Estimating the ratio of pond size to irrigated soybean land in Mississippi: a case study

Ying Ouyang, Gary Feng, John J. Read, Theodor D. Leininger and Johnie N. Jenkins

ABSTRACT

Although more on-farm storage ponds have been constructed in recent years to mitigate groundwater resources depletion in Mississippi, little effort has been devoted to estimating the ratio of on-farm water storage pond size to irrigated crop land based on pond metrics and its hydrogeological conditions. In this study, two simulation scenarios were chosen to determine such a ratio as well as to investigate pond hydrological processes using a Structural Thinking, Experimental Learning Laboratory with Animation (STELLA) model, one scenario with and the other without using pond water for irrigation for a typical pond that represented the average conditions in East Mississippi. Simulation results showed that pond water level changed moderately for conditions without using its water for irrigation, whereas pond water level changed dramatically for conditions with using its water for irrigation. A reasonable ratio of pond size to irrigated soybeans land was 1:18 if the irrigation rate was 2.54 cm/d (or 1 inch/d) and the low limit of the pond water level was drawn to near zero (0.08 m). For the ratio of 1:18, our simulations further revealed that a 1-ha soybeans land could save about 542 m^3 groundwater each year. This study suggests that the STELLA model is a useful tool for estimating the ratio of pond size to irrigated crop land.

Key words | Mississippi, on-farm water storage pond, pond hydrology, pond size to irrigated crop land ratio, STELLA model

Ying Ouyang (corresponding author)
USDA Forest Service,
Center for Bottomland Hardwoods Research,
775 Stone Blvd., Thompson Hall, Room 309,
Starkville,
MS 39762,
USA
E-mail: *youyang@fs.fed.us*

Gary Feng
John J. Read
Johnie N. Jenkins
USDA-ARS,
Crop Science Research Laboratory,
810 Hwy 12 East,
Starkville,
MS 39762,
USA

Theodor D. Leininger
USDA Forest Service,
Center for Bottomland Hardwoods Research,
432 Stoneville Road,
Stoneville,
MS 38776,
USA

INTRODUCTION

Groundwater withdrawal in the United States has increased dramatically during the 20th century (Hutson *et al.* 2004) and a consequence of such withdrawals is the depletion of water resources from subsurface aquifers (Konikow 2013). This is also true in Mississippi, especially in the Mississippi Delta. Mississippi is a major state for agricultural crop production in the Southeast United States. In 2012, soybean revenue ($1.16 billion) ranked number one in Mississippi as compared with all other crops, exceeded only by broilers/egg/chickens productions as an agricultural commodity (http://www.dafvm.msstate.edu; http://www.msfb.org). The desire by most producers to stabilize or enhance crop yields through irrigation has led to the overdraft of groundwater resources in many regions of Mississippi (Konikow 2013; Vories & Evett 2014) and around the world (Sahoo & Panda 2014). In these regions, groundwater constitutes 80% of all the freshwaters used for agricultural, domestic, and industrial activities (Hossain 2014). In an effort to better understanding of the irrigation requirements of different crops in the Mississippi Delta, a groundwater usage survey has been performed recently and the average loss of groundwater is about 493,000,000 m^3/y from 1987 to 2014 in Mississippi Delta (YMD 2015).

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With an increasing concern about groundwater and stream water depletion, more irrigation farm and tail water retention ponds have been constructed in recent years in East Mississippi and the Mississippi Delta. Although there is a high amount of rainfall in Mississippi, only 30% occurs during the period from May to October when the major crops are produced (Kebede *et al.* 2014). The temporal mismatch between annual rainfall and crop water demands is a major reason for using water storage ponds as a source of irrigation water. However, the hydrological processes, water budget, and environmental benefits and consequences of water storage ponds in Mississippi are yet to be fully quantified and exploited. For many agricultural practices, farm pond capacity must be adequate to meet crop water use requirements, which vary with crop species, seasons, soil types, hydrological conditions, and climate environments.

Currently, little effort has been devoted to estimating the ratio of pond size to irrigated crop land in Mississippi. Staff from USDA-NRCS in Mississippi have roughly approximated that the pond size to crop irrigation area is about 1:13 based on the soil-plant-air-water (SPAW) model simulation (personal communication). That is, to irrigate 160 ha of crop land, a 12 ha of pond area is needed with the pond bottom to be 10 ha and the embankment footprint to be 2 ha. However, an accurate estimation of such a ratio based on pond hydrological processes, local climate conditions, and crop irrigation demands has yet to be performed. The knowledge of this ratio is crucial to cost-effective pond size estimation for construction and pond water for irrigation management in Mississippi and the regions with similar land uses and climate conditions.

Recently, we developed a Structural Thinking, Experiential Learning Laboratory with Animation (STELLA) model to assess pond hydrological processes and water budget (Ouyang *et al.* 2016). In this companion study, we applied this model to estimate the ratio of pond size to irrigated soybeans land in East Mississippi. Our specific objectives were to: (1) investigate the annual pattern of pond hydrological processes; (2) determine the ratio of pond size to irrigated soybeans land; and (3) estimate the mitigation of groundwater depletion from the use of on-farm water storage ponds.

MODEL DESCRIPTION AND SIMULATION SCENARIOS

A STELLA model has been developed to characterize pond water balance and hydrological processes (Ouyang *et al.* 2016). As shown in Figure 1, this model includes rainwater collection, runoff water gathering, surface water evaporation, irrigation water use, pond water spillway release, and soil seepage and infiltration losses. Although an elaborate description of the model can be found in Ouyang *et al.* (2016) and is

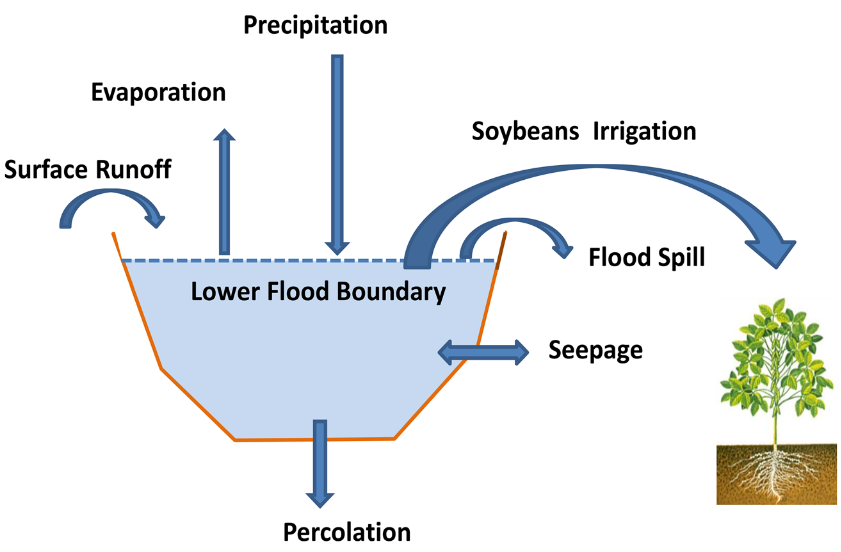

Figure 1 | Pond hydrological processes used in this study.

beyond the scope of this study, a moderate depiction of the model's major components, including surface runoff, evaporation and infiltration, is given below for readers' convenience.

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

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

where R is the surface runoff rate (cm/h), P is the rainfall rate (cm/h), and S is the watershed retention parameter.

Abtew (2005) compared the rates of ET from open water for the Bowen ratio-energy balance measurements with the simple equation predictions and found that the simple equation can be adequately used to estimate open water evaporation. Based on the observation, the pond water evaporation is estimated using the following equation (Abtew 2005):

$$E = K_1 \frac{R_s}{\lambda} \quad (2)$$

where E is the evaporation from pond water (cm/h), K_1 is the coefficient (dimensionless), R_s is the solar radiation (kJ/cm^2/h), and λ is the latent heat of vaporization (kJ/g).

The soil water infiltration rate is estimated by the following equation (Mullins *et al.* 1993):

$$D_{\text{inf}} = \alpha(\theta - f_c) \quad (3)$$

where D_{inf} is the infiltration rate (cm^3/h), α is the percolation rate coefficient (cm^3/h), θ is the volumetric water content (cm^3/cm^3), and f_c is the field water capacity (cm^3/cm^3).

The model has been validated using experimental data in our previous study. The regression equation between the predicted and measured pond water evaporation was $Y_{\text{Prediction}} = 0.98X_{\text{Measurement}}$ with $R^2 = 0.94$ and $p < 0.001$, whereas the regression equation between the predicted and measured pond water level was $Y_{\text{Prediction}} = 0.95X_{\text{Measurement}}$ with $R^2 = 0.50$ and $p < 0.001$. These statistical results represented very good to reasonable correlations between the model predictions and the experimental measurements. Then, the model was applied to estimate diurnal and seasonal pond hydrological processes as well as pond water budget in the Mississippi Delta with promising results. An elaborate description of the mathematical functions and procedures used to develop the model is beyond the scope of this study but can be found in Ouyang *et al.* (2016).

In this study, a typical on-farm water storage pond with an area of 5.06 ha and an average depth of 2 m was selected (Figure 2). This pond size reflects the average field conditions near Macon, East Mississippi. Two simulation scenarios were performed in this study. The first scenario was chosen to predict the annual patterns of pond hydrologic processes under conditions without using pond water for soybeans irrigation. The second scenario was selected to estimate the annual patterns of pond hydrological processes with using pond water for soybeans irrigation. In this second scenario, all of the simulation conditions and input parameters were the same as those used in the first scenario except for the pond water used to irrigate for different soybeans land sizes. Table 1 lists the number of irrigations, irrigation rate, and total irrigation for each year and their 10-year averages during the growth of the soybeans in East Mississippi. These irrigation data were obtained from our previous study (Feng *et al.* 2016) and were used as model inputs in this study. It should be noted that the irrigation rate was 2.54 cm/d (or 1 inch/d), which is a very common practice in East Mississippi. Comparison of the simulation results from the two scenarios allowed us to evaluate the impacts of irrigation upon pond hydrological processes and to determine the ratio of pond size to irrigated soybeans land. The simulation period was 10 years started on the first day of 2002 and terminated at the end of 2011, for each scenario an hourly time step was used. All of the input parameters for these scenarios are given in Table 2.

RESULTS AND DISCUSSION

Pond hydrological processes

Changes in pond water evaporation, pond water spill, and pond water level and corresponding to rainfall for the

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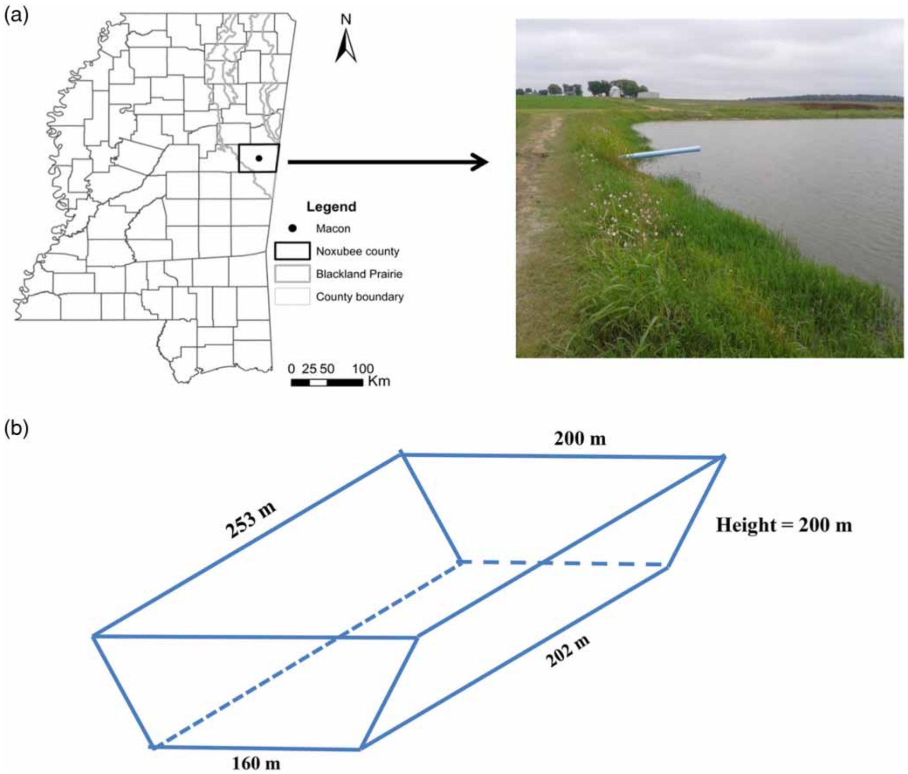

Figure 2 | Location of a pond (a) and its dimension (b) selected for simulation.

Table 1 | Irrigation data used as model input in this study

Year	Number of irrigations	Irrigation rate each time (mm)	Total irrigation (mm)
2002	3	25.4	76.2
2003	2	25.4	50.8
2004	1	25.4	25.4
2005	5	25.4	127.0
2006	12	25.4	304.8
2007	8	25.4	203.2
2008	7	25.4	177.8
2009	2	25.4	50.8
2010	4	25.4	101.6
2011	7	25.4	177.8
10-year average	5.1	25.4	129.5

The data were obtained from Feng *et al.* (2016) and the number of irrigations each year was determined based on rainfall amount and soil moisture regime.

simulation scenario without using pond water for irrigation over a 10-year period are shown in Figure 3. A typical annual pond evaporation pattern, increasing from winter to summer followed by decreasing from summer to next winter, was observed for the entire simulation period (Figure 3(b)). In general, the mean rate of pond evaporation ranged from 20 cm^3/d/pond in winter to 50 cm^3/d/pond in summer. The highest rate of pond evaporation (63 cm^3/d/pond) was found in the summer of 2007 when it was in dry conditions with less rainfall (Figure 3(a)). A zero rate of pond evaporation was also observed because the STELLA model assumed no evaporation occurred with rain and during the night. The annual pond evaporation pattern happened because of the annual cycles of solar radiation and air temperature with more intensive radiation and warmer temperatures during summer compared with winter. Results showed that annual pond evaporation was controlled by air temperature and solar radiation.

Daily changes in pond water spill (Figure 3(c)) for the simulation scenario without using pond water for irrigation over a 10-year period corresponded well to rainfall events (Figure 3(a)), i.e., the rate of pond water spill increased

Table 2 | Input parameter values used in this study

Parameter	Value	Source
Hydrological conditions		
Curve number	89	Rawls *et al.* (1992)
Hourly rainfall (cm/h)	Time series measurements	Local weather station
Effective land area for runoff (cm^2)	15,297,117,277 (or 153 ha)	Estimated
Pond drainage (cm^3/h)	0.00005	Estimated
Lateral seepage (cm^3/h)	0	Estimated
Evaporative coefficient K_1 in Equation (3)	0.0022	Calibrated
Hourly solar radiation (kJ/ cm^2/h)	Time series data	Measured
Hourly air temperature (°C)	Time series data	Measured
Pumping for irrigation rate (cm^3/h)	Time series measurements	Estimated
Irrigation area (cm^2)	varied for different ratios	Assumed
Pipe flow		
Manning roughness coefficient, *n*	0.01	Maidment (1992)
Bottom slope of pipe	0.003	Measured
Radius of the pipe (cm)	60	Measured
Pond Matrix		
Bottom pond width, *a* (cm)	1.60E + 04	Measured
Bottom pond length, *b* (cm)	2.02E + 04	Measured
Maximum top pond width, *Wm* (cm)	2.00E + 04	Measured
Maximum top pond length, *Lm* (cm)	2.53E + 04	Measured
Maximum pond height, *Hm* (cm)	2.00E + 02	Measured
Pumping low limit of pond level (cm)	5.00E + 01	Measured
Maximum pond volume (cm^3)	6.51E + 10	Calculated
Initial pond volume (cm^3)	6.50E + 10	Assumed
Pipe spill level	1.80E + 02	Measured
Pond spill level	1.99E + 02	Measured

with the rate of rainfall. The highest rate of pond spill was 11,559 m^3/d/pond during early 2004 when the highest rate of rainfall was 0.42 cm/d. This occurred because the sources of water entering the pond were from rainwater interception directly by pond as well as from rainwater collection indirectly by pond through surface water runoff. Figure 3(d) showed the moderate variations in pond water level over the 10-year period. It seems that pond water level was relatively stable under natural conditions and without using pond water for irrigation.

Variations of pond evaporation, pond spill, and pond level in corresponding to rainfall for the simulation scenario with using pond water for irrigation over a 10-year period are shown in Figure 4. The ratio of pond size to soybeans irrigation land area was 1:18. Comparison of Figures 3(b) and 4(b) showed that changes in pond evaporation for conditions with and without using pond water for irrigation were very similar in trend and magnitude. Results indicated that the impact of pond water used for irrigation upon pond evaporation was trivial. In contrast, dramatic differences in pond spill and water level were observed for conditions with and without using pond water for irrigation. Pond spill occurred most of the times when raining for the condition without using pond water for irrigation (Figure 3(c)), whereas pond spill occurred only for four periods for the condition with using pond water for irrigation (Figure 4(c)).

Comparison of Figures 3(d) and 4(d) revealed that a dramatic decline in pond water level occurred when the pond water was used for irrigation. Although such declines varied from year to year, a lowest pond water level of 0.08 m was observed in the summer of 2007 during the entire 10-year simulation period. This was just because there were lower rainfall rates (Figure 4(a)) plus the use of pond water for irrigation (Figure 4(e)) during the summer of 2007. Comparison of Figures 4(d) and 4(e) further demonstrated that a decline of pond water level corresponded well to the use of pond water for irrigation. The ratio of pond size to the irrigated soybeans land for the results shown in Figure 4 was 1:18 and the irrigation rate was 2.54 cm/d (or 1 inch/d). In other words, if the low limit of pond water level was above 0.08 m, a 1-ha pond with an average depth of 2 m could irrigate 18 ha soybeans land over a 10-year simulation period. This simulation finding is very useful to farmers and water resources managers for on-farm water storage pond construction and soybeans irrigation.

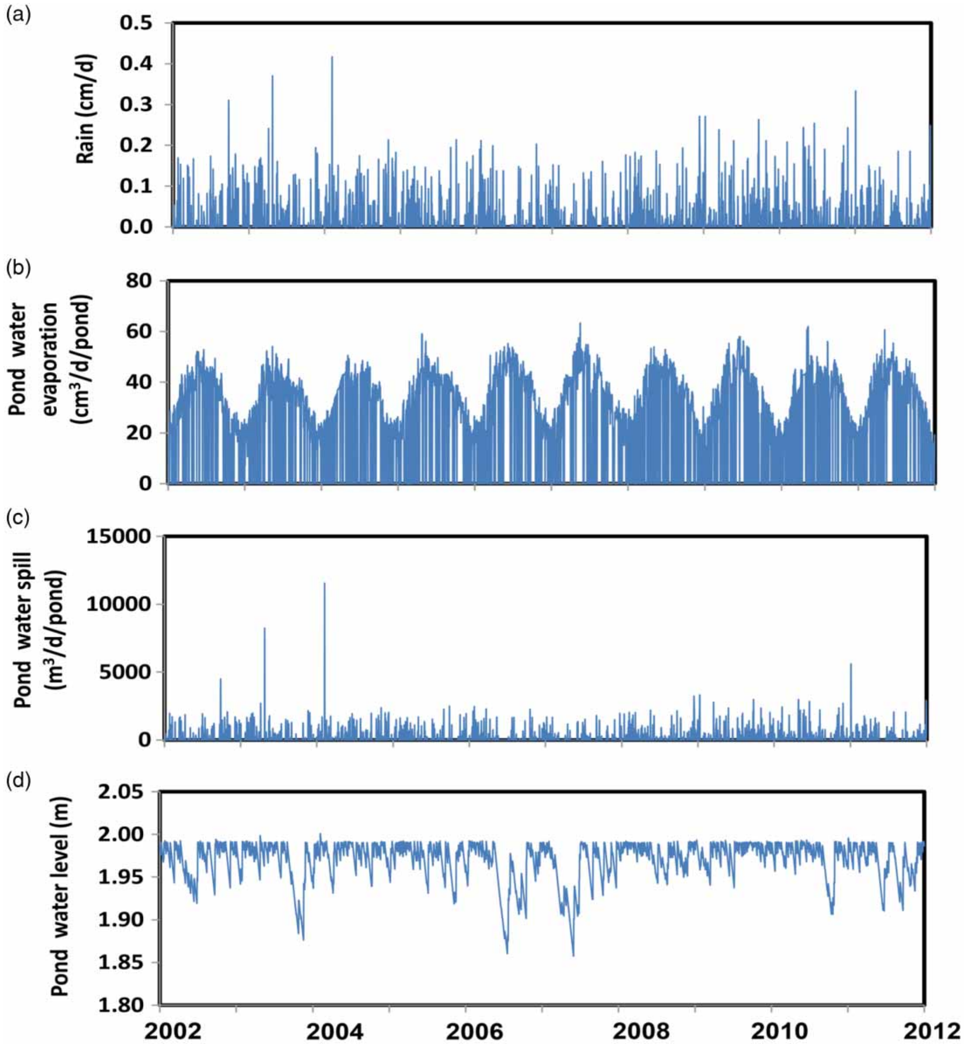

Figure 3 | Annual variations of daily rainfall (a), pond evaporation (b), pond spill (c), and pond level (d) during a 10-year simulation from 2002 to 2012 for conditions without using pond water for soybeans irrigation.

Ratio of pond size to irrigated soybean land

Little effort has been devoted to estimating the ratio of pond size to irrigated soybeans (or other crops) land in Mississippi. Staffs from USDA-NRCS in Mississippi have roughly approximated that the ratio is 1:13 (personal communication). However, an accurate estimation of such a ratio based on pond and its surrounding hydrological processes, local climate conditions, and crop irrigation demands has not yet been performed. Figure 5 showed the variations of pond water level under the following three ratios: 1:13, 1:18, and 1:23. This figure was constructed by changing the irrigated soybeans land area from 13 to 23 ha while keeping the same pond size and irrigation rate. When the ratio increased, more pond water was drawn for irrigation. As a result, a greater decline in pond water level was observed. The lowest pond water levels were 0.95 m for the ratio of 1:13 (Figure 5(a)), 0.08 m for the ratio of 1:18 (Figure 5(b)), and 0.0 m for the ratio of 1:23 (Figure 5(c)) during the 10-year simulation period from 2002 to 2012. It seems that there was almost no water left in the pond on two occasions for the ratio of 1:23, whereas there was plenty of water left in the pond for the ratio of 1:13. The ratio of 1:18 would be a reasonable choice for this region if farmers would like to keep the pond water level

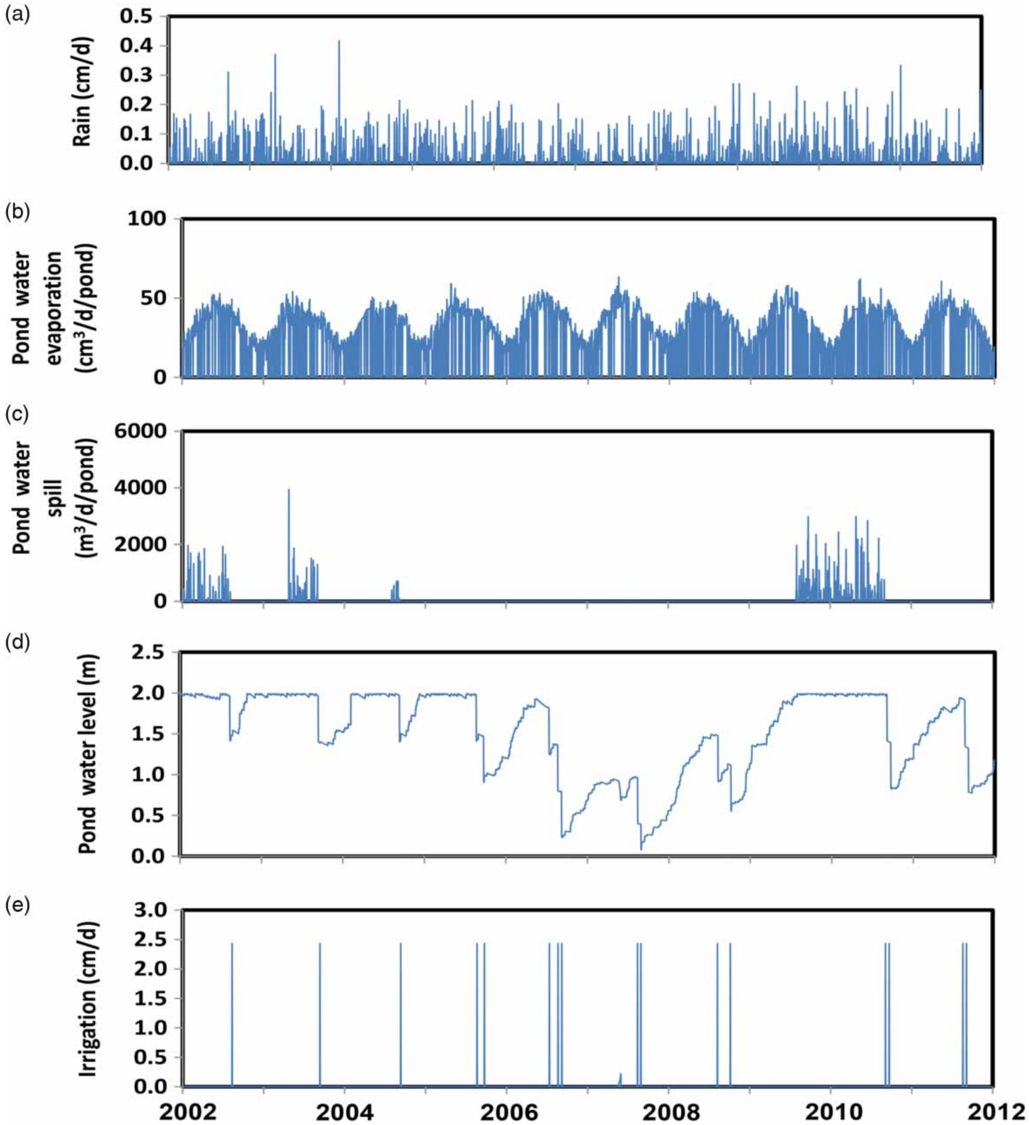

Figure 4 | Annual variations of daily rainfall (a), pond evaporation (b), pond spill (c), pond level (d), and irrigation rate (e) during a 10-year simulation from 2002 to 2012 for conditions with using pond water for soybeans irrigation.

above 0.08 m. More specifically, this 5-ha pond in Macon, Mississippi can supply enough water to irrigate 90 ha soybeans land during the entire 10-year period.

Figure 5(c) further revealed that the maximum ratio of pond size to irrigated soybeans land could be extended to 1:23 for the entire 10-year period if the pond water level was occasionally drawn to zero. Within this ratio, there were only two dry conditions in 2007 when the pond water was drawn to zero, while for the rest of the time, the pond water level was always above 0.28 m (Figure 5(c)).

Water resources conservation estimation

Figure 6 shows that about 390,313 m^3 of pond water was used to irrigate 72 ha of soybeans land over a 10-year period if the ratio was 1:18. In other words, about 542 m^3 of ground or surface water was saved per hectare of soybeans each year if these waters were used for irrigation. Although there were no data available for East Mississippi, it has been reported that the average loss of groundwater is about 493,000,000 m^3/y from 1987 to 2014 in the Mississippi

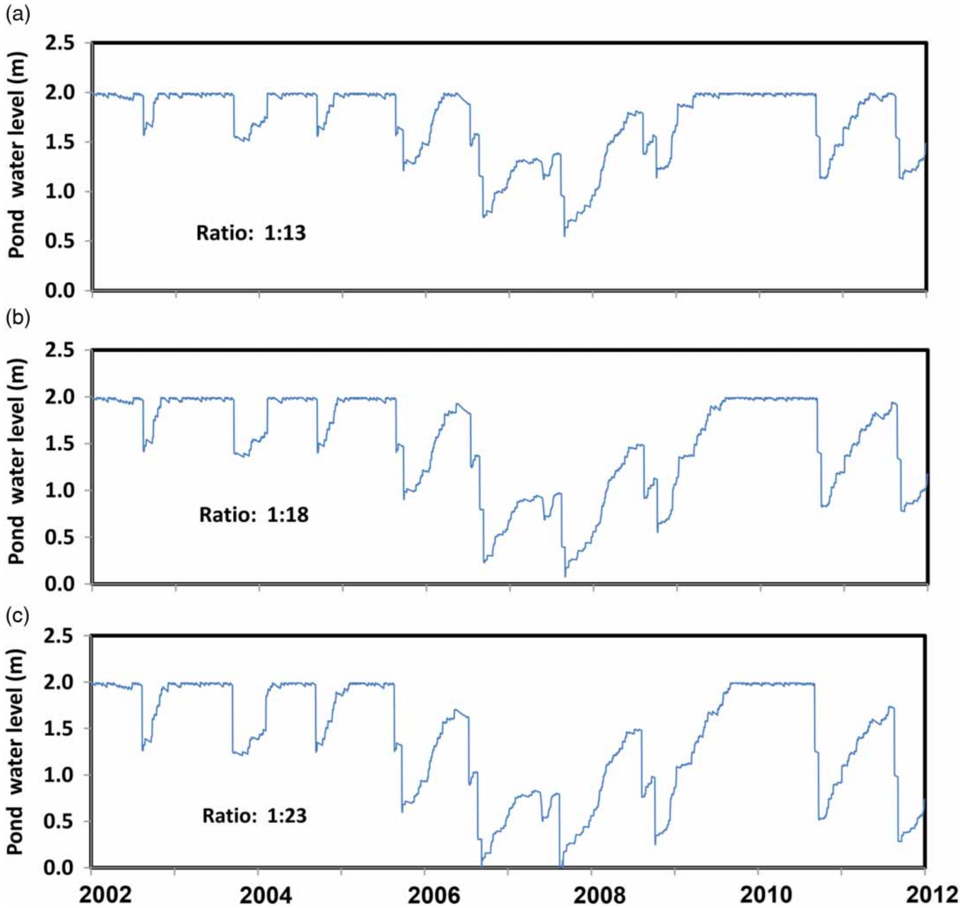

Figure 5 | Comparison of pond water levels among ratios of pond size to soybeans irrigation land areas: 1:13 (a), 1:18 (b), and 1:23 (c) during a 10-year simulation from 2002 to 2012.

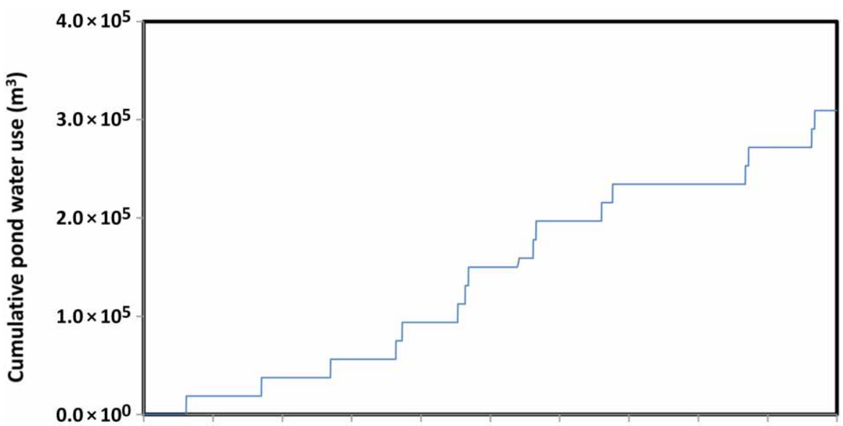

Figure 6 | Cumulative pond water use at the ratio of pond size to soybeans irrigation land areas of 1:18 during a 10-year simulation from 2002 to 2012.

Delta. If a 10,000-ha of soybean land is irrigated with pond water in the Mississippi Delta, it would reduce the loss of groundwater by 11% (5,420,000/4,930,000,000 = 11%) when the ratio of pond size to irrigated soybeans land was 1:18. Results showed that on-farm water storage pond is one of the promising alternatives to conserve groundwater resources.

SUMMARY

In this study, a STELLA model developed previously was applied to investigate the annual pattern of pond hydrological processes, determine the ratio of pond size to irrigated crop land, and estimate the mitigation of groundwater depletion due to the use of an on-farm storage pond.

A typical annual pond evaporation pattern, with increasing from winter to summer followed by decreasing from summer to next winter, was observed for a 10-year simulation period. The annual pond evaporation was controlled by air temperature and solar radiation and the pond water level was relative stable for conditions without using pond water for irrigation. In contrast, dramatic changes in pond spill and water level were observed for conditions with using pond water for irrigation. A reasonable ratio of pond size to the soybeans irrigation land area was estimated to be 1:18 if the irrigation rate was 2.54 cm/d (or 1 inch/d) and the average pond water level was above 0.08 m. A maximum ratio of pond size to irrigated soybeans land could be 1:23 for the entire 10-year period if the pond water level was occasionally drawn to zero.

We postulated that if a 10,000-ha soybean land was irrigated with pond water under the ratio of 1:18, it could reduce the loss of groundwater by 11%. This study showed that on-farm water storage pond is one of the promising alternatives to conserve groundwater resources. Results suggested that the STELLA model is a useful tool to estimate the pond size for desired crop irrigation land. Further study is warranted to estimate the optimal contributing drainage watershed area for runoff water collected by the pond.

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