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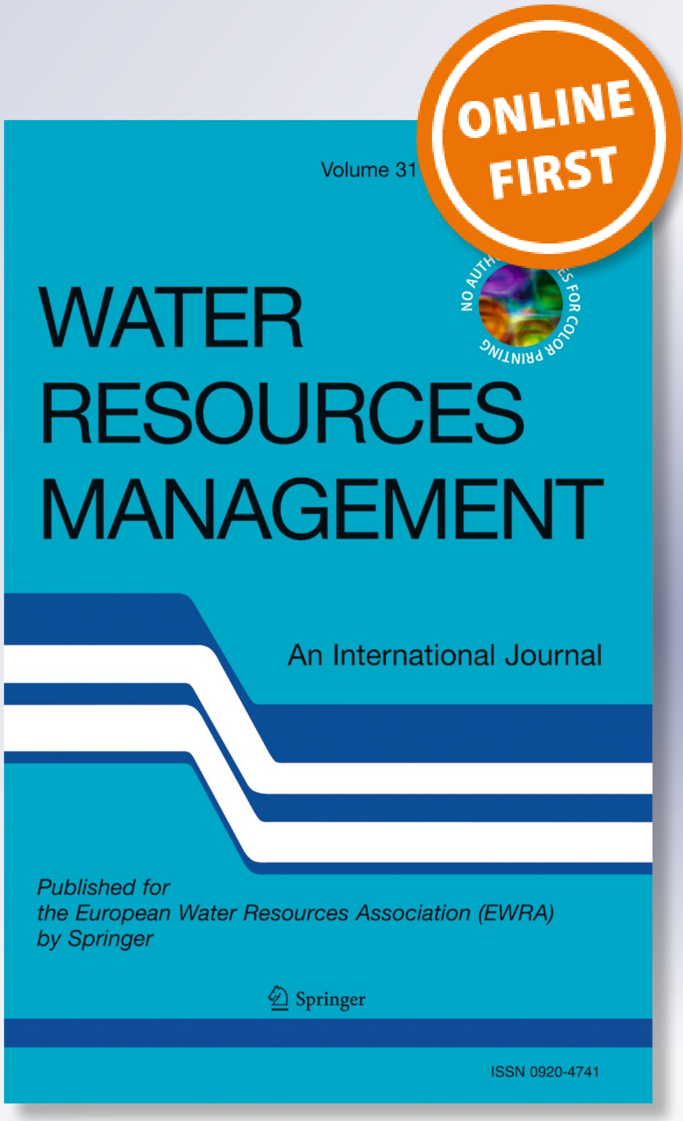

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A Model to Estimate Hydrological Processes and Water Budget in an Irrigation Farm Pond

Ying Ouyang[1] · Joel O. Paz[2] · Gary Feng[3] · John J. Read[3] · Ardeshir Adeli[3] · Johnie N. Jenkins[3]

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Abstract With increased interest to conserve groundwater resources without reducing crop yield potential, more on-farm water storage ponds have been constructed in recent years in USA and around the world. However, the hydrological processes, water budget, and environmental benefits and consequences of these ponds have not yet been fully quantified. This study developed a computer model to estimate farm pond hydrological processes and water budgets using the STELLA (Structural Thinking and Experiential Learning Laboratory with Animation) software. The model was applied, as demonstrations, to estimate the diurnal and seasonal pond hydrological processes and water budget at Metcalf Farm (33° 39′ 48″ N, 90° 39′ 12″W) in Porter Bayou Watershed located in Mississippi Delta, USA. Two simulation scenarios were chosen in this study, one without and the other with pumping pond water for soybeans irrigation. Simulations showed that the evaporative loss of water from the pond was minimal, while the runoff water from rainfall was a major source of water entering into the pond. Therefore, factors that would affect surface water runoff should be considered in locating and sizing a farm pond in Mississippi. The seasonal rainwater and runoff water collected by the pond was: winter > spring > summer > fall, which corresponded well to the seasonal rainfall events; whereas seasonal order of pond evaporation was: summer > spring > fall > winter, which corresponded well to the seasonal solar radiation and air temperature. The STELLA model developed proved to be a useful tool for estimating pond water budget and consequently irrigation practices for crops.

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1 Introduction

Farm pond is one of important sources of irrigation water to ensure optimal crop yields, particularly for small farms with field crops and vegetables. It also can supply water for frost protection, recharge groundwater, and provide a wide range of additional economic and environmental benefits. Farm pond is normally filled by collecting precipitation, capturing runoff, storing reclaimed water, and diverting water from streams at peak flows.

Mississippi is a major state for agricultural crop production in the Southeast United States. The desire by most farmers to stabilize or enhance crop yields through irrigation has led to the overdraft of groundwater resources in many regions of Mississippi, particularly the Mississippi Delta (Konikow 2013). In this region, groundwater pumping has resulted in an average decline during the past 10 years of 370,044,557 m^3 water per year from the alluvial aquifer (Powers 2007). Unlike the Mississippi Delta where groundwater is the principal source of irrigation, surface waters impounded in farm ponds are commonly used to irrigate crops in the Blackland Prairie region of east-central Mississippi due to the deeper groundwater aquifer between 61 and 91 m.

With increasing concerns on surface groundwater depletion and interests in conserving water resources (Tayfur et al. 2016), more irrigation farm ponds have been constructed in recent years in Mississippi, USA and around the world (Carvajal et al. 2014; Ouyang et al., 2016). However, the hydrological processes, water budget, and environmental benefits and consequences of ponds 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, hydrological conditions, and climate environments. To our best knowledge, there is currently no suitable tool to estimate the relationship between the pond water availability and the crop water use around the world. A commonly used method for timing irrigation is based on the "feel-of-the soil", that is, without measurements of soil and crop water use status. Knowledge of farm pond hydrological processes and water availability is therefore crucial to apply pond water to the most profitable crops, maximize water use efficiency, and reduce surface and groundwater usage.

The Soil-Plant-Air-Water (SPAW) model developed in the 1980s (Saxton and McGuinness 1982) has since been modified for studies on agricultural field hydrology (Saxton et al. 1992), soil water characteristics (Rawls et al. 1982), and water budget estimates for wetlands and lagoons (Saxton and Willey 1999; Saxton et al. 2006). SPAW is a valuable research tool for estimating the daily content and movement of water and nutrients in field soils, daily water budgets for agricultural wetlands, ponds and reservoirs (http://hydrolab.arsusda.gov/SPAW/Index.htm). However, the model is reasonably complex and requires some advanced training to use, as well as a large amount of input data that may be time consuming to obtain through field experimentation. These limitations of the SPAW model make it impractical for wide use by farm managers and practitioners. Therefore, a need exists to develop a less-intensive and yet realistic tool to quantify farm pond hydrology and water budget.

The objectives of this study were to: (1) develop a STELLA (Structural Thinking, Experiential Learning Laboratory with Animation) model to characterize pond water balance and hydrological processes such as rain water collection, runoff water gathering, reclaimed water recharge, surface water evaporation, irrigation water use, pond discharge pipe release, pond spillway release, and soil seepage and drainage losses; (2) validate the model using experimental data; and (3) apply the validated model to estimate diurnal and seasonal pond hydrological processes as well as pond water budget under natural conditions (i.e., without pumping) in Mississippi.

2 Materials and Methods

2.1 Theoretical Description

Development of a STELLA model is based on several farm pond hydrological processes shown in Fig. 1. For surface water runoff, the curve number method is used and given as follows (Rawls et al. 1992; Mullins et al. 1993):

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

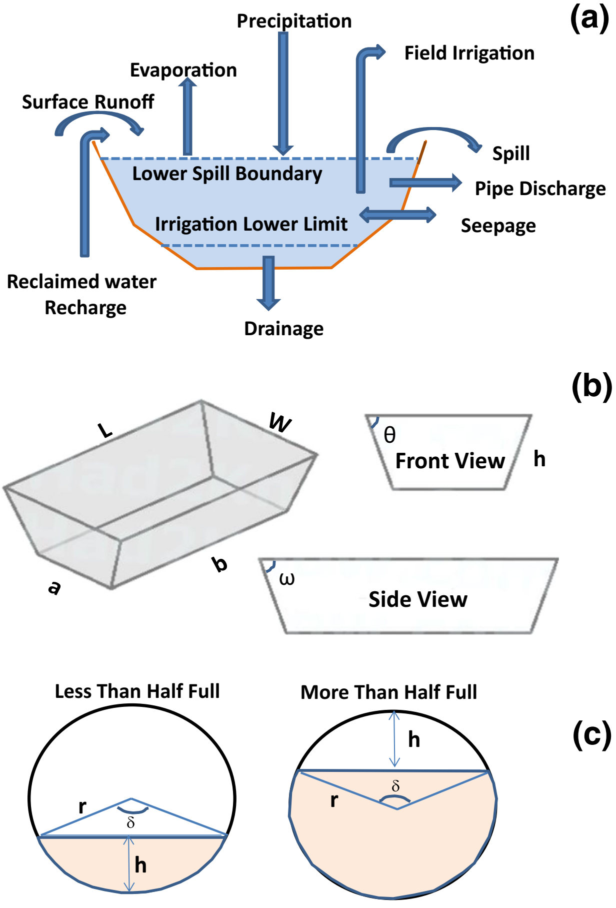

Fig. 1 Schematic diagram of a pond matrix showing the hydrological processes (**a**), the trapezoidal trough (**b**), and pipe flow (**c**) used in this study

where R is the surface runoff rate (cm h^{-1}), P is the rainfall rate (cm h^{-1}), and S, the watershed retention parameter, is estimated by:

$$S = \frac{1000}{CN} - 10 \tag{2}$$

where CN is the runoff curve number. Curve numbers are a function of soil type, soil physical property, crop type, and management practice. Surface water runoff occurs only when the rainfall rate exceeds the infiltration capacity of a soil and surface water ponding occurs. Additionally, if (P - 0.2*S) is negative in Eq. (1), the surface water runoff is zero (Rawls et al. 1992). Surface water runoff can also be measured directly using runoff collectors, whereas rainfall data can be obtained from a site or nearby weather station.

For evapotranspiration (ET) from wetland and open water, there are currently six equations that are based on local meteorological data (Abtew 1996). Although Penman Combination equation is the best for estimating open water ET (Allen et al. 1998; Abtew 1996), it requires an extensive set of meteorological data. Abtew (2005) compared the rates of ET from wetland and open water in the Florida Everglades for the Bowen ratio-energy balance measurements and the simple equation predictions and found the simple equation can be adequately used to estimate open water evaporation and wetland ET. Based on this observation, pond water evaporation in the present study is estimated using this simple equation below (Abtew 1996 & Abtew 2005):

$$E = K_1 \frac{R_s}{\lambda} \tag{3}$$

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 latent heat is the amount of heat required to evaporate or condense a unit mass of water and can be estimated as (Rogers and Yau 1989):

$$\lambda = 2.501 - 0.002361T + 0.0000016T^2 \tag{4}$$

where T is the air temperature (°C). Eq. (4) is accurate in a range of −25 to 40 °C and λ has a unit of kJ cm^{-3} assuming the density of water is approximately 1 g cm^{-3}.

The lateral seepage of water from saturated soil into pond or vice versa can be estimated by Darcy Law:

$$D_{\text{lateral}} = AK \frac{h_{\text{soil}} - h_{\text{pond}}}{l} \tag{5}$$

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). It is assumed that no water exchange between the pond and the surrounding soil under the saturated condition because of the extremely low saturated hydraulic conductivity for the heavy clayey soil in Mississippi, where most farm ponds are currently constructed. Similarly, it was assumed that no drainage occurs from the bottom of the pond into the deeper soil profile due to the same reason. Other hydrological processes presented in Fig. 1, including reclaimed water recharge, field irrigation, pond water levels for overflow (pond spill) and irrigation lower limit, are pond-specific and can be obtained from experimental measurements.

After incorporating all of the hydrological processes into STELLA (see next section), the model automatically calculates the volume of water stored in the pond at any given time (inherit nature of the STELLA model). However, the surface area and water level of the pond, which change through time, are not generated automatically in the model. Because surface area of pond water affects model estimates for evaporation and precipitation, and water level in the pond affects model estimates for overflow and irrigation lower limit, these two parameter values were calculated as described below.

Assuming that the pond is a trapezoidal trough (Fig. 1b), the volume of water in the pond can be calculated as:

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

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). For a specific pond (or a trough), the values of *a* and *b* are constant, while the values of W, L, and $h_{p.}$ change with the volume of the pond water, which are functions of time. For a given $h_{p.}$ at time t, W and L can be calculated as:

$$W(t) = \frac{2h_p(t)}{\tan\theta} + a \tag{7}$$

and

$$L(t) = \frac{2h_p(t)}{\tan\omega} + b \tag{8}$$

with

$$\tan\theta = \frac{2h_m}{(W_m - a)} \tag{9}$$

and

$$\tan\omega = \frac{2h_m}{(L_m - b)} \tag{10}$$

where θ and ω are the angles (Fig. 1b) and the subscript m denotes the maximum values of the parameters for a trough, which are known for a specific pond. Rearranging Eq. (6) for a given time, we obtain:

$$h_p(t) = \frac{6V(t)}{[W(t)L(t) + (W(t) + a)(L(t) + b) + ab]} \tag{11}$$

Equation (11) is used to obtain the relationship between the pond water level and the pond water volume at a given time (t) through linear regression. As an example, the relationship between the pond water level and the pond water volume for the trapezoidal trough used in this study is given in Fig. 2a. Since the volume of pond water at a given time is automatically stored in the STELLA model, the height of pond water level can be obtained using the linear regression equation shown in Fig. 2a.

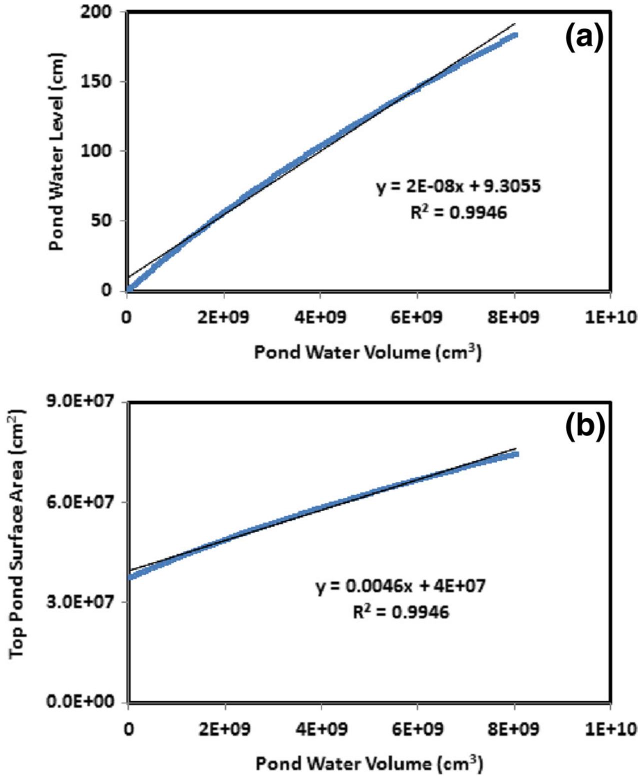

Fig. 2 Relationships of pond water level (**a**) and top pond surface area (**b**) to pond volume for the trapezoidal pond used in this study

The surface area of a pond at a given time, t, can be calculated as:

$$A(t) = W(t)L(t) \tag{12}$$

where A is the surface area of the pond (cm^2). Analogues to the case of pond water volume vs. pond water level, Eqs. (6) and (12) are used to obtain the relationship between the pond surface water area and the pond water volume at a given time (t) through linear regression (Fig. 2b).

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 can be used to calculate water discharge out of the pond from a pipe (Chow 1959):

$$Q = \left(1.49/n\right)A_p\left(R_h^{2/3}\right)S_b^{1/2} \tag{13}$$

With

$$R_h = \frac{A_p}{P_{wp}} \tag{14}$$

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). When the pipe is not full flow, the values of A_p and P_{wp} change over time and can be calculated as:

$$A_p = \frac{r^2(\delta - \sin\delta)}{2} \tag{15}$$

$$P_{wp} = r\delta \tag{16}$$

$$\delta = 2\arccos\left(\frac{r-y}{r}\right) \tag{17}$$

$$y = h \tag{18}$$

for less than half-full flow (Fig. 1c) and

$$A_p = \pi r^2 - \frac{r^2(\delta - \sin\delta)}{2} \tag{19}$$

$$P_{wp} = 2\pi r - r\delta \tag{20}$$

$$\delta = 2\arccos\left(\frac{r-y}{r}\right) \tag{21}$$

$$y = 2r - h \tag{22}$$

for more than half-full flow (Fig. 1c), where r is the radius of the pipe (cm), δ is the angle (radians), and y is the height of the water column in the pipe (cm).

Under heavy rainfall, the pond water level may exceed the pond spillway level which results in pond overflow. This case is included in the STELLA model. In other words, any excess water (i.e., > maximum pond water storage capacity) will flow out of the pond ether through the discharge pipe or through the discharge pipe and pond spillway.

2.2 STELLA Model

STELLA is a modeling software package for constructing a pictorial diagram of system processes and then allocating the appropriate values and mathematical functions to the system (Isee Systems 2014). The major features of STELLA consist of the following four tools: (1) Stocks, which are the state variables for accumulations, they gather whatever flows into and out of the system; (2) Flows, which are the exchange variables that govern the arrival or the exchanges of information between the state variables; (3) Converters, which are auxiliary variables, can be represented by constant values or by values dependent on other variables, curves or functions of various categories; and (4) Connectors, which are to connect among modeling features, variables, and elements. STELLA has been widely used in the biological, ecological, and environmental sciences (Peterson and Richmond 1996; Ouyang 2008; Ouyang et al. 2012). A complete description of the STELLA package can be found in Isee Systems (2014).

The first step in STELLA model development is to build a basic structure or map (Fig. 3) to capture the hydrological processes given in Fig. 1. For instance, the pond water surface evaporation described by Eq. (3) can be translated into a STELLA model component as shown in Fig. 3b. In this figure, the converters (represented by empty circles) denote the Evaporation Rate, Latent Heat, Air Temperature, Solar radiation, and K_1 variable, which are then linked together through the use of connectors (represented by single lines with arrows). Having developed the basic structure (or map), the second step is to assign the initial values for

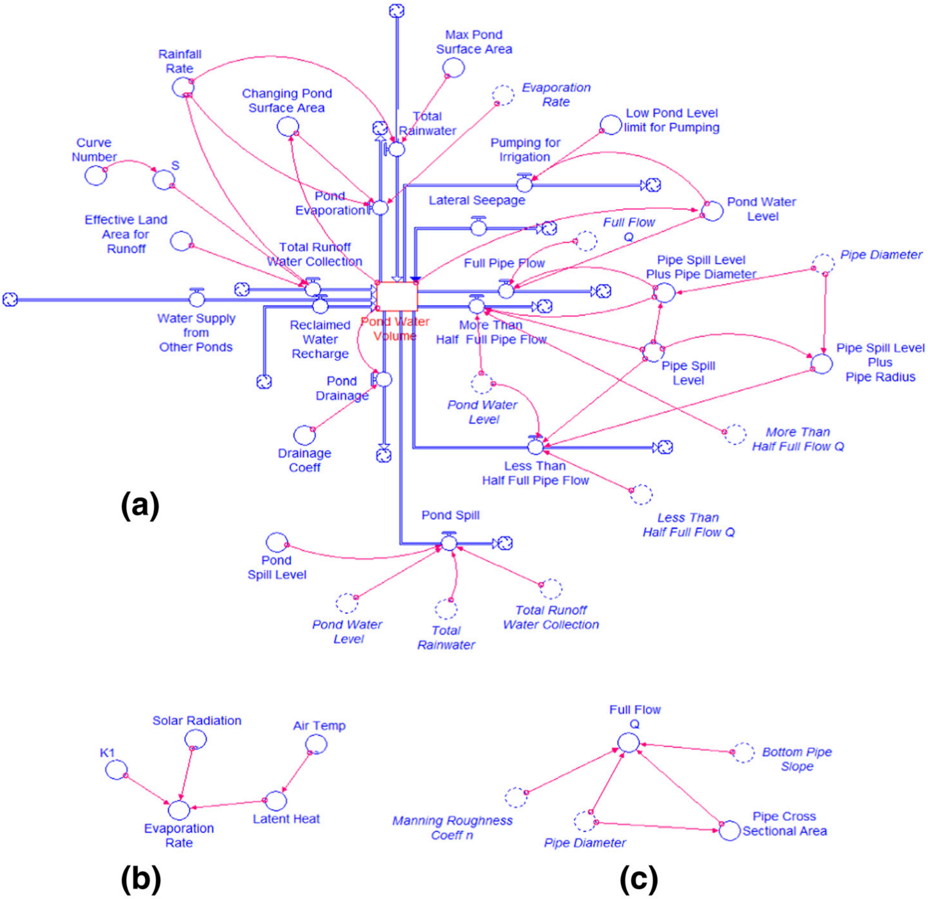

Fig. 3 A STELLA model for pond water hydrology (**a**), evapotranspiration (ET), and full pipe flow (**c**) calculations

stocks, equations for flows, and input values for converters. The major STELLA model map with key components was shown in Fig. 3.

2.3 Model Validation

Before the STELLA model can be used to estimate pond hydrological processes and water budget, the model needs to be validated using observed data. Model validation is a process of obtaining the best fit between the observed data and predicted results without changing any input parameter values that are taken from experimental measurements, theoretical calculations, and literature reports. In this study, we attempted to validate the model using experimental data obtained at a tailwater recovery (TWR) canal (hereafter referred to as a pond) at Metcalf Farm (33° 39′ 48″ N, 90° 39′ 12″W), which is located within the Porter Bayou Watershed, Mississippi. Metcalf Farm has an area of 76.5 ha with corn and soybean rotation. The single TWR pond runs approximately through the middle of the property and its dimensions are given in Table 1. A Spectrum TechnologiesTM, WatchDog 2900ET weather station was installed at Metcalf Farm with sensors that measured rainfall, solar radiation, wind direction, wind dust, wind speed, air temperature, and dew point temperature. Water level sensors (Global Water model WL 16) were installed to record pond water levels. Table 1 lists all of the input parameter values used for

Table 1 Input parameter values used for model validation and application

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)	7,000,000,000 (or 7 ha)	Estimated based topography
Water supply from other canals (cm^3/h)	0	Estimated
Reclaimed water recharge (cm^3/h)	0	Estimated
Pond drainage (cm^3/h)	0	Estimated
Lateral seepage (cm^3/h)	0	Estimated
Evaporative coefficient K_1 in Eq. (3)	0.0022	Calibrated
Hourly solar radiation (kJ/cm^2/h)	Time series data	Measured
Hourly air temperature (°C)	Time series data	Measured
Pumping out rate (cm^3/h)	23,166,715.32	Estimated based on data
Irrigation area (cm2)	1,000,000,000 (1 ha)	
Irrigation lower limit (cm)	15.24	Measured
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)	457	Measured
Bottom pond length, b (cm)	81,880	Measured
Maximum top pond width, Wm (cm)	909	Measured
Maximum top pond length, Lm (cm)	81,980	Measured
Maximum pond heigth, Hm (cm)	183	Measured
Pumping low limit of pond level (cm)	75	Measured
Maximum pond volume (cm^3)	7,963,461,245	Calculated
Initial pond volume (cm^3)	5.56E + 07	Assumed based on the site
Pipe spill level	114	Measured
Pond spill level	184	Measured

model validation. These input parameter values were obtained either from experimental measurements, theoretical calculations, or literature reports.

Comparisons of the observed and predicted E and pond water level are shown in Figs. 4 and 6, respectively. The regression equation of the predicted E against its corresponding measured E was $Y_{Prediction} = 0.98X_{Measurement}$ with $R^2 = 0.94$ and $p < 0.001$, whereas the regression equation of the predicted pond water level against its corresponding measured pond water level was $Y_{Prediction} = 0.95X_{Measurement}$ with $R^2 = 0.50$ and $p < 0.001$. These represented very good to reasonable correlations between the model predictions and the experimental measurements. Additionally, the monthly E (Fig. 4b) and hourly pond water level (Fig. 5b) from model predictions matched well graphically with those from field observations.

2.4 Model Application

Two simulation scenarios were selected for model application. The first scenario was chosen to estimate the diurnal and seasonal pond hydrological processes and water budget at Metcalf Farm under natural field conditions. All of the simulated conditions and input parameter values for this scenario were the same as those used during model validation except that no pumping was operated. This scenario reflected the natural field conditions and provided a unique opportunity to address the natural pond hydrological characteristics. Approximately one-year simulation period was chosen for this scenario, which started at 0 h (midnight) on March 10, 2012 and ended on February 28, 2013. The reason for selecting this simulation period is the availability of climate data (i.e., rainfall, air temperature, and solar radiation) at the study site

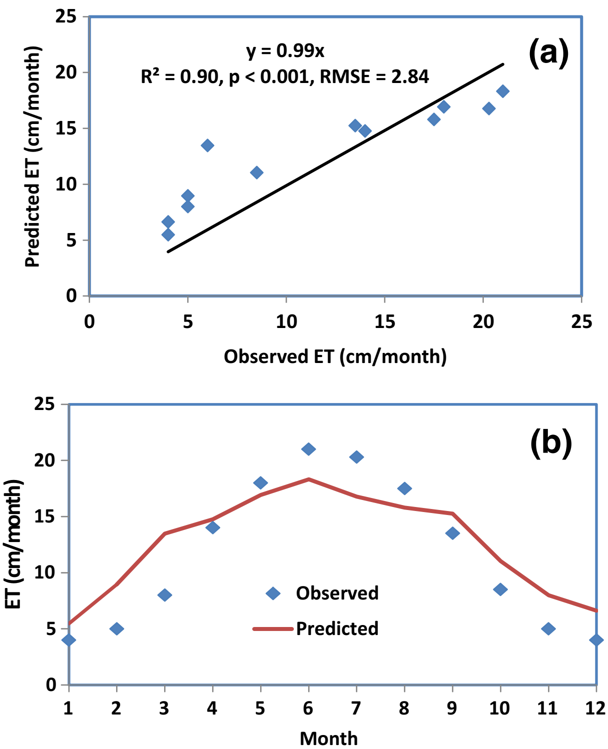

Fig. 4 Statistical (**a**) and graphical (**b**) comparison of model predicted and field measured ET

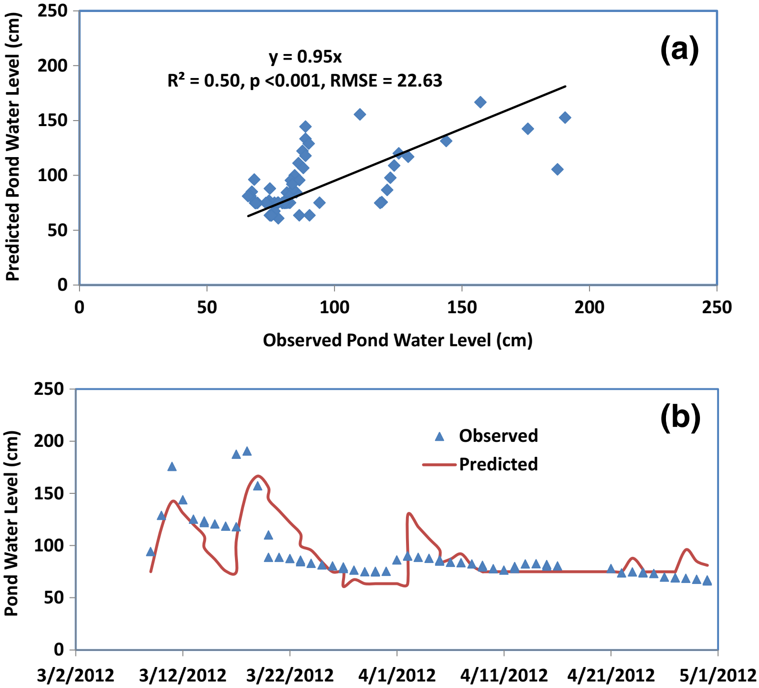

Fig. 5 Statistical (**a**) and graphical (**b**) comparisons of model predicted and field measured pond water level

(i.e., Metcalf Farm). The second scenario was chosen to evaluate the pond water availability for soybean irrigation. All of the input data for the second scenario were the same as those for the first scenario except that pond water pumping was operated for soybean irrigation. The pumping for irrigation was started from June 5, 2013 with one-day duration and restarted every five-day until September 15, 2013. The pumping for irrigation rate varied with times and was estimated based on Mississippi Delta soybean growth practices. It was further assumed for this second scenario that pond water pumping for irrigation will be stopped when rainfall starts or when the pond water level reaches its low pumping limit at 75 cm. The major input parameter values used for these scenarios are given in Table 1.

3 Results and Discussion

3.1 Diurnal Hydrological Processes

Simulated daily changes in pond evaporation, pond water level, and pond water volume over a week (168 h) simulation period along with the corresponding rainfall, solar radiation, and air temperature are shown in Fig. 6. A typical diurnal pond evaporation pattern, with increasing during the day followed by decreasing at night, was observed from Day 3 to Day 6 (Fig. 6d). For example, the evaporation rate at 96 h (midnight) was near zero and reached its maximum of 2.57 cm^3/h at 107 h (around noon) and finally decreased from 107 h to near zero at 120 h (next midnight) at Day 5. This diurnal pattern occurred because of the daily cycles of solar radiation and air temperature with more intensive radiation and warmer temperature during the day than at night.

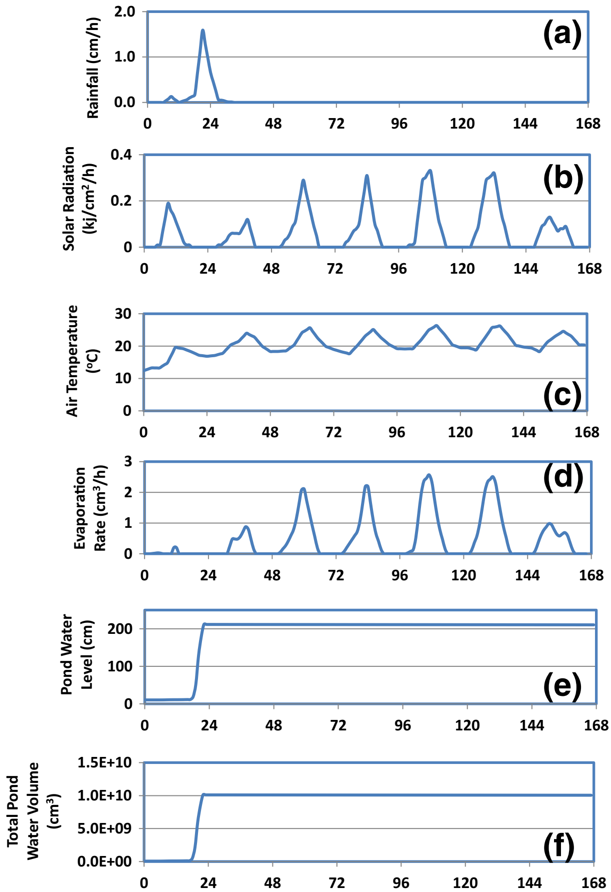

Fig. 6 Diurnal variations of rainfall, solar radiation, air temperature, pond evaporation, and pond water volume during a one-week simulation

In contrast, very little pond evaporation was found at Day 1 (0 to 24 h) (Fig. 6d) and occurred due to the effect of the rain event (Fig. 6a). It is assumed that pond evaporation virtually ceases during rainfall. Additionally, rainwater is normally colder than the surface water and could cool the air temperature, which contributes to low pond evaporation. Comparison of Fig. 6b and d at Day 7 (144 to 168 h) revealed that beside rainfall and air temperature, solar radiation also had a discernable impact upon pond evaporation. For example, when the maximum solar radiation reduced from 0.32kj/cm^2/h at Day 6 to 0.11kj/cm^2/h at Day 7, the maximum pond evaporation rate decreased from 2.52 cm^3/h at Day 6 to 0.95cm^3/h at Day 7. A 2.9-fold reduction in solar radiation resulted in about 2.7-fold decrease in pond evaporation. Results demonstrated that pond evaporation was strongly governed by rainfall, air temperature, and solar radiation.

No diurnal variations were observed for pond water level and volume (Fig. 6e & f). The initial pond water level and volume were set to 138 cm and 5.56E + 07 cm^3 and both of them increased dramatically at Day 1 due to the heavy rainfall (Fig. 6a) and stayed steady for the rest of the week because of no rainfall.

The daily changes in pond rainwater collection, runoff collection, spill (overflow), evaporation, volume, and level over a one-year simulation are shown in Fig. 7. It is apparent that

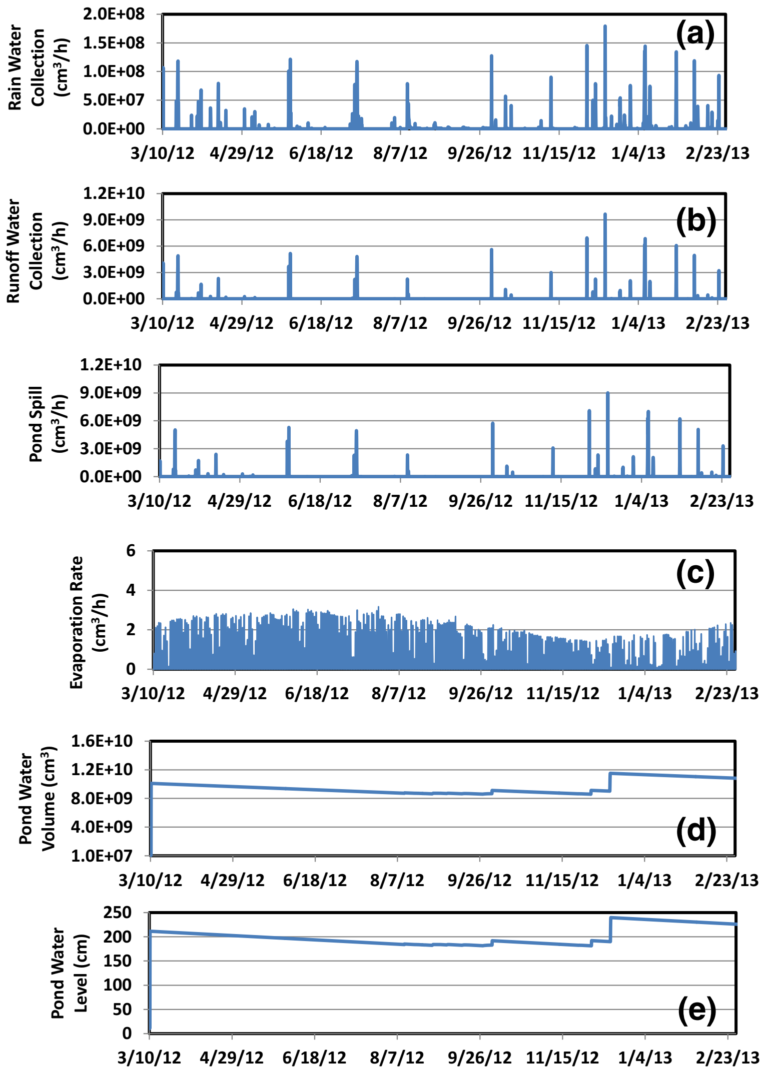

Fig. 7 Diurnal variations of rainwater collection, runoff water collection, pond spill, pond evaporation, and pond water volume during a one-year simulation

collection of rainwater and runoff by pond as well as pond spill were highly corresponding to the rainfall events, of which, more runoff water was collected by the pond than from rainwater. For instance, the rate of rainwater collected by pond was 1.18E + 08 cm^3 on March 19, 2012 (Fig. 7a), whereas the rate of runoff water collected by pond was 5.03E + 09 cm^3 the same date (Fig. 7b). The latter was about 43 times greater than the former. Starting from spring, the daily pond evaporation rate increased and reached its maximum during summer and declined to its minimum during winter (Fig. 7d). This trend occurred mainly due to the seasonal variations in air temperature and solar radiation.

Data in Fig. 7 further reveal decreases in pond water volume and level from the beginning of the simulation on March 10, 2012, with minimum values reached on December 12, 2012.

Subsequently, several rainfall events resulted in increased pond water volume and level. It can be concluded that rainfall was a major driving force for pond water storage at Metcalf Farm assuming little or no seepage and drainage occurred due to heavy clay soil.

3.2 Seasonal Hydrological Processes

Seasonal variations in volume (logarithmic scale) of pond rainwater collection, pond runoff collection, pipe outflow, pond evaporation, and pond spill during the one-year simulation period are shown in Fig. 8. The order of rainwater collected by pond was: winter (9.01E + 09 cm^3) > spring (5.32E + 09 cm^3) > summer (3.82E + 09 cm^3) > fall (2.58E + 09 cm^3), which corresponded well to the seasonal rainfall events. As expected due to the seasonality of rainfall, a similar seasonal order was obtained for runoff collection and pond spillover. In contrast, the seasonal order of pond evaporation was: summer (1.51E + 03 cm^3) > spring (1.49E + 03 cm^3) > fall (9.26E + 02 cm^3) > winter (6.67E + 02 cm^3), which corresponded well to seasonal changes in solar radiation and air temperature and suggests pond evaporation was governed less by rainfall than by solar radiation and air temperature.

Because pond water level was almost always above the pipe outflow level during the one-year simulation period (Fig. 7e), the volume of pipe outflow was fairly steady and therefore the four seasons were similar. Seasonal average water volume for each hydrological process can be deduced from Fig. 8. Overall, they were in the following order: pond spill (1.09E + 11 cm^3) > runoff collection (1.07E + 11 cm^3) > rainwater collection (5.19E + 09 cm^3) > pipe outflow (8.03E + 08 cm^3) > pond evaporation (1.15E + 03 cm^3). It should be noted that this order was for natural conditions (without pumping). These results provide a clear reason on why Metcalf Farm managers decided to pump water out of this pond for irrigation in order to minimize pond spillage.

3.3 Pond Water Budget

The water budget, water inflow, and water outflow of the pond for each hydrological process at the end of the simulation are given in Fig. 9. The water inflow (4.98E + 11 cm^3) was the sum of rainwater and runoff water collected by pond, while the water outflow (4.87E + 11 cm^3) was the sum of spill, pipe outflow, and evaporation of water out of the pond. The excess water of 1.04E + 10 cm^3 (i.e., the difference between inflow and outflow) was stored in the pond.

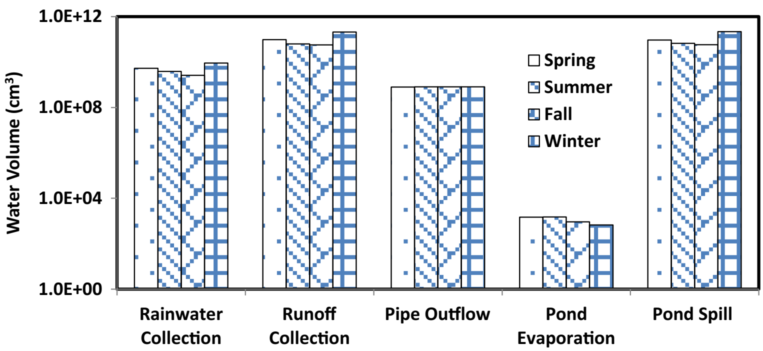

Fig. 8 Seasonal changes in water volume of pond hydrological processes

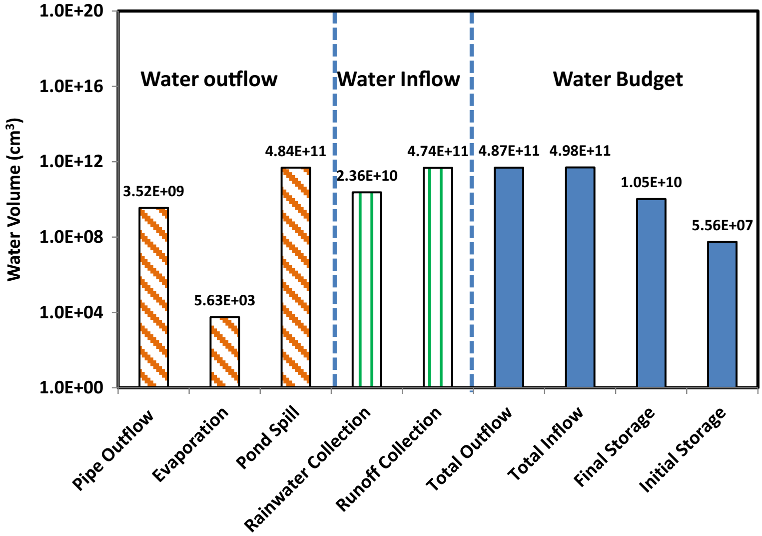

Fig. 9 Pond water inflow, outflow, and budget

Among the water outflow, the pond spill, pipe outflow, and pond evaporation accounted for 99.28%, 0.72%, and 0.00% (near zero), respectively. Results indicated that for a small pond (maximum area = 7.45E + 07 cm^2) at the Metcalf Farm, the loss of water from the pond due to evaporation was trivial under normal climate conditions. Of the water inflow, the runoff collection and rainwater collection accounted for 95.25% and 4.75%, respectively. Therefore, runoff water was a major source of water entering into the pond. Results indicated surface water runoff factor was a key component for designing the size of a pond.

3.4 Pond Water Availability for Irrigation

Changes in daily pond water level (cm) and pumping rate in volume (cm^3/h) for soybean irrigation lands of 0.3, 0.4, and 0.5 ha are given in Fig. 10, which were obtained from the second simulation scenario. The unit pumping rates (cm/h) are given in Table 1, while the pumping rates in volume (Fig. 10) were calculated by multiplying the unit pumping rates with the irrigation land areas. Different soybean irrigation areas (i.e., 0.3, 0.4, and 0.5 ha) were selected to estimate the pond water availability for irrigation based on the ratio of pond size to irrigation area. The average size of the pond used in this study was 0.056 ha with a depth of about 1.8 m (Table 1). This pond can supply sufficient water to irrigate soybean growth for a 0.4-ha land without decreasing pond water level to its low pumping limit of 0.75 m (Fig. 10b). Thus, the ratio of pond size to irrigation area was about 7. In other words, every 1-ha pond with a depth of about 1.8 m can supply water to a 7-ha land grown with soybean in Mississippi Delta. This ratio will increase dramatically if the low pumping limit is set at a much lower pond water level (rather than 0.75 m).

4 Conclusion

A typical diurnal variation pattern was observed for pond water evaporation, with increasing from sunrise to early afternoon followed by decreasing from early afternoon to sunset. In

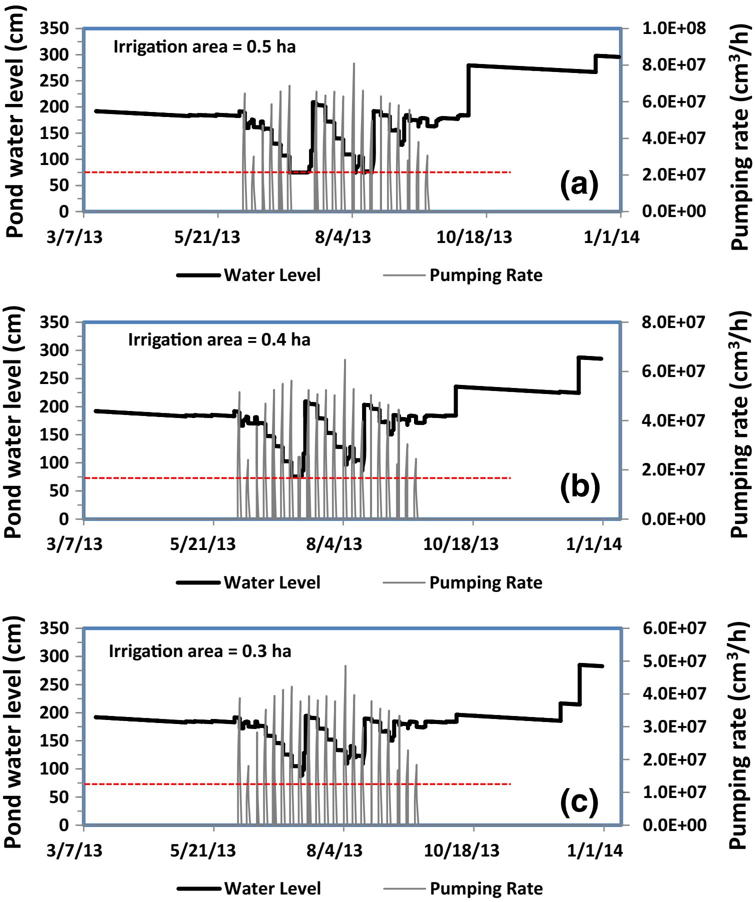

Fig. 10 Pond water level and pumping rate as a function of date for the soybean irrigation areas of 0.5 ha (**a**), 0.4 ha (**b**), and 0.3 ha (**c**). The horizontal dash lines are the low pumping limit at 75 cm

contrast, no diurnal variations were found for pond water volume and level. Results demonstrated that pond evaporation was strongly governed by air temperature and solar radiation.

Collection of rainwater and runoff water by pond and pond spill were highly corresponding to the rainfall events. More runoff water was collected by pond than that of rainwater. Runoff water collection resulted from rainfall was a major source for pond water storage at the Metcalf Farm where there are little to no seepage and drainage occurred due to the heavy clay soil.

Seasonal order of rainwater and runoff collected by pond was: winter > spring > summer > fall, which corresponded well to the seasonal rainfall events. However, seasonal order of pond evaporation was different: summer > spring > fall > winter, which corresponded well to the seasonal solar radiation and air temperature.

Seasonal average water volume for each hydrological process was: pond spill > runoff collection > rainwater collection > pipe outflow > pond evaporation. Result provided a good reason on why the farmer pumped the water out from this pond most of the time to avoid pond spill.

The loss of water from the pond due to evaporation was trivial under normal climate conditions, while the runoff water collection was a major source of water entering into the pond. Therefore, surface water runoff factor should be considered when designing the size of a pond. Every 1-ha pond with a depth of 1.8 m can supply sufficient water to a 7-ha land grown with soybean in Mississippi Delta.

The STELLA model developed in this study was shown to be a useful tool for estimating pond water hydrological processes and water budget. Knowledge of pond water budget can provide a guide to farmers on how much water is available for crop irrigation.

It should be pointed out that soil cracking is not considered in this study, which could be a problem for Sharkey clay soils in Mississippi. Therefore, further study is warrant to investigating on how soil cracking affects pond water seepage.

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