Liquid Balance Model for Swine Waste Management Systems Using Single–Stage Anaerobic Lagoons

H. J. Cumba, D. W. Hamilton

Abstract. *The most important wastewater operation for farmers using lagoons to treat swine waste is maintaining the liquid level within the operational levels to avoid overflows and to satisfy the water demand for irrigation. This study describes a model developed to determine liquid levels of single–stage anaerobic lagoons. Using this model, swine producers can determine the best liquid handling for their operations. Inputs required are lagoon dimensions; hog numbers, sizes, sex, and place in breeding cycle; records of management decisions; and accurate measurements of temperature, precipitation, humidity, wind speed, and solar radiation. The model was calibrated and validated for three single–stage lagoons in different climatic regions within the state of Oklahoma. Simulation results indicate that the model predicted liquid level within 3% of the observed values.*

Determining evaporation proved to be the most critical component of the water balance for lagoons. Evaporation was found to follow the modified Penman equation. A linear equation to relate net radiation to solar radiation was found to be sufficiently accurate to estimate evaporation from the lagoons used in calibration and validation. A single set of evaporation coefficients accurately predicted lagoon evaporation for the examined set climatic regions, lagoon depths, and lagoon colors.

Sensitivity of the model to errors in nine input parameters was determined for two sites by simulating model performance over a one–year period. If accurate estimates of farm water use are available, then the model is most sensitive to errors in estimating precipitation and evaporation. Solar radiation proved to be the most sensitive single parameter for estimating surface evaporation.

Keywords. *Swine waste, Lagoons, Modeling, Evaporation, Wastewater.*

Efficient management of liquid waste is essential to economical operation of modern swine facilities. Liquid management in swine waste systems is especially critical in Oklahoma due to the state's diverse climate. On average, annual rainfall exceeds evaporation by 15 cm in the southeast corner of Oklahoma, while the northwest corner has a –127 cm annual moisture deficit (OWRB, 1984). Most wastewater generated by hog production in the southern interior of the U.S. is treated and stored in lagoons. Lagoons are natural ecosystems with constantly changing liquid volumes due to the environment (rainfall and evaporation), introduction of liquids from buildings and holding areas, recycling of effluent for flushing, and removal of effluent for irrigation. Figure 1 is a schematic drawing showing all possible flows in and out of a lagoon–based handling system. Liquid balance for the lagoon itself depends on mass leaving and entering its system boundary, shown as a dashed box in figure 1.

Lagoon operational liquid levels should always be maintained within an effluent storage zone for proper treatment and odor control (MWPS, 1985; USDA–NRCS, 1992; *ASAE Standards*, 1998). Keeping liquid levels between maximum operating level and maximum drawdown level may require dramatically different strategies depending on one's location in the state of Oklahoma. A swine producer in the southeast corner has to manage his lagoon to reduce the potential for overflows, while a swine producer in the panhandle must conserve liquid in order to have sufficient effluent to irrigate crops. The Oklahoma Cooperative Extension Service saw the need to develop a computer model to train swine facility operators to properly manage liquids.

The following describes the development of the liquid balance computer program for swine treatment lagoons, and the interaction of individual liquid components on lagoon storage. Operational data and lagoon surveys from three facilities across the state of Oklahoma were used for model calibration and validation. Historical weather data from the Oklahoma Mesonet was used to determine rainfall entering and evaporation leaving the lagoon.

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The authors are **Hector J. Cumba**, **ASAE Student Member**, Research Engineer, and **Douglas W. Hamilton**, **ASAE Member Engineer**, Associate Professor, Department of Biosystems and Agricultural Engineering, Oklahoma State University, Stillwater, Oklahoma. **Corresponding author**: Hector J. Cumba, Dept. of Biosystems and Agricultural Engineering, Oklahoma State University, 222 Ag Hall, Stillwater, OK 74078; phone: 405–744–6519; fax: 405–744–6059; e–mail: cumba@okstate.edu.

Model Development

Liquid Balance

From figure 1, a mass balance across the system yields the following:

$$P + W_C + W_S + R_S + R + R_e = I + S + E + O + R_e + \Delta S \qquad (1)$$

where ΔS is change in storage. If no effluent is lost when liquid is recycled to buildings, then R_e values are equivalent

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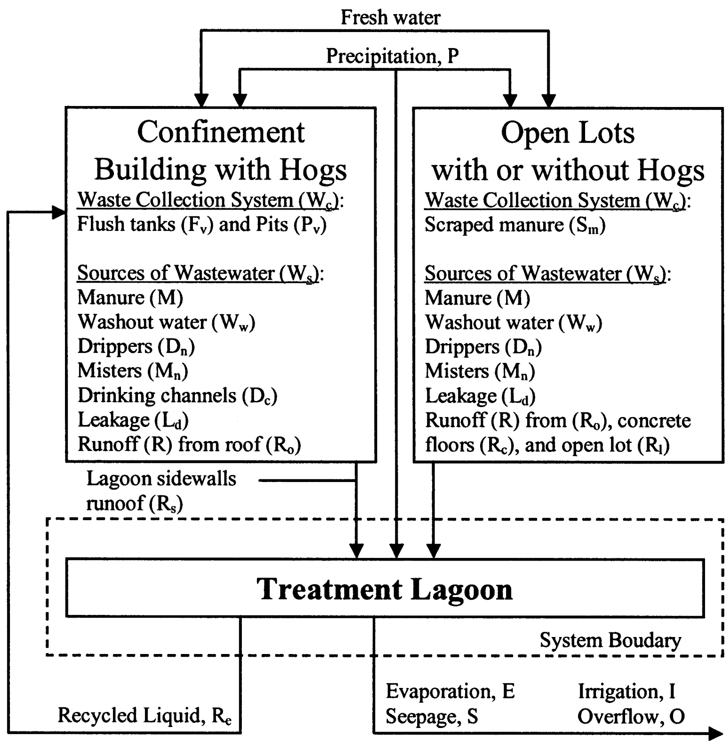

Figure 1. Mass flow of liquids for hog farms with a single–stage lagoon.

on both sides of the equation. Rearranging equation 1 to solve for change in storage gives:

$$\Delta S = P + W_C + W_S + R_S + R - I - S - E - O \quad (2)$$

For simplicity, it is assumed that all the inputs and outputs have the same density. Equation 2 further simplifies to:

$$\Delta V = V_{in} - V_{out} \quad (3)$$

where

V_{in} = volume entering into the lagoon $(P + W_c + W_s + R_s + R)$ (m^3)

V_{out} = volume leaving the lagoon $(I + S + E + O)$ (m^3).

For a daily time step:

$$\Delta V = V_{(d)} - V_{(d-1)} \quad (4)$$

where

$V_{(d)}$ = volume at the end of the day (m^3)

$V_{(d-1)}$ = volume at the end of the previous day (m^3).

Combining equation 3 and 4 gives:

$$V_{(d)} = V_{(d-1)} + V_{in} - V_{out} \quad (5)$$

Volume of a rectangular basin at any depth (h) is determined by:

$$V = w*l*h + s*h^2(w+l) + \frac{4}{3}s^2*h^3 \quad (6)$$

where

V = lagoon volume (m^3)

w = lagoon bottom width (m)

l = lagoon bottom length (m)

h = lagoon depth (m)

s = lagoon sidewall slope (m/m).

Likewise, lagoon surface area, A_s (m^2), at any depth is determined by:

$$A_S = w*l + 2s*h(w+l) + 4s^2h^2 \quad (7)$$

The model uses Newton's method to solve for h (Swokowski, 1988). Predicted lagoon volume at the end of the day, $V_{(d)}$, is calculated by adding liquid inputs and subtracting outputs from the volume calculated for the end of the previous day, $V_{(d-1)}$. The difference between the two volumes is used to calculate an intermediate depth, h_i:

$$h_i = h_{(i-1)} + h_{(i-1)}\left[\frac{V_{(d)} - V_{(i-1)}}{V_{(d)}}\right] \quad (8)$$

The value of $h_{(i-1)}$ is substituted into equation 6 to get an intermediate estimate of $V_{(d)}$ called $V_{(i-1)}$. When the difference between $V_{(d)}$ and $V_{(i-1)}$ is very small, the change in h (Δh_i) between iterations is also very small:

$$\Delta hi = \left|h_i - h_{(i-1)}\right| \quad (9)$$

This procedure is repeated until Δh_i is less than 0.001 m; then the model sets h_i as $h_{(d)}$ and begins calculating volume changes for the next day.

Inputs

Rainfall and Runoff

Rainfall and runoff volumes entering the lagoon are obtained from precipitation data. The rainfall volume (R) is the total amount of rainfall falling on the lagoon surface and is calculated from:

$$R = P*A_S \quad (10)$$

All lagoons can receive runoff (R_s) from the freeboard area of the lagoon sidewalls. Other areas that may contribute to runoff include roofs, concrete floors, and land areas draining into the lagoon. Runoff from the sidewalls and land areas is estimated using the Soil Conservation Service curve number method (USDA–NRCS, 1972). The curve number (CN) is adjusted based on the season and 5–day antecedent precipitation. Rainfall falling on roofs and concrete areas is assumed to flow directly to the lagoon without initial extraction.

Manure and Wastewater Volume

Fresh water and recycled effluent entering the buildings are transformed into wastewater and liquid transport water. Fresh water is used for washout, evaporative cooling, and drinking water, while recycled lagoon effluent is only used as liquid transport volume. The total volume of manure and wastewater is broken into wastewater volume (fig. 1):

$$Ws = M + W_w + D_n + M_n + D_c + L_d \quad (11)$$

and liquid transport volume:

$$W_c = F_v + P_v + S_m \quad (12)$$

Manure volume (M) is calculated by the number of animals and the volume of manure generated according to their classification (table 1). Farmers do not use a specific amount of washout water (W_w) every day; therefore, an average volume is calculated from the frequency of cleaning, time spent cleaning, and the flow rate of cleaning equipment.

Some facilities use drinking channels instead of automatic waterers or nozzles. Wastewater from the channels (D_c) can be determined by the flow rate and the time spent per operating cycle. It is recommended to measure the flow rate at the end of the channel. If the flow rate is measured at the beginning of channel (e.g., distribution line), then the amount consumed by the animal must be subtracted using the following equation (NRC, 1979):

$$D_c = B_f - F_d * 0.003 \quad (13)$$

where

B_f = volume at the beginning of the channel (m^3)
F_d = amount of dry feed consumed daily (kg/day).

Another significant source of wastewater is the volume of water used for evaporative cooling through misters (M_n) and drippers (D_n):

$$M_n = N_m * F_m * T_m \quad (14)$$

$$D_n = N_d * F_d * T_d \quad (15)$$

where

N = number of misters (m) and drippers (d)
F = rate of fresh water used for cooling (m^3/hr)
T = operating time (hr/day).

Table 1. Daily manure volume production as excreted (from Hamilton et al., 1997).

Animal	Volume (m^3/day)
Boar	3.68×10^{-3}
Gilt	3.68×10^{-3}
Gestation sows	3.68×10^{-3}
Sow and litters	11.61×10^{-3}
Nursery	1.59×10^{-3}
Growers (23 to 56 kg)	2.70×10^{-3}
Finishers (56 to 79 kg)	3.68×10^{-3}
Finishers (79 to 113 kg)	4.23×10^{-3}

An operating temperature to activate misters and drippers must be entered into the model in order to calculate the daily volume of wastewater.

Broken pipes and automatic waterers generate a large volume of wastewater. This volume can be measured and inputted in the model as leakage volume (L_d).

The liquid transport volume is the daily volume of fresh water or recycled liquids required to flush gutters and recharge pits. The volume of the recharge pits (P_v) and flushing tanks (F_v) can be either entered directly into the model or calculated from dimensions. The program allows the user to input the number of recharge pits and flush tanks with a maximum of six different sizes of pits and flushing tanks per building. The recycling effluent is entered individually for each flush tank and recharge pit.

Outputs

Irrigation and Overflow

Lagoon effluent is periodically removed for irrigation to adjacent lands. The irrigation volume (I) removed at any time is entered directly into the model by the operator. Overflow volume (O) is neglected in this model, since overflow is considered to be system failure in single–stage lagoons.

Recycled Effluent

Treated effluent is commonly recycled back to facilities through the flushing system to reduce fresh water usage and to decrease the total volume of lagoon storage. The model uses the following algorithm to calculate recycle volume:

$$R_e = P_v * PP_r + F_v * PF_r \quad (16)$$

where

R_e = recycle volume (m^3)
PP_r = fraction of pit volume recycled
PF_r = fraction of flush volume recycled.

Seepage

Liquid removal by seepage varies because of physical characteristics and properties of the soil liner, biological transformation of organic matter, and age of the treatment lagoon (Barrington and Jutras, 1985). Recent lagoon design follows NRCS standards, which require a hydraulic conductivity less than 10^{-7} cm/sec (USDA–NRCS, 1992). However, the hydraulic conductivity can decrease to 10^{-10} cm/sec depending on the level of construction (Hootkany et al., 1994).

The model uses the USDA–NRCS (1993) application of Darcy's law to determine seepage based on liquid depth and liner hydraulic conductivity:

$$v = k \frac{h + l_t}{l_t} \quad (17)$$

where

v = specific discharge rate (cm/sec)
k = hydraulic conductivity (cm/sec)
l_t = thickness of the liner (m).

The model uses a default value of 0.45 m (18 inches) for the liner thickness. The seepage of the lagoon is calculated by multiplying the cross–sectional area of the flow (C_a) by the specific discharge rate:

$$S = C_a * v \quad (18)$$

The cross–sectional area is determined from the wetted area at the lagoon liquid level:

$$C_a = \left[(W+L)\left(2h\sqrt{s^2+1}\right)\right] + 4\left(sh\sqrt{h^2+(sh)^2}\right) \tag{19}$$

where

C_a = wetted area at liquid level (m^2)
W = lagoon width at operating depth h (m)
L = lagoon length at operating depth h (m).

Evaporation

Evaporation is perhaps the most difficult measurable component of the liquid balance, and the component that contributes to the greatest loss of liquid from the lagoon. Various empirical equations for determining lake evaporation have been proposed and developed (Rohwer, 1931; Meyer, 1942), but there is no one acceptable empirical equation to determine evaporation without calibration for local atmospheric conditions and topography. Most of the commonly used empirical evaporation equations have been developed and calibrated for pan evaporation, requiring only three parameters (wind velocity, air temperature, and humidity). For short periods (less than 60 days), these equations work well, but significant errors result under winter conditions (Cumba, 1998). Other empirical equations require more parameters, but their general utility is limited since costly instrumentation is needed (Jensen et al., 1990). Another method used to estimate lake evaporation is direct measurement from an evaporation pan. Pan evaporation can be used to estimate lake evaporation after introducing an appropriate pan–to–lake evaporation coefficient in the range of 0.70 to 0.75 (Jones, 1991). This coefficient can be applied on a year–to–year basis, resulting in small variation; however, serious errors are introduced into the balance when applied on a daily basis. Errors from pan evaporation estimations occur when the energy stored in the lagoon is neglected.

The equation used to estimate lagoon evaporation in the model was originally developed by Penman (1948) and is referred to as the combined aerodynamic and energy balance method. This equation combines components to account for a supply of radiation energy and a mechanism to remove water vapor from the immediate proximity of the evaporation surface. The original equation uses an empirical linear function for wind, which in practice accounts for the ability to transport vapor away from the surface. Researchers have modified the combined aerodynamic and energy balance method first developed by Penman and adapted a more theoretical vapor transfer function based on a wet surface with zero resistance to vapor transfer (Jensen et al., 1990). The resulting equation to estimate evaporation from a water surface is:

$$E = \frac{1}{\Delta+\gamma}\left[\left(\frac{R_n\Delta}{l_v\rho_w}\right) + \left(\frac{0.622k^2\rho_a u_2\gamma}{p\rho_w\left[\ln\left(\frac{z_2}{z_o}\right)\right]^2}\right)(e_{as}-e_a)\right] \tag{20}$$

where

E = evaporation rate from an open water surface (mm/day)
Δ = gradient of the saturated vapor pressure curve (Pa/° C)
γ = psychrometric constant (Pa/° C)
R_n = net radiation (W/m^2)
l_v = latent heat of vaporization (J/kg)
ρ_w = water density, taken as a constant value of 997 kg/m^3
k = von Karman's constant (k = 0.4)
ρ_a = air density (kg/m^3)
p = atmospheric pressure (101.3 kPa)
u_2 = wind velocity measured at height z_2 (m/s)
z_o = roughness height taken as a constant value of 0.002 cm
e_{as} = saturated vapor pressure (Pa)
e_a = actual vapor pressure (Pa).

A complete description of each variable in the evaporation equation is available in Jensen et al. (1990).

The energy balance largely governs the evaporation rate from large open water surface areas (Chow, 1988; Jensen et al., 1990; Jones, 1991). Solar radiation (R_s) is the main source of heat energy at the earth's surface. The intensity of solar radiation received on the earth's surface is continually changing due to absorption by clouds, scattering in the atmosphere, and the obliqueness of the earth's surface to the incoming radiation. When solar radiation strikes a surface, it is either reflected or absorbed. The fraction reflected is called the albedo, α ($0 \leq \alpha \leq 1$). Net radiation (R_n) at the earth's surface is the major energy input for evaporation of water and is estimated by subtracting the emitted radiation (outgoing longwave radiation, R_b) from the absorbed radiation:

$$R_n = R_s(1-\alpha) - R_b \tag{21}$$

Estimating the emitted radiation is a very complex process, requiring many parameters, some which are specific to climatic regions. Although the albedo for treatment lagoons has not been determined, it is expected that lagoons absorb most of the radiation they receive due to their dark color. Daily solar radiation (R_s) is commonly measured at weather stations; however, net radiation (R_n) is used in equation 20. Since net radiation is closely correlated with solar radiation, researchers have developed a simple linear regression to estimate net radiation:

$$R_n = aR_s + b \tag{22}$$

There is a wide range in hourly net radiation on cropped surfaces, but fairly steady values for daily observations throughout the year at any location. Jensen et al. (1990) reported values for the parameter a in the range of 0.63 to 0.77 and for b in the range of 1.1 to 5.3 (W/m^2). These ranges are accurate over many weather conditions, cropped surfaces, and latitudes. Value for a and b for crops cannot be used to estimate net radiation from lagoons, since the energy budget for swine lagoons behaves differently from energy balances for crops. However, there are a number of advantages to using coefficients a and b for net radiation estimation from lagoons. Use of empirical coefficients reduces the introduction of errors from measurements or estimations of variables required for the energy budget. Equation 22 also takes into account liquid physical properties (albedo), chemical properties (salinity), and surface–to–volume ratio, which affects lagoon evaporation. Values for a and

b for swine lagoons were determined during model calibration using operational data from one lagoon.

Required climatic data to determine evaporation in this model are: solar radiation (R_s), air temperature (T_c), relative humidity (R_h), and wind speed (u_2). Evaporation losses from the lagoon surface are calculated by multiplying E, determined from equation 20, times the lagoon surface area, A_s:

$$E_l = E * A_S \qquad (23)$$

Experimental Procedure

Calibration

The model was developed and calibrated using operational and management information for the lagoon located at the OSU Swine Research Center (OSU–SRC) in Stillwater, Oklahoma. Operational parameters for the facility are given in table 2. The facility is primarily used by OSU's Animal Science Department and College of Veterinary Medicine to conduct physiological and nutritional studies. Throughout the years, the facility has undergone numerous physical changes caused by population increase in hog production. To accommodate the increase in hog numbers, the size of a single–stage anaerobic lagoon was increased. A single–stage lagoon is design to allow sludge storage, treatment volume, effluent storage, and stormwater freeboard in one lagoon cell. Manure and wastewater generated in the buildings are collected in several different types of waste collection systems including pit buildings, flush buildings, and scraped open lots. Water meters were installed inside buildings to measure water used for recharging the pits and for cleaning. Water flow rate was measured from misters and all washout hoses. Lagoon dimensions were extensively surveyed, and operation was followed using monthly interviews with the farm manager.

The model was calibrated by comparing observed with predicted lagoon elevation for the period of 15 May 1996 to 2 October 1997. Weekly liquid elevation data were taken from a staff gauge graduated at 3–cm intervals. No effluent was removed for irrigation during this time period. Three model parameters were adjusted during calibration using the following procedure:

1. CN was adjusted by matching predicted lagoon rises to observations after short storm events using data taken from 15 August 1996 to 17 November 1996.
2. Evaporation coefficients a and b were adjusted until the predicted lagoon level fit the general trend of observations between rainfall events occurring during the 15 August 1996 to 17 November 1996 period. Seepage losses were assumed to be negligible, given the fact that the difference in depth caused by seepage during this period is less than 1 cm when a hydraulic conductivity of 10^{-7} cm/sec is used.
3. Liner conductivity (k) was adjusted until predicted water levels closely matched observed values from 15 May 1996 to 2 October 1997.

Validation

Two facilities with similar operational characteristics located in different climatic regions were selected to validate the model. Operational parameters for the validation sites are given in table 2. The farms were located in Pottawatomie (Shawnee) and LeFlore (Poteau) Counties, in the central and southeastern region of Oklahoma, respectively. Both facilities are 600–sow breeding farms. The Shawnee facility began operation in 1995, and the Poteau farm started operating in 1994.

The facilities were inspected to gather information on the number of animals and the operation and management of wastewater throughout the system. Facility managers provided liquid level data taken from staff gauges graduated at 7.6–cm intervals. The lagoons were surveyed to determine actual top dimensions, operational levels, and depth.

Validation was accomplished by comparing predicted to observed liquid level data. Validation on each site was preceded by a brief calibration procedure to account for variations in CN, evaporation coefficients, and liner seepage. Values for these parameters were the same as those use during calibration. Only operational input data were changed during validation in each site.

Weather Data

Weather data used for model calibration and validation were obtained from the Oklahoma Meso–network (Mesonet), which is an extensive network of automated weather stations deployed across the state of Oklahoma (Elliott et al., 1994). The Mesonet weather stations collect continuous readings, summarized every five minutes and reported at 15–minute intervals to the Oklahoma Climatological Survey located at the University of Oklahoma in Norman. Data are analyzed to provide average daily values of a variety of

Table 2. Operational information for the facilities located in Stillwater (OSU–SRC), Shawnee, and Poteau.

	OSU–SRC	Shawnee	Poteau
Waste collection system	Recharge pits, flush gutters, and scraped floors	Recharge pits	Flush gutters
Transport liquid	100% fresh water	Fresh water and recycled effluent	100% recycled effluent
Runoff areas	Roof and concrete floors	None	None
Irrigation during study period	None	Yes	Yes
Volatile solids (kg/day)	240	274	216
Wastewater volume (m^3/day)	12	5 to 23	15
Lagoon surface[a] (m^2)	8,094	3,359	2,469
Lagoon volume[a] (m^3)	24,274	6,355	5,194
Maximum operating level (m)	3.35	3.20	2.68
Minimum operating level (m)	2.67	2.27	2.23
Lagoon color during research	Red	Brown and red	Brown and red
Average annual net rainfall minus evaporation (cm)	–43	–43	20

[a] At maximum operating level.

weather parameters for dissemination to users via a computer bulletin–board system and over the Internet. Periodic inspection of all Mesonet weather stations is performed to avoid instrument reading errors. Required daily weather data were available for all the studied facilities during the studied time period. Weather data from the nearest Mesonet station was used in the liquid balance. For the calibration site, the Mesonet station is located at the OSU's Agronomy Farm, which is less than 1.6 kilometers north of the swine facility. To corroborate precipitation readings from the Mesonet, a plastic rain gauge was installed on top of the lagoon bank. Based on the least square method, no statistical difference was found between the Mesonet data and the on–site rain gauge; therefore, only precipitation data from the Mesonet was used for model calibration. A statistical difference was found between Mesonet stations and on–site rain gauges for the two validation sites, so on–site rain gauge observations were used in validation.

Sensitivity Analysis

A sensitivity analysis was performed using nine parameters including facility operational data, weather data, and internal parameters required by the model. These parameters were manure and washout water volume, evaporation, precipitation, hydraulic conductivity, solar radiation, temperature, relative humidity, wind velocity, and CN for lagoon sidewalls. A constant percent change of ±10% was applied to each parameter from the baseline condition during each run while keeping the other parameters unchanged. The effect of the ±10% change of each parameter was analyzed only with respect to the liquid level. In addition, the effect of seepage on the model output was studied by altering the hydraulic conductivity. The effect of altering more than one parameter at a time was not investigated. Data from the OSU's Swine Research Center and Poteau were selected for the sensitivity analysis. The model was run using the same input data and the same adjusted variable values obtained from the model calibration and validation.

Results and Discussion

Calibration

Sidewall CN was determined to be 95 for the OSU–SRC lagoon by observing peaks on lagoon level and stormwater runoff. This CN resulted in a good estimation of runoff volume during the growing and dormant seasons. After several simulations of the model, it was determined that the values for evaporation coefficients a and b were 0.64 and –0.85, respectively. Hydraulic conductivity of the lagoon liner was determined to be 10^{-8} cm/sec. A statistical analysis with these coefficients indicates that the model prediction compares well with the observation data ($r^2 = 0.99$) (Cumba, 1998).

With the adjusted parameters, the predicted liquid levels for the OSU–SRC were almost identical to observed elevations, as illustrated in figure 2. The model was able to predict the daily liquid level within 4 cm during the simulation period that started 15 May 1996 and ended 2 October 1997. A statistical analysis of the results shows that the model prediction compares well with the observed data ($r^2 = 0.98$). Predicted liquid level is within ±1.5% of the observed data. The peaks in figure 2 were caused by the volume of rainfall on top of the lagoon and runoff.

Validation

A CN of 95 for side slope runoff was used on the validation sites. Both the Poteau and Shawnee sites had identical values for evaporation parameters a and b: 0.64 and –0.85. Hydraulic conductivity of all three liners was determined to be less than 10^{-7} cm/s.

At Poteau, the simulation was performed from 11 November 1996 through 22 September 1997. Results were compared with the observed elevation data taken from farm records. The model prediction compares well with the observed data ($r^2 = 0.92$), as shown in figure 3. The drops in the predicted and observed lagoon elevation are caused by the removal of lagoon effluent for irrigation. During the simulation period, the facility operator irrigated ten times for a total volume of 4,400 m^3. The computer program allows users to modify the input data and make changes to the liquid operation while the simulation is running. Simulation was readjusted to start at

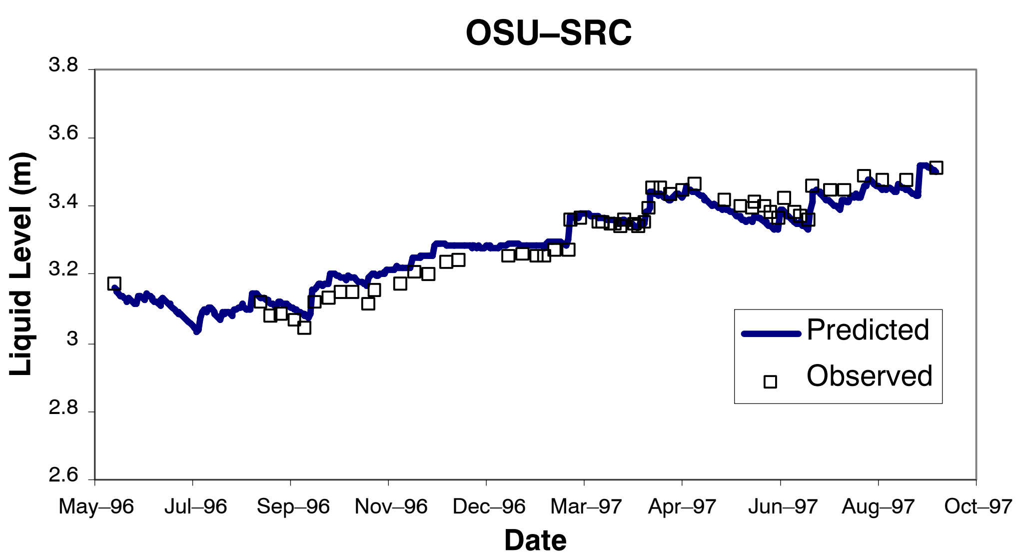

Figure 2. Observed and predicted lagoon elevations for OSU–SRC from 15 May 1996 to 2 October 1997.

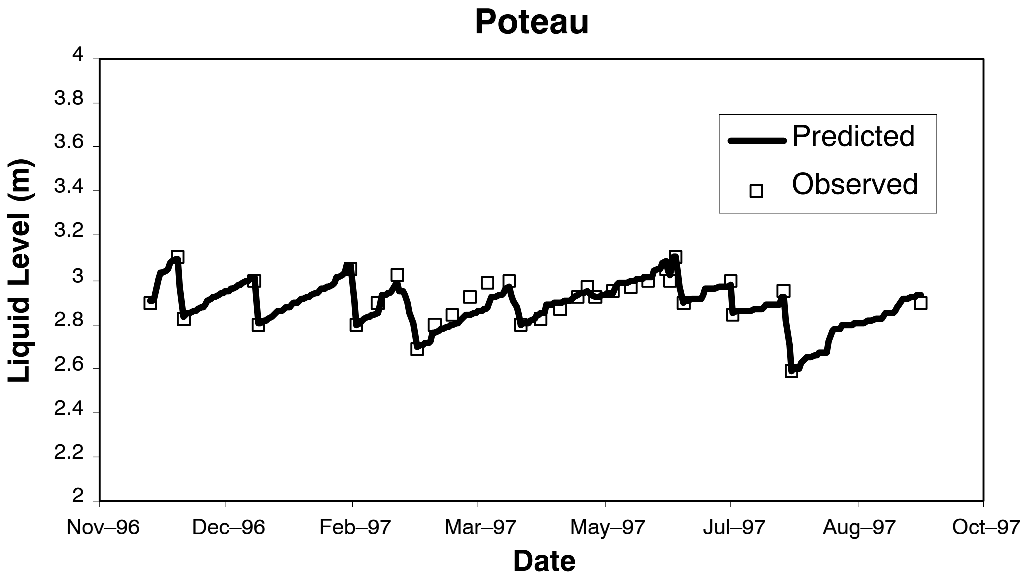

Figure 3. Observed and predicted lagoon elevations for the facility located in Poteau from 11 November 1996 to 22 September 1997.

the producer's water level after irrigation. The program also allows users to input the irrigation dates and the volume pumped or the difference in liquid level during the period.

Similar results were obtained at Shawnee. The model was run for the period starting 21 May 1996 to 15 May 1997, and results were compared with the observed elevation data recorded by the producer (fig. 4). The facility operator frequently changed liquid practices during the studied period (table 3). These changes included the frequency of pit recharge and the addition of fresh water or recycle lagoon effluent to the pits. According to the facility manager, the liquid operation is determined by how close the liquid level is from the maximum operation level and the season. In winter, the manager prefers to recharge the pits more often (every 7 days) to reduce odorous emission from the pits. All the changes in the liquid operation were entered into the model according to the dates presented in table 3. A total of 3,800 m^3 of lagoon effluent was removed by irrigation. After irrigation, the simulation was stopped and reset at the producer–provided water level. The simulated liquid level properly matched the lagoon liquid level observations (r^2 = 0.90), although during some periods the predicted level varied slightly from the observed level. Further investigation of the observed elevation and the rainfall data revealed several errors in the recorded elevation data. Most of these errors can be explained by rounding of values observed by the farm manager.

Sensitivity Analysis

Results of the sensitivity analysis for the Poteau and OSU–SRC facilities are shown in table 4. The order of sensitivity differs between the two facilities due to type and size of operation as well as the weather conditions. At the calibration site (OSU–SRC), evaporation had the greatest effect on the performance of the model, followed by precipitation, volume of manure and wastewater volume, and hydraulic conductivity. At the Poteau validation site, the volume of manure and wastewater volume had the highest

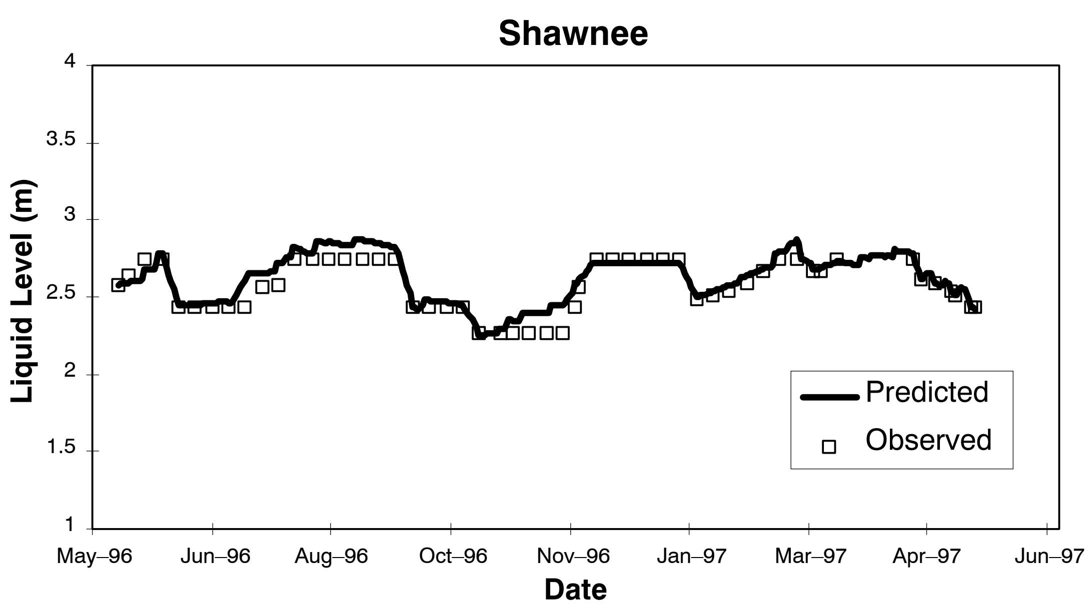

Figure 4. Observed and predicted lagoon elevations for the facility located in Shawnee from 21 May 1996 to 15 May 1997.

impact on the model output, followed by precipitation, evaporation, and seepage. The difference in the order of model sensitivity between the two facilities is attributed to the ratio of input volume to lagoon surface. OSU–SRC has a large surface area relative to daily wastewater input; therefore, it is more sensitive to errors in evaporation than errors in wastewater input. Poteau, on the other hand, has large daily input due to drinking water channels; therefore, the model showed a greater sensitivity to wastewater input at this location. The weather parameter with the highest impact on the model output is solar radiation. Lagoon evaporation is the most important component in the lagoon liquid balance and the one that requires most data for estimation; therefore, it is more likely to obtain uncertainty in the model output through the evaporation component than other components in the model.

Because a ±10% change in hydraulic conductivity does not substantially change seepage values, its sensitivity on the model output was also tested by changing the order of magnitude above and below 10^{-7} cm/sec (fig. 5). Decreasing the hydraulic conductivity below 10^{-7} cm/sec resulted in errors of less than 5% in more than two–thirds of the runs. The greatest deviation in predicted liquid depth was obtained when increasing the hydraulic conductivity above 10^{-6} cm/sec. These results give credence to the observation that all of the lagoons used in this study had liner hydraulic conductivities less than 10^{-7} cm/s. The model will easily predict an effect of seepage when hydraulic conductivity is greater than 10^{-7} cm/s.

Table 3. Recorded operational data from Shawnee.

Period	Recycled Effluent (%)	Pit Recharge Frequency (days)
21 May 96 to 2 Aug 96	0	21
3 Aug 96 to 23 Nov 96	100	21
24 Nov 96 to 5 Dec 96	0	7
6 Dec 96 to 17 Jan 97	100	7
18 Jan 97 to 17 Mar 97	0	21
18 Mar 97 to 15 May 97	100	21

Table 4. Relative sensitivity of the hydraulic balance parameters.

Parameters	Relative Sensitivity	
	OSU–SRC	Poteau
Evaporation (E)	0.43	0.28
Precipitation (P)	0.35	0.33
Manure and wastewater volume (W_t)	0.17	0.63
Hydraulic conductivity (k)	0.01	0.01
Solar Radiation (R_s)	0.36	0.26
Temperature (T_c)	0.16	0.14
Relative humidity (R_h)	0.10	0.06
Wind (u_2)	0.07	0.02
Sidewall curve number	0.02	0.01

Model Performance at OSU–SRC Using Data Collected after the Calibration Period

A second lagoon liquid level simulation was run on the OSU–SRC facility for the period 2 October 1997 to 31 August 2000. This simulation shows how effectively the model responds to changes in the waste handling system and system operation. No changes were made to calibration and operational input values, and the lagoon itself did not undergo any physical changes. The operator irrigated five times to adjacent land during this time period.

Two key changes were made to physical operation of the facility. The area contributing runoff to the lagoon was increased during the time period September 1998 to May 1999, while repairs were made to open lot finisher floors. In addition, the frequency of flushing in the growing unit was increased during winter 2000, but the farm manager did not keep a record of the change in flushing frequency.

Predicted lagoon levels are compared with observed data in figure 6. The model performed well during the simulation. The five gaps in the plot are irrigation periods, which extend from one to two weeks. The model slightly underestimated lagoon levels after periods of intense rainfall events in winter–spring 1998–1999 due to increased runoff area. The greatest difference between observed and predicted values occurred between December 1999 and May 2000, the period of uncertain flushing frequency in the grower unit. The simulation closely followed the observed level data for the entire period. A regression analysis indicated that the model prediction compares well with the observed data, with an r^2 value of 0.91 for the entire period and 0.96 excluding the data from January to May 2000.

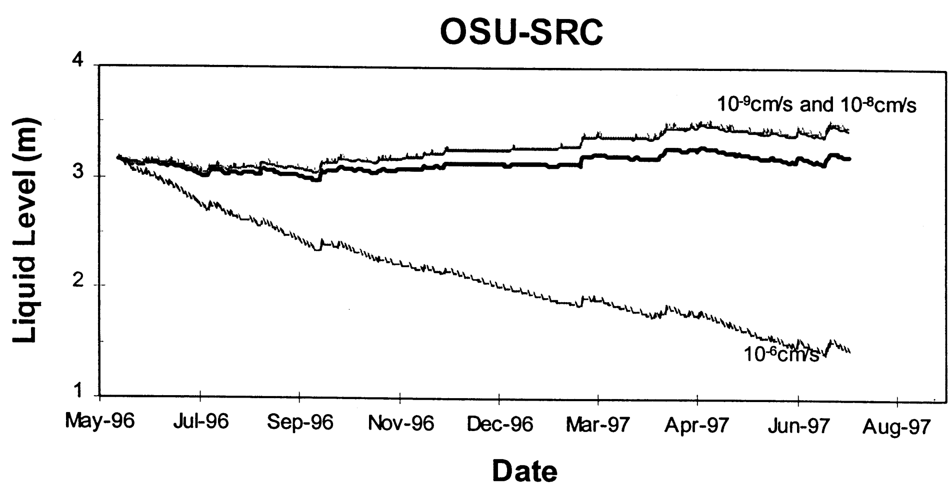

Figure 5. Model response to changes in liner hydraulic conductivity for the OSU–SRC lagoon simulation period (15 May 1996 to 31 July 1997).

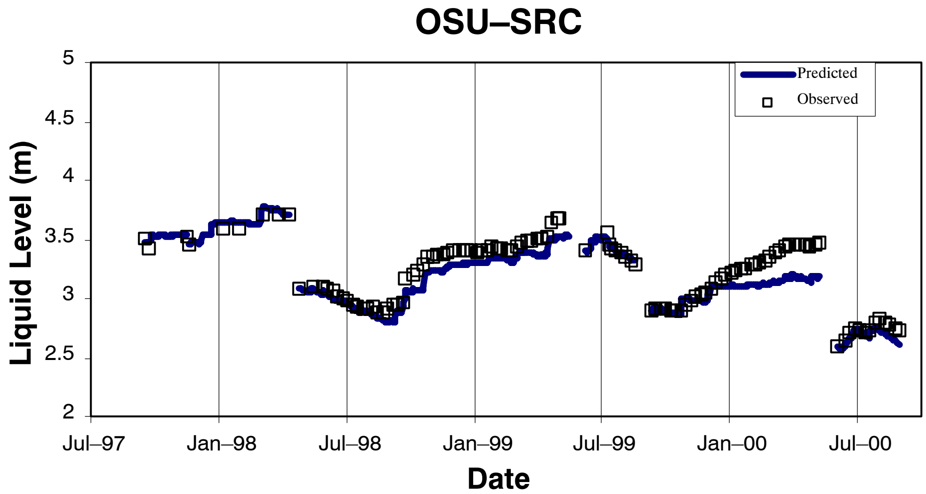

Figure 6. Observed and predicted lagoon elevations for OSU–SRC from 2 October 1997 to 31 August 2000.

Conclusions

The performance of the model was evaluated by comparing simulated lagoon liquid level to observed liquid level. After a series of simulations, the model successfully predicted the daily water levels in three anaerobic lagoons in Oklahoma within ±3% of actual levels over a one–year period. There was excellent agreement between observed and predicted liquid level at the Stillwater site after running the model for an additional two and a half year's data.

Evaporation from lagoon surfaces is the most critical portion of the water balance. Good estimates of lagoon evaporation were achieved using the modified Penman equation (Jensen et al., 1990). A sensitivity analysis showed that accurate solar radiation measurements are the most important data required by the model. The equation used by Jensen et al. (1990) to estimate net radiation from solar radiation was used in the model. Coefficients *a* and *b*, which relate net radiation to solar radiation, were determined to be 0.64 and –0.85, respectively. These coefficients successfully predicted evaporation at three different sites representing a wide range of climate (annual rainfall minus evaporation of –1150 mm to +150 mm), lagoon albedo, and lagoon depth (2.2 m to 3.3 m). Furthermore, these values closely predicted evaporation through all seasons in Oklahoma. Calibration of these coefficients may be required to accurately measure evaporation of lagoons falling outside the climatic and physical limits shown in table 2.

Deviations in hydraulic conductivity of only ±10% from a base line of 10^{-7} cm/sec caused a change of less than 1% in model output for the periods tested. However, the effect of lagoon seepage could easily be seen if hydraulic conductivity is increased above 10^{-6} cm/sec.

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