to crop growth characteristics and the MAD is set to 50% of field water capacity (Ozdogan et al. 2010). That is, when the root zone soil water content is less than or equal to MAD, the soil is irrigated to its field capacity or to a prescribed value. The Irrigation Model has been validated and successfully applied to determine irrigation demand for soybeans in Blackland Prairie of East-central Mississippi (Feng et al. 2017). The validation was performed to match the model predicted soil water content and surface runoff to those of our field observations with a very good agreement. An elaborate description of the Irrigation Model can be found in Feng et al. (2017).

2.3 Integration of pond and irrigation models

The Pond Model and Irrigation Model are very useful tools for estimating agricultural pond water availability and crop irrigation demand, respectively. However, crop irrigation demand

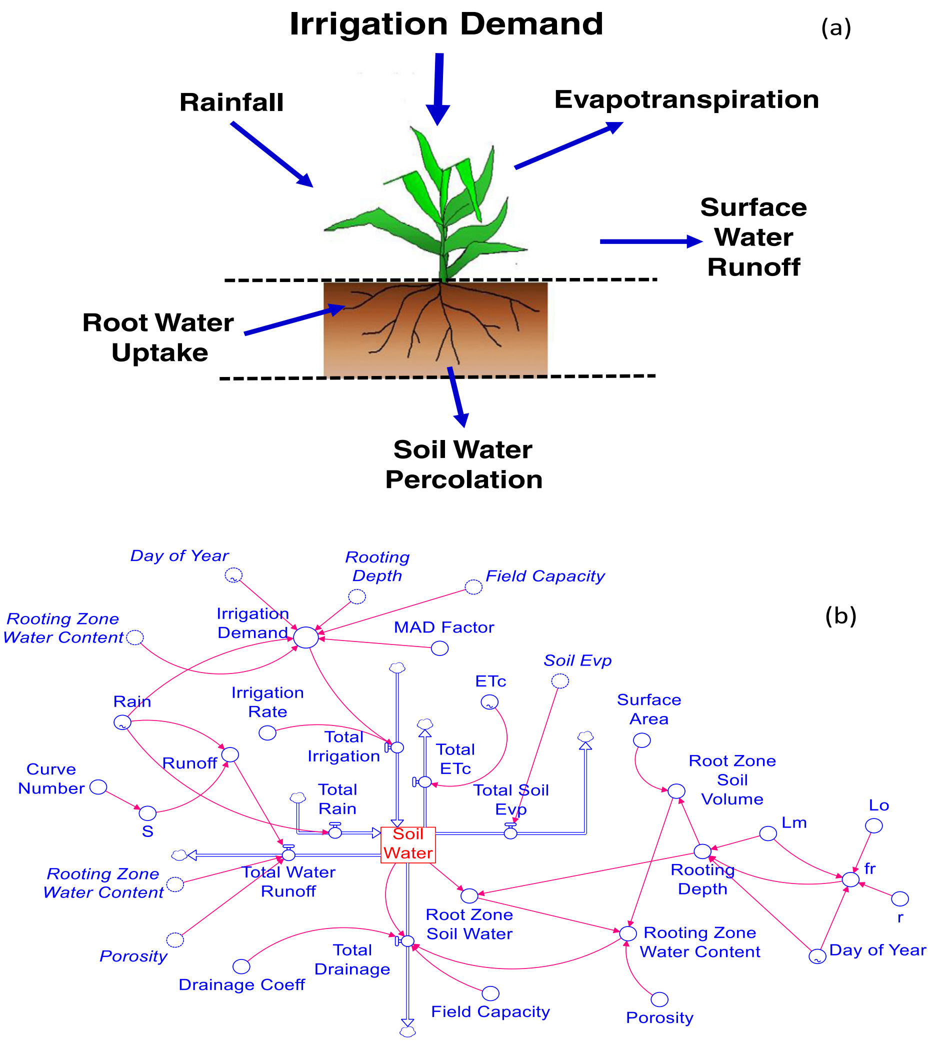

Fig. 2 Conceptual diagram of the crop field hydrological processes with irrigation demand (**a**) and a STELLA model to implement these soil water dynamics and irrigation demand (**b**)

and pond water availability is an interactive phenomenon and occurred simultaneously in natural conditions. Therefore, it is very necessary to couple the two models together for a user-friendly estimation of pond water availability and crop irrigation demand. Figure 3 shows a STELLA-based model (hereafter referred to as Pond-Irrigation Model or PIM) for simultaneously estimating pond water availability and crop irrigation demand. In the PIM, the amounts of water and times needed for crop irrigation are determined from the Irrigation Model. Using three input variables of rainfall, prescribed irrigation rate and ET, the Irrigation Model can predict, among others, the soil water storage and root zone water content and determine the times when to irrigate and the amount of water needed for irrigation based on MAD (Fig. 2). The timing and amount of water needed for irrigation are then passed to the Pond Model (Fig. 3), which calculates the amount of pond water availability for crop irrigation

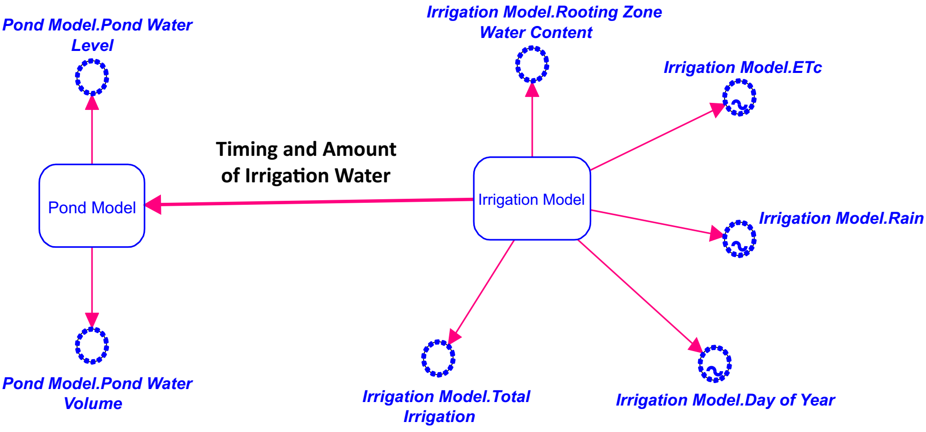

Fig. 3 A STELLA model for couple estimation of pond water hydrology and crop irrigation demand

through the pond water level (Fig. 1). If the pond water level is drawn to near zero, there will be no water available from the pond for irrigation. Additionally, some major variables such as pond water level, pond water volume, root zone water content, and the total amount of irrigation, ET and rainfall at any given day of year can be output for analysis.

2.4 Simulation Scenarios

Three simulation scenarios, namely Scenario 1 for corn, Scenario 2 for cotton and Scenario 3 for soybeans, were selected to simultaneously estimate agricultural pond and crop land hydrological processes as well as crop irrigation demand and pond water availability during the growing season. In these scenarios, a typical agricultural pond with an area of 5 ha and an average depth of 2 m located in Macon, Mississippi was selected (Fig. 4). This pond size reflects the average field conditions in East Mississippi and the simulation scenarios imitated

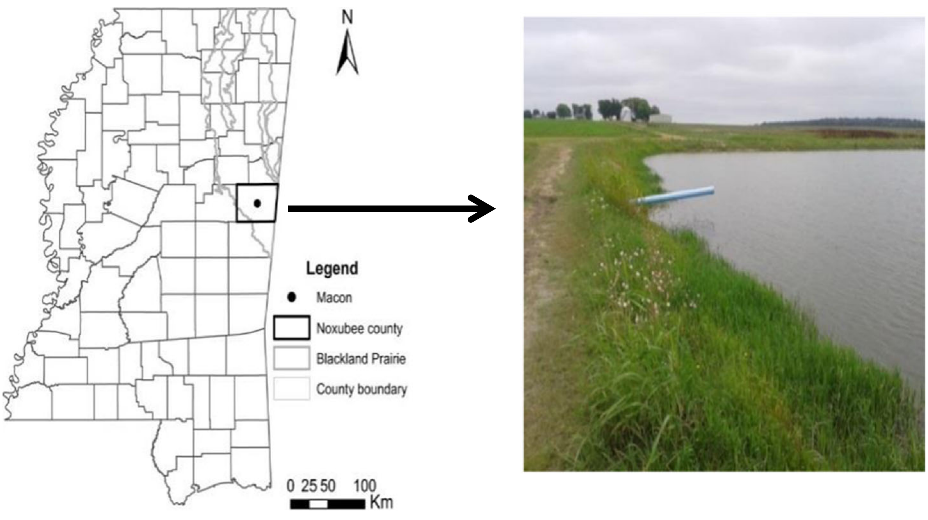

Fig. 4 Location of a farm at Macon, Mississippi used for model simulations in this study

natural field conditions and average agricultural practices in this region. About 120-year simulation period was chosen for these scenarios, which started on February 1, 1894 and ended on December 31, 2014 with a daily time step. The weather data such as rainfall, solar radiation, and air temperature (Fig. 5) were obtained from local weather monitoring stations, whereas the three crop ET rates (Fig. 6) were approximated based on long-term agricultural practices (Feng et al. 2017). All other input parameter values for the pond and crop land can be found in Ouyang et al. (2017) and Feng et al. (2017).

3 Results and discussion

3.1 Root zone water, irrigation demand and pond water availability

Simulated daily changes in root zone soil water content, irrigation time, and pond water level over about 120-year simulation period for corn, cotton, and soybeans are shown in Figs. 7, 8 and 9. Results showed that root zone soil water content corresponded well to crop irrigation

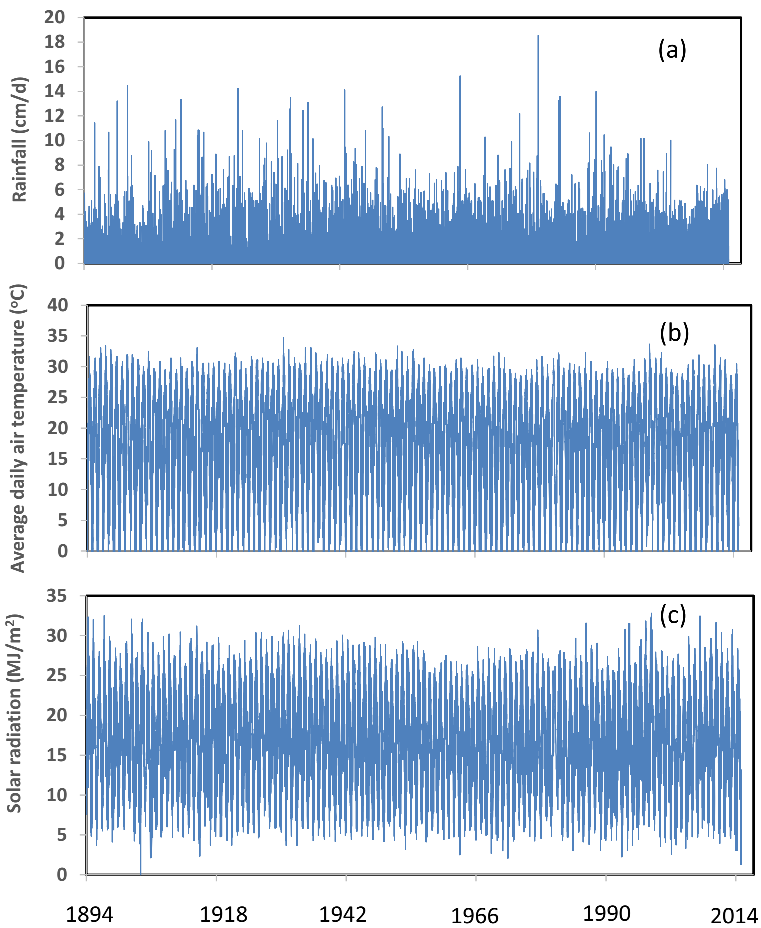

Fig. 5 Rainfall (**a**), air temperature (**b**), and solar radiation (**c**) used as input data for model simulations

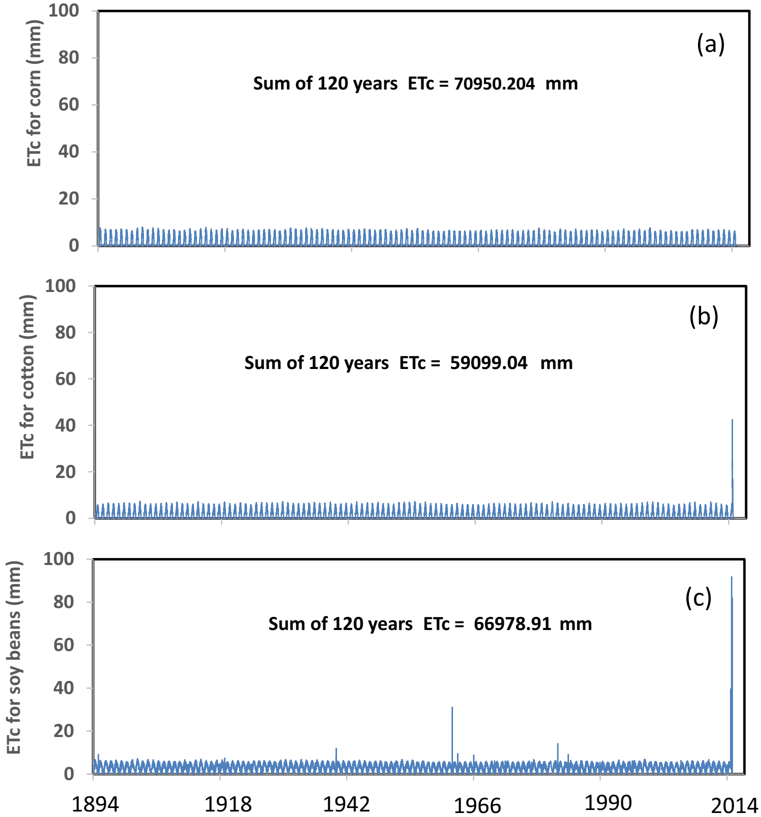

Fig. 6 Evapotranspirations for corn (**a**), cotton (**b**), and soybeans (**c**) used as input data for model simulations

demand. In other words, the crop irrigation started when the root zone soil water content was equal to or below MAD (or 0.225 cm^3/cm^3) during the crop growing season over the 120-year simulation period. It should be noted that a constant irrigation rate of 2.54 cm (or one inch) was used for these scenarios. This irrigation rate reflected the common irrigation rate used by farmers in Mississippi although the model can handle any other irrigation rate such as to irrigate soils to field water capacity. An elaborated analysis revealed that there were 104 times for corn, 62 times for cotton, and 111 times for soybeans when the root zone water contents were equal to or less than that of MAD during the growing season over the 120-year simulation period. This was also true for irrigation times. That is, there were 104, 62, and 111 times of crop irrigation, respectively, for corn, cotton, and soybeans over the 120-year simulation period. Apparently, the amounts and times needed for crop irrigation were in the following order: soybeans > corn > cotton. This order was in consistent with that reported from Yazoo Mississippi Delta Joint Water Management District (YMD) (Kebede et al. 2014). It was also apparent from Figs. 7, 8 and 9 that for some years, there was no need for crop irrigation, whereas for other years, more than one irrigation was needed each year.

Our simulations further revealed that more irrigations were needed from 1894 to 1953 than from 1954 to 2013 for corn (Fig. 7b), cotton (Fig. 8b), and soybeans (Fig. 9b). Results indicated that this region was relatively dried in early part of twentieth century than in later part of the century. This finding was further confirmed through our rainfall analysis. We found

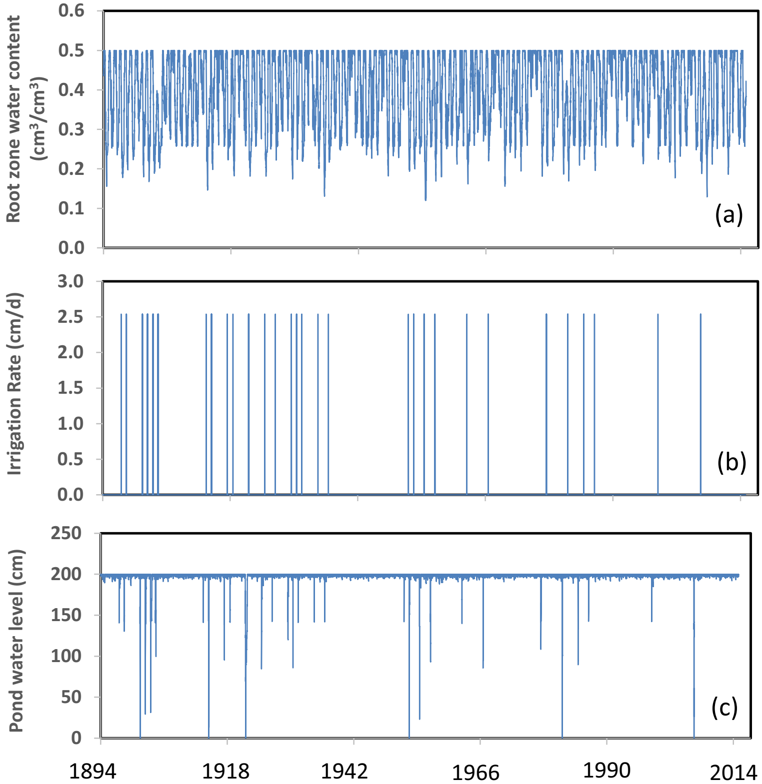

Fig. 7 Simulated rooting zone water content (**a**), irrigation rate (**b**), and pond water level (**c**) for corn over a 120-year simulation period

that the amount of rain was 78,634 mm from 1894 to 1953 but was 80,360 mm from 1954 to 2013. A plot of the amount of rainfall in a 20-year interval showed an increased trend in rainfall over a 120-year period from 1894 to 2013 (Fig. 10). An F-test demonstrated that the difference in rainfall amount shown in Fig. 10 was statistically significant. Therefore, the climate in this region during the past 120 years seems to be wetter gradually. Further study is therefore warrant to tackle this issue although it is beyond the scope of this study.

Pond water level variations corresponded to irrigation demands for corn, cotton, and soybeans are in Figs. 7, 8 and 9. The ratio of pond size (or pond area) to crop irrigation land (or area) used in this study for the three simulation scenarios was 1:18. In other words, a 1-ha pond with an average depth of 2 m was used to irrigate 18-ha of crop species. This ratio was chosen based on previous our study (Ouyang et al. 2016), in which we found that a reasonable ratio of pond size to irrigated soybeans land is 1:18 if the irrigation rate is 2.54 cm d^{-1} (or 1 in. d^{-1}) and the low limit of the pond water level is drawn to near zero. Using this ratio, we observed from the simulations that there were 34 times for corn, 41 times for cotton, and 97 times for soybeans when the pond water level was drawn to zero during the growing season over the 120-year period. Apparently, soybeans needed more water than corn and cotton. Furthermore, most of the times with near-zero pond water level occurred in the early part of twentieth century due to less rainfall. For example, based on our simulation data, there was only one time for corn, zero time for cotton, and two times for soybeans when the pond water

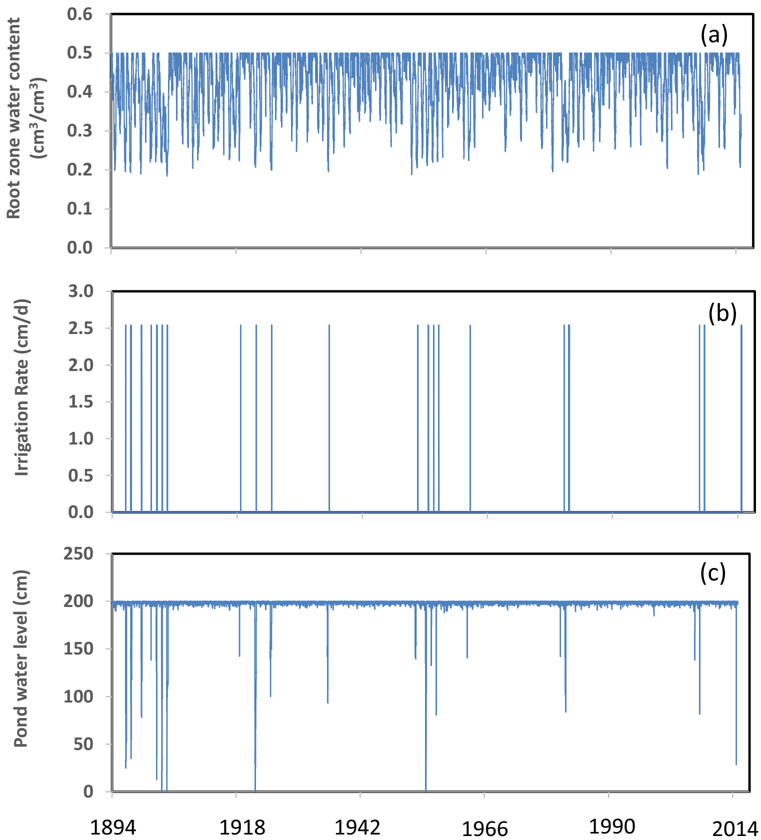

Fig. 8 Simulated root zone water content (**a**), irrigation rate (**b**), and pond water level (**c**) for cotton over a 120-year simulation period

level was drawn to near-zero from 2005 to 2014 for the simulation conditions used in this study. Several approaches could be used to store sufficient pond water for crop irrigation, including (1) reduce the ratio of pond size to irrigated crop land for using less pond water, (2) increase the depth of the pond for holding more pond water, (3) increase the drainage area so that the pond can collect more runoff water, (4) irrigate the soil water to its field capacity rather than a constant rate of one inch per day, and (5) monitor soil-water content in real time to reduce crop water demand and to increase precipitation use efficiency.

3.2 Long-term crop water use and rainwater supply estimation

Crop water use, rainwater supply, surface runoff, ET, and irrigation water during the growing season over a 120-year simulation period are given in Table 1. Of which, rainfall and ET are the model inputs, while surface water runoff, rainwater entering soil, and irrigation water are model outputs. Results showed that more rainfall occurred for corn (63,891 mm) than for soybeans (50,618 mm) with cotton (56,677 mm) in between during the growing season over the 120-year period. In other words, there was 12% more rain for cotton than for soybeans as well as 26% more rain for corn than for soybeans. However, the surface water runoff due to

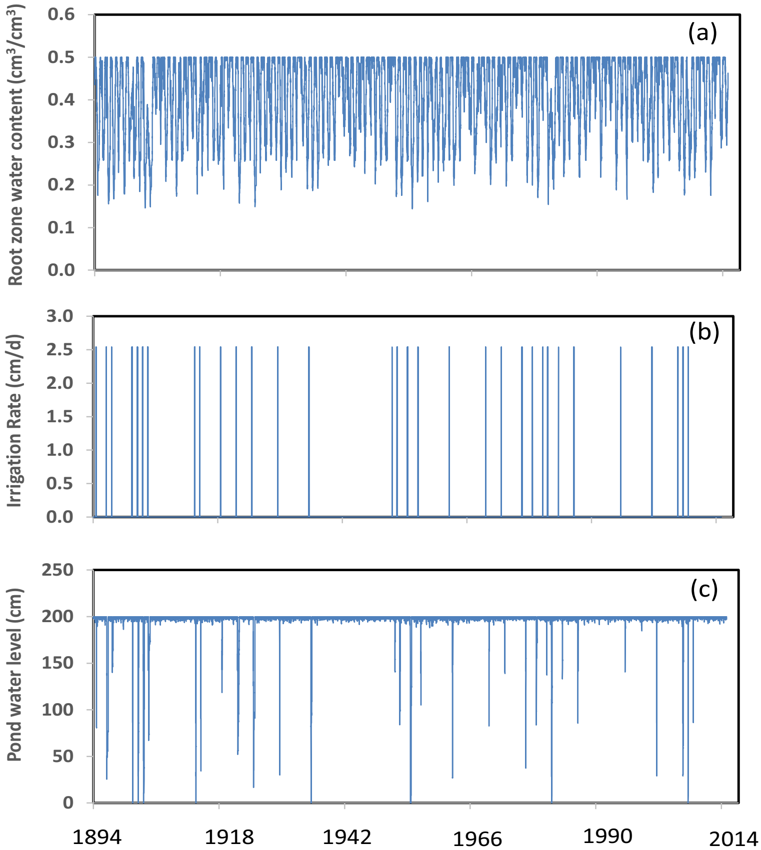

Fig. 9 Simulated root zone water content (**a**), irrigation rate (**b**), and pond water level (**c**) for soybeans over a 120-year simulation period

rainfall during the growing season for corn was more than twice higher than for cotton and soybeans. As a result, the net amount of rainwater entering into the soil was: soybeans growing season < corn growing season < cotton growing season (Table 1). This finding explained why

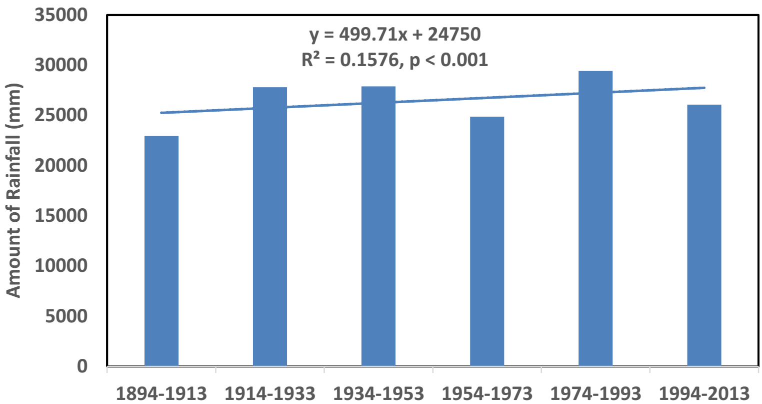

Fig. 10 Measured amount of rainfall in a 20-year interval over a 120-year period from 1894 to 2013

Table 1 Total rainfall, surface runoff, rainwater entering the soil, ET, and irrigation water demand for corn, cotton, and soybeans over a 120-year simulation period

Crop species	Growing period (Day of Year)	Rainfall (mm)	Surface runoff (mm)	Rainwater entering soil (mm)	Evapo-transpiration (mm)	rrigation water (mm)
Corn	86–236	63,891	18,504	45,386	70,950	1778
Cotton	141–296	56,677	8719	47,958	61,493	1422
Soybeans	128–260	50,618	8708	41,910	66,979	2464

soybeans need more irrigated water than corn and cotton. Based on the results given in Table 1, our conclusion was that corn used more soil water (or higher ET) for growth than soybeans although soybeans needed more irrigation water than corn. This occurred because there was less rainwater input into the soil during the soybeans growing season than that of corn.

3.3 Long term crop land water balance

Long-term crop land water budget for corn, cotton, and soybeans at the end of the 120-year simulation period is given in Table 2. Results showed that although the water losses from the soil varied with crop lands, they were, in general, in the following order: crop ET > surface runoff > non-growing season soil evaporation > soil percolation for all of the three crop species. The water losses from the soil due to ET accounted for 44, 38, and 42%, respectively, for corn, cotton, and soybeans; whereas the water losses from the soil due to the surface runoff resulted primarily from rainfall accounted for 32, 34, and 31%, respectively, for corn, cotton, and soybeans growing season. In other words, more than 70% of water losses from the soil were the results of ET and surface water runoff. There were more than 28, 38, and 20 times of rain runoff water than irrigation water, respectively, for corn, cotton, and soybeans (Table 2). This finding indicated there was sufficient runoff water to be collected and stored in agricultural ponds for crop irrigation.

Table 2 also revealed that rainwater was about 89, 111, and 64 times larger than irrigation water needed for corn, cotton, and soybeans, respectively, over the 120-year simulation period although most of the rainwater was not available during crop growth. Results further confirmed that there was sufficient rainwater for constructing agricultural ponds for crop

Table 2 Simulation soil water dynamics at the crop lands over a 120-year simulation period

Crop species	Corn	Cotton	Soybeans
Crop Evapotranspiration (mm)	70,950	61,494	66,979
Non growing season soil evaporation (mm)	35,208	39,798	40,599
Soil percolation (mm)	3463	3991	3643
Surface runoff (mm)	50,502	54,565	49,583
Irrigation (mm)	1778	1422	2464
Rainfall (mm)	158,328	158,328	158,328
Soil water storage at the end of simulation (mm)	404	342	415
Soil water storage at the beginning of simulation (mm)	440	440	440
Total water input to soil (mm)	160,106	160,106	160,791
Total water lost from soil (mm)	160,124	159,848	160,804
Soil water balance (mm)	18	1	12

irrigation. Finally, the soil water balance analysis showed the percentage errors were 0.01% or less (Table 2), indicating the PIM simulated water budget well.

4 Conclusions

A new modeling (or PIM) was developed for simultaneously estimating agricultural pond and crop land hydrological processes as well as for determining crop irrigation demand and pond water availability.

Simulation results showed that there were 104 times for corn, 62 times for cotton, and 111 times for soybeans with the root zone water contents that were equal to or less than that of MAD during the growing season over the 120-year simulation period. The amounts and times needed for crop irrigation were in the following order: soybeans > corn > cotton.

An increased trend in rainfall over a 120-year period from 1894 to 2013 was observed. Therefore, the climate in this region during the past 120 years seems to be wetter gradually. Further study is thus warrant to tackle this issue.

There was only one time for corn, zero time for cotton, and two times for soybeans when the pond water level was drawn to near zero from 2005 to 2014 for the simulation conditions used in this study. Results further showed that corn used more soil water for growth than soybeans although soybeans needed more irrigation water than corn. This occurred because there was less rainwater input into the soil during the soybeans growing season than that of corn.

More than 70% of water losses from the soil were the results of ET and surface water runoff. There were more than 28, 38, and 20 times of runoff water than irrigation water, respectively, for corn, cotton, and soybeans. This finding indicated that there was sufficient runoff water to be collected and stored in agricultural ponds for crop irrigation. Finally, the soil water balance analysis showed the percentage errors were 0.01% or less, indicating the PIM simulated water budget well.

Acknowledgements This project (62-2015) was funded by Mississippi Soybean Promotion Board.

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