MODELING SEEPAGE FROM AN UNLINED BEEF CATTLE FEEDLOT RUNOFF STORAGE POND

D. B. Parker, D. E. Eisenhauer, D. D. Schulte, D. L. Martin

ABSTRACT. *A site-specific water balance model was developed to evaluate the effects of sludge accumulation, starting stage, and annual precipitation on seepage from an unlined beef cattle feedlot runoff storage pond. The computer model predicted daily inflows due to precipitation and runoff, and outflows due to evaporation and seepage. The seepage component was estimated using the SWMS_2D finite element saturated/unsaturated flow model, while feedlot runoff was estimated using the Natural Resource Conservation Service runoff method. Evaporation, precipitation, and temperature data from a nearby weather station were used in the model. Based on results of 9,100 annual simulations, the mean seepage volume ranged from 31 900 m*^{3}*/y with no sludge accumulation to 19 300 m*^{3}*/y with 22 years of sludge accumulation (1.5 m of sludge). The mean seepage rate ranged from 1.11 cm/day with no sludge accumulation to 0.50 cm/day with 22 years of sludge accumulation. Sidewall seepage volumes ranged from 49 to 73% of the total pond seepage volume. Increasing the pond stage from 0 to 250 cm at the beginning of the simulations caused a 200% increase in annual seepage volumes, yet only a 20% increase in annual seepage rates. Annual seepage volumes increased as much as 62% when annual precipitation increased from 44 to 96 cm/y. Average annual seepage rates varied little with varying annual precipitation. Seepage losses were 1.5 to 3.2 times as great as evaporation losses. This research provides information on variability in seepage rates that will be valuable to regulatory personnel when writing new environmental regulations, and to engineers when designing new storage ponds and lagoons.*

Keywords. *Seepage, Model, infiltration, Lagoon, Pond, Manure, Animal waste, Feedlot runoff, Water balance model.*

Feedlot operators are required by federal and state regulations to collect and store runoff from pens, alleys, and adjacent areas (USEPA, 1993; TNRCC, 1995; KDHE, 1993). Feedlot runoff storage ponds prevent sediment and nutrients from entering streams and lakes, and they are used to store runoff until it is applied to the land (ASAE, 1997). One of the environmental concerns with feedlot runoff storage ponds is that liquid can seep from the pond and contaminate groundwater, potential drinking water supplies, or surface water (Ciravolo et al., 1979; Clark, 1975; Robinson, 1973; McElroy, 1993).

Because of the possibility for groundwater contamination from leaky lagoons and ponds, many states have chosen to regulate maximum allowable seepage rates, while others have chosen to regulate construction standards and maximum allowable hydraulic conductivities (Parker et al., 1999a). The Natural Resource Conservation Service (NRCS) has chosen hydraulic conductivity as the primary criteria for soil liner design, though they mention that other criteria such as the estimated volume of water seeping from the pond, the mass of nitrogen leached, or the projected mixed nitrate concentration of the receiving groundwater could also have been selected (McElroy, 1993). One drawback to regulatory agencies using hydraulic conductivity or construction standards is that these two regulatory methods do not address seepage volumes, which vary depending on pond size and configuration. Regulatory agencies also do not address the temporal variability in seepage rates caused by fluctuating pond stages, nor do they it address the potential for sealing of the pond with time. A better understanding of how these variables affect seepage would help engineers design better feedlot runoff storage ponds, and help regulatory personnel regulate more efficiently.

Previously, researchers developed water balance models to assist in sizing feedlot runoff storage ponds to minimize the risk of overflow (Koelliker et al., 1975; Wensink and Miner, 1975). Koelliker's and Wensink's models did not include seepage losses from the pond. In our research, we developed a site-specific mathematical water balance computer model which included the seepage component to assess variability in seepage caused by variations in sludge accumulation, starting stage, and annual precipitation. We estimated the seepage component using a finite element saturated/unsaturated flow model (Simunek et al., 1994), while feedlot runoff was estimated using the Natural Resource Conservation Service (NRCS) runoff method. Site specific soil hydraulic parameters and weather data were use in our model, and the model was calibrated with measured seepage information. The objectives of our research were to:

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The authors are **David B. Parker**, ***ASAE Member Engineer***, Agricultural Engineer and Assistant Professor, West Texas A&M University, Canyon, Texas; **Dean E. Eisenhauer**, ***ASAE Member Engineer***, Professor, Dept. of Biological Systems Engineering, **Dennis D. Schulte**, ***ASAE Member Engineer***, Professor, Dept. of Biological Systems Engineering, and **Derrel L. Martin**, ***ASAE Member Engineer***, Professor, Dept. of Biological Systems Engineering, University of Nebraska, Lincoln, Nebraska. **Corresponding author:** David B. Parker, West Texas A&M University, Box 60998, Canyon, TX 79016; voice: (806) 651-5281, fax: (806) 651-2504, e-mail: dparker@mail.wtamu.edu.

1. Determine the relationship between sludge thickness and seepage rates and volumes.
2. Predict differential seepage rates and volumes from the sidewalls and pond bottom.
3. Determine the effect of varying annual precipitation and pond stage fluctuation on seepage rates.
4. Determine whether evaporation or seepage was a larger contributor to liquid loss from the pond.
5. Estimate how many years of sludge accumulation would be required before the unlined pond would meet the maximum seepage rate allowed by Nebraska.

SITE DESCRIPTION

The modeled pond is located at the USDA-ARS Meat Animal Research Center (MARC) near Clay Center, Nebraska. Runoff from the 10-ha watershed area, which includes a 3,500 head beef cattle feedlot, flows into a 80- × 36- × 2-m-deep sedimentation basin, then into a 88- × 36- × 2.6-m-deep storage pond, and finally into a 160- × 36- × 3-m-deep storage pond. The three retention structures are hydraulically connected through underground piping. The ponds were excavated in Crete silt loam in 1974. Other than indirect compaction from heavy equipment at the time of construction, there were no measures taken for lining the ponds to prevent seepage.

Field research, which included collecting and analyzing soil samples for chemical and physical characteristics, was performed at the site during the summer of 1994 (Parker et al., 1999b). A map showing the layout of the three ponds is shown in figure 1.

POND SYSTEM CONCEPTUAL MODEL

Prior to development of the mathematical model, we developed a conceptual model that describes the factors affecting seepage from the feedlot runoff storage pond. The conceptual model describes a complex physical-chemical-biological system including factors such as (1) the sidewall soil texture, gradation, and hydraulic properties, (2) the sludge thickness and properties, and (3) the liquid level fluctuations in the pond. The sludge thickness relates to the time since cleaning or, in the case of new ponds, the time it has been in service. Liquid level fluctuations affect the wetted perimeter, cracking, growth of weeds, and macropore development from earthworms, insects, and weed root channels (fig. 2).

DEVELOPMENT OF THE WATER BALANCE MODEL

The model performed a daily water balance by determining feedlot runoff, evaporation from the pond surface, rainfall on the pond surface, overflow, pumpage, and seepage (fig. 3). Daily inputs to the model included precipitation, reference crop evapotranspiration (which was converted to pond evaporation), and average soil temperature. Values for these three meteorological input parameters were obtained from a nearby weather station. The water balance was calculated by summing the individual components using the following equation:

$$V_t = V_{t-1} + Q_{t-1} + R_{t-1} - E_{t-1} - S_{t-1} - O_{t-1} - P_{t-1} \quad (1)$$

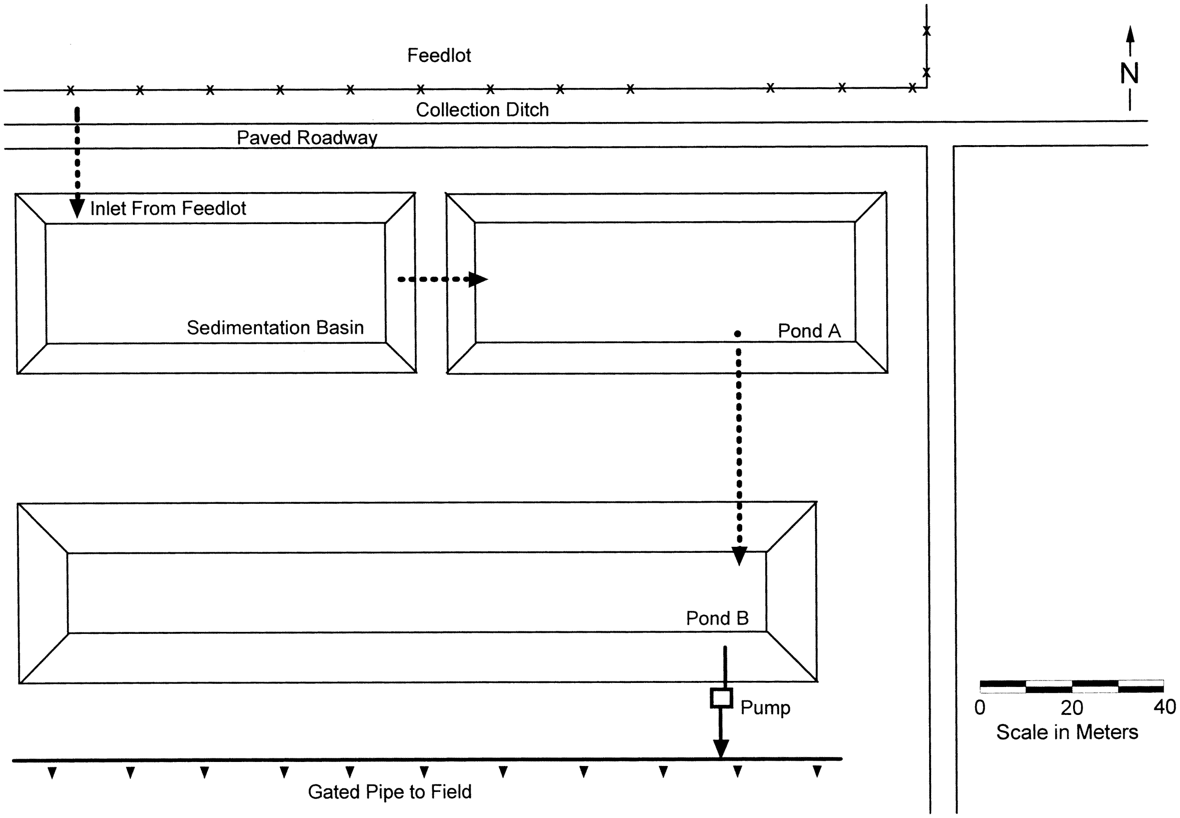

Figure 1–Layout of sedimentation basin and ponds.

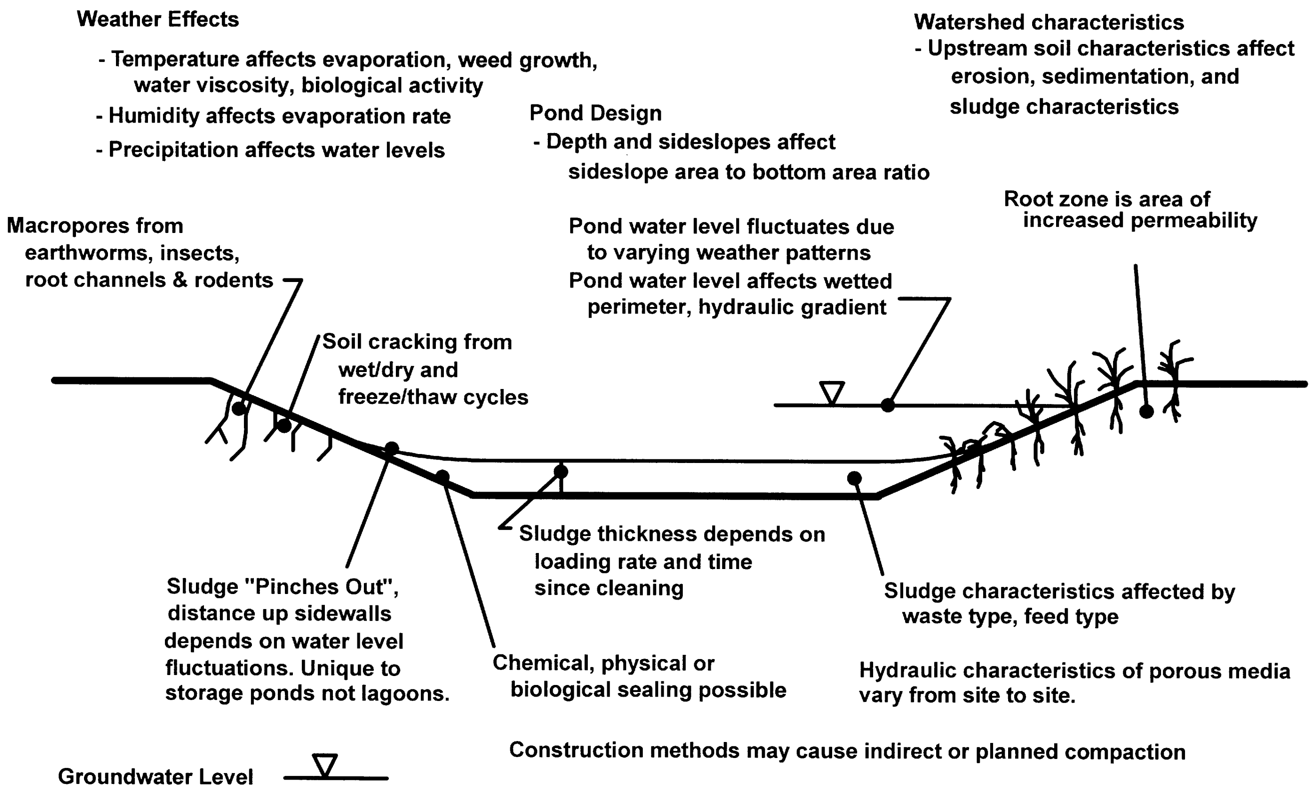

Figure 2–Conceptual model of the beef cattle feedyard runoff storage pond.

where V_t was the volume on the current day (t), V_{t-1} was the previous day's (t–1) volume, Q_{t-1} was the runoff from the feedlot, R_{t-1} was the volume of rainfall that fell on the pond, E_{t-1} was the evaporation volume, S_{t-1} was the seepage volume, O_{t-1} was the overflow volume, and P_{t-1} was the pumpage volume.

RAINFALL, PUMPAGE, AND OVERFLOW

The model used available weather data from the nearest weather station, which was located about 5 km northeast of the feedlot. Parameters available at the weather station included daily precipitation, daily reference crop evapotranspiration (ET_r), and average daily soil temperature (10 cm depth). The station had been operational since 1982, so 13 years of weather data were available (1982-1994).

The rainfall volume, R, was calculated by multiplying the daily precipitation times the pond area. The feedlot operator had a standard practice of pumping the pond periodically. At this site, the water was applied to a nearby alfalfa field through a gated pipe. The timing of application depended on factors such as the feedlot operator's schedule and cropping practices. For purposes of the stage modeling, the pond was assumed to be pumped on the seventh day following anytime the pond filled, and pumping was allowed during the growing season only (May through October). Thus, for May through October, overflow would occur only during the seven-day time period between pond full and pumping time, while during November through April the pond could overflow at any time when the current volume plus the daily runoff and rainfall volumes exceeded the pond capacity.

EVAPORATION

The evaporation volume from the pond, E, was calculated by multiplying the daily pond water evaporation rate times the water area. Daily ET_r values were obtained from the nearby weather station. The ET_r values had been calculated by the state climatologist using the modified Penman equation (Burman et al., 1983) with alfalfa as the reference crop. A correction coefficient was applied to the daily ET_r values to obtain daily pond liquid surface evaporation using the following formula:

$$E_{pws} = k\,ET_r \tag{2}$$

where E_{pws} was the pond liquid surface evaporation rate (cm/day), and k was the correction coefficient. A comparison of May-October potential evapotranspiration (ET_p) (81 cm) and free water evaporation estimates (98 cm) from isopleth maps for 1956-1970 data (NOAA, 1982) was used to obtain a correction coefficient, k, of 0.83. In the model, all daily ET_r values were multiplied by 0.83 to obtain daily pond water evaporation.

FEEDLOT RUNOFF

Total runoff from the feedlot area was calculated using the NRCS method (Schwab et al., 1981). Runoff curve numbers were selected following guidelines developed by previous feedlot watershed modelers (Koelliker et al., 1975; Wensink and Miner, 1975). Curve numbers of 91, 94, and 97 were selected for antecedent moisture conditions (AMCs) of I, II, and III, respectively. AMCs were calculated for two time periods following NRCS guidelines (Schwab et al., 1981), with the growing season selected as

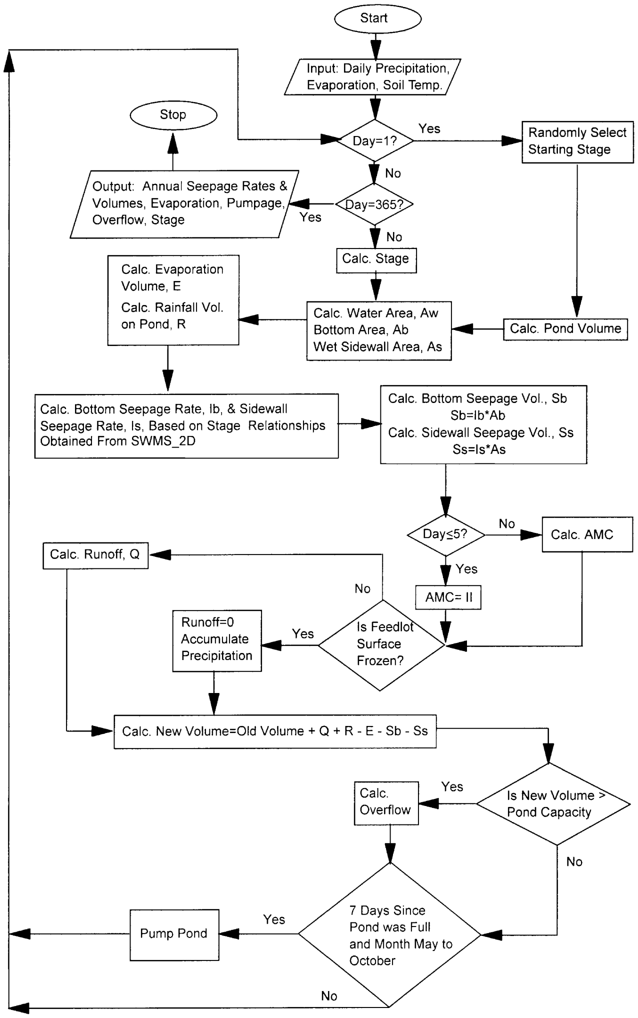

Figure 3–Flowchart of the water balance model.

May through October, and the dormant season as November through April.

Runoff was allowed to occur only when the soil temperature equaled or exceeded 0.5°C. Whenever the soil temperature was less than 0.5°C, precipitation was accumulated on the soil surface. When the soil temperature exceeded 0.5°C (i.e., the soil thawed), the volume of runoff from the accumulated precipitation was added to the pond. The effects of evaporation and sublimation from the feedlot surface when the soil was frozen were not included in the model.

POND SEEPAGE

The SWMS_2D model, Version 1.21 (Simunek et al., 1994) was used to develop relationships between seepage rate and stage (water level in pond) for use in the water balance model. SWMS_2D is a Fortran program for simulating two-dimensional saturated/unsaturated flow. The model uses the Galerkin finite-element method (Wang and Anderson, 1982) to numerically solve the Richards equation (Skaggs and Khaleel, 1982).

The different sizes and depths of the three ponds complicated the two-dimensional modeling for seepage prediction because the Fortran code had to be modified significantly for the various sludge depths and variable head boundary conditions. To simplify the modeling process, a "pseudo" pond was used with the same width (36 m) and sideslopes (3:1) as the three ponds and a length of 393 m to obtain the combined volume of the three ponds. Relationships between average daily seepage rate and pond stage were developed using the SWMS_2D modeling results. These relationships were then used in the water balance model to predict seepage from the "pseudo" pond based on the pond stage.

At the time of the field research at the site, the middle feedlot runoff storage pond had accumulated 150 cm of sludge over a 22-year period (Parker et al., 1999b). During this period, sludge had never been removed from the pond. Assuming a linear deposition rate, 6.8 cm of sludge was deposited per year. Seepage modeling with SWMS_2D was performed using sludge depths of 0.0, 6.8, 34.0, and 150 cm, which corresponded to sludge accumulation periods of 0, 1, 5, and 22 years, respectively. Pond configurations for the four sludge accumulation periods are shown in table 1. All modeling simulations presented in this manuscript were for the "pseudo" pond.

GRID LAYOUT AND BOUNDARY CONDITIONS

Finite element grids were prepared for each of the four sludge accumulation periods using a computer-aided grid generator. Summary information for each of the grids is presented in table 2. Because the SWMS_2D model uses nodal averaging to calculate the hydraulic conductivity of elements (Simunek et al., 1994), care was taken when constructing the grids to minimize the averaging effect. This was accomplished by providing two rows of nodes a few centimeters apart at the interface between the sludge and the soil beneath the sludge. An example grid for the 22-year sludge accumulation period is shown in figure 4.

The groundwater level was 30 m below the ground surface at this site. A unit hydraulic gradient boundary condition was used for the bottom boundary. The bottom boundary was placed 5 m below the bottom of the sludge in all cases. McCord (1991) previously demonstrated that the unit hydraulic gradient was a reasonable boundary condition for modeling deep groundwater conditions. The top boundary (the pond liquid level) was a variable head boundary condition, implemented by assigning constant head boundary conditions that changed daily depending on the predicted stage level from the water balance model. The SWMS_2D code was modified (courtesy of

Table 1. Pond configurations used in the modeling

Sludge Period (cm)	Sludge Depth (yrs)	Top Width (m)	Top Length (m)	Side-slope (Hor :Vert)	Bottom Width (m)	Bottom Length (m)	Depth (m)	Volume (m^3)
0	0.0	36	393	3:1	11.4	368	4.1	37,200
1	6.8	36	393	3:1	12.0	369	4.0	36,770
5	34.0	36	393	3:1	13.2	370	3.8	35,840
22	150.0	36	393	3:1	20.4	377	2.6	28,300

Table 2. Finite element grid summary information

Sludge Condition	Number of Nodes	Number of Elements	Number of Boundary Nodes
No sludge	322	568	51
1 year (6.8 cm sludge)	269	477	46
5 years (34 cm sludge)	734	1,364	67
22 years (150 cm sludge)	1,048	1,975	80

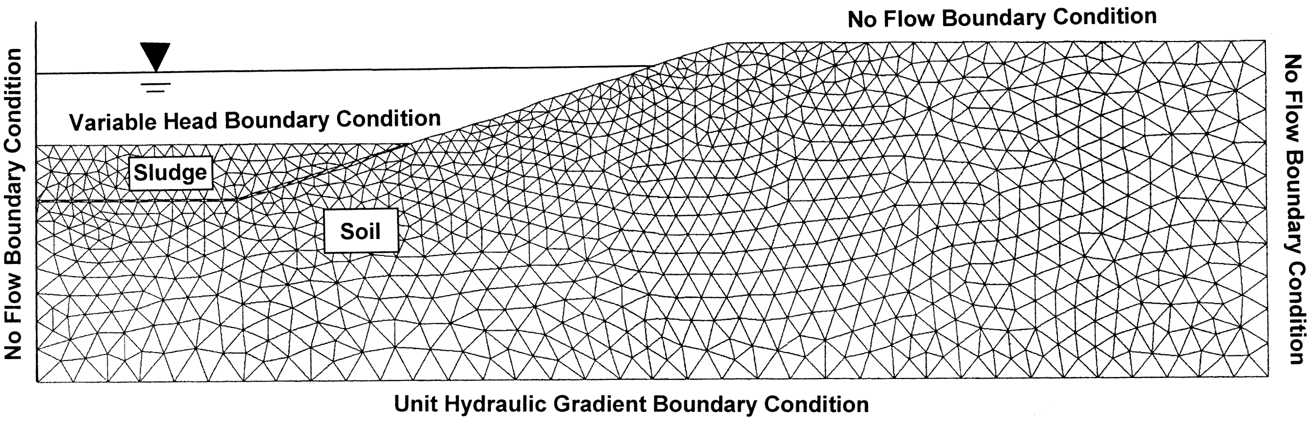

Figure 4–Finite element grid and boundary conditions for the 22-year sludge accumulation simulation.

J. Simunek, the model developer) to accommodate the variable head boundary condition for the upper boundary nodes. The model determined which of the top boundary nodes were beneath the water level, and assigned head values corresponding to the depth below the pond water surface. Those nodes located beneath water were assigned a constant head boundary condition for the next 24 h, while the boundary nodes located above water were assigned no flow boundary conditions. Because the node numbers for the pond bottom were different for each grid, the SWMS_2D code was modified for each sludge accumulation thickness. No flow boundary conditions were used for the sidewalls and ground surface above the pond water level (fig. 4). Because of symmetry, a no flow boundary condition was assigned to the left side (center of pond). The no flow boundary on the right side was placed 14 m from the edge of the pond to minimize possible effects from horizontal flow. Evapotranspiration losses from weed growth on the sidewalls were not included in the SWMS_2D modeling.

We defined the pond bottom area as the area occupied by the interface between the top of the sludge and the liquid in the pond, and the sidewall area was defined as the remaining area not covered by sludge. We made visual and physical observations during the field study that there was little sludge on the sidewalls, and the sludge that was previously deposited on the sidewalls resembled topsoil (Parker et al., 1999b). It is probable that desiccation from water level fluctuations, combined with root and insect action on the sidewalls, caused the sludge on the sidewalls to degrade such that physical characteristics were similar to the sidewall soil. Since no vegetation was observed growing in the sludge, it is probable that an elevated salt content or lack of oxygen in the sludge prohibited weed growth.

INITIAL CONDITIONS

Initial soil water content is one of the most important factors affecting seepage into the soil profile (Haan et al., 1982), with dry soils having higher initial seepage rates than moist soils. To obtain realistic initial soil water pressure head conditions, a one-year simulation was performed using the SWMS_2D model with a constant pond stage of 90 cm. The head values for each node after the one-year period were then used as the initial soil water pressure heads for the first year of the 13 years of continuous SWMS_2D modeling.

SOIL HYDRAULIC PARAMETERS

As part of a field study at the site (Parker et al., 1999b), soil samples were collected to depths of 6.1 m from 14 locations. Sludge and sidewall soil samples were analyzed for particle size distribution, saturated hydraulic conductivity, and moisture release characteristics (Parker et al., 1999b). For the SWMS_2D modeling, two soil conditions were used, the sidewall soil and the sludge on the pond bottom. The sidewall soil was a silt loam, while the sludge was classified as clay using the USDA classification. The soil beneath the sludge was assumed to have the same hydraulic properties as the sidewall soil.

Moisture release curves were developed using equations proposed by van Genuchten (1980) using a nonlinear curve fitting program (van Genuchten, 1978):

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{\left(1 + |\alpha h|^n\right)^m} \qquad \text{for } h < 0 \tag{3}$$

$$\theta(h) = \theta_s \qquad \text{for } h \geq 0 \tag{4}$$

where $\theta(h)$ = volumetric water content (cm^3/cm^3) at soil water pressure head h (cm), θ_s = saturated volumetric water content (cm^3/cm^3), θ_r = residual volumetric water content (cm^3/cm^3), and α, n, and m are variables. All parameters in the equation are curve fitting parameters. For the sludge, the following parameters were used in the modeling: α = 0.00048 cm^{-1}, n = 1.505, θ_s = 0.540, and θ_r = 0.0. For the sidewall soil, the parameters used were: α = 0.00028 cm^{-1}, n = 1.345, θ_s = 0.382, and θ_r = 0.0. The geometric mean hydraulic conductivity (K_s) of 0.022 was used for the sludge. K_s for the sidewall soil was highly variable, possibly due to macropores. Therefore, the sidewall K_s was chosen as a calibration variable. Sidewall K_s was varied in the SWMS_2D model until seepage rates matched those measured during the field study. Consequently, a K_s of 0.86 cm/day was used for the sidewall soil in the modeling.

Seepage Rate versus Stage Curves

As discussed previously, the SWMS_2D model was used to develop the seepage rate versus stage curves needed in the water balance model. However, the SWMS_2D model needed daily stage values as an input parameter. To get the stage values necessary for the SWMS_2D model input, the water balance model was run without the seepage component, so that variation in pond stages was due only to evaporation. Water balance simulations were performed using the 13 years of actual weather data, and the daily stages were then used as input into the SWMS_2D model. Average daily seepage rates for the whole pond, bottom only, and sidewalls only were then plotted against pond stage for the 4,745 days of modeling (13 years × 365 days/year). Curves were fitted to the data using regression techniques, then the seepage rate versus stage relationships were used in the water balance model to obtain the daily seepage output.

Modeling Simulations

A total of 9,100 annual simulations were performed. To evaluate the effect of varying annual precipitation and runoff on seepage rates, modeling was initially performed using the 1984, 1988, and 1993 data sets. The 1988 data represented the lowest annual precipitation of the 13 years of weather data (44 cm). The 1984 data was selected as a representative "average annual precipitation" since the precipitation for 1984 was 69 cm, and the average precipitation for the 13 years of data was 68 cm. The 1993 data represented the maximum annual precipitation for the 13 years of data (96 cm). Fifty annual simulations were performed for the 1984, 1988, and 1993 data sets for each sludge accumulation period using a randomly selected starting stage (between pond empty and pond full) on 1 January of each year.

The effect of annual precipitation was investigated further by performing 500 annual simulations for each of the 13 years of weather data for the 5-year sludge condition. For each simulation, a starting stage was selected at random.

To evaluate the effect of sludge thickness, 500 annual simulations were performed for each sludge accumulation period. Starting stage and annual weather was randomly selected for each simulation.

Results and Discussion

Runoff versus Precipitation

The average precipitation (rain and snow) for the 13 years of data was 68 cm (SD = 14.6 cm, maximum = 96.4 cm, minimum = 43.1 cm). The average runoff from the modeling was 26.1 cm (SD = 6.9 cm). On the average, 38% of the precipitation ran off, which compares well to an annual runoff of 40% measured by Gilbertson and Nienaber (1973) for a feedlot near Nebraska City, Nebraska.

Runoff data generated using the NRCS method were fit by linear regression:

$$R = 0.39P - 0.28 \qquad R^2 = 0.67 \tag{5}$$

where R = annual runoff (cm), and P = annual precipitation (cm).

Effect of Varying Annual Precipitation

Seepage generally increased with increasing annual precipitation. However, at the 22-year sludge accumulation period the seepage volume decreased with an increase in annual precipitation, a result of pumping at the higher precipitation level (table 3). Had pumping not occurred for the 1993 data, then the seepage volume would have been greater.

Annual seepage volumes for the five-year sludge accumulation period were plotted against annual precipitation and annual runoff (fig. 5). There was a trend of increasing annual seepage volume with increasing precipitation. However, the two data points for annual runoff equal to 35 and 40 cm did not follow the trend. The reason was that runoff was great enough for these two simulations that the pond was pumped, resulting in less annual seepage. The pond was not pumped for any of the other annual simulations (table 3). Seepage rates varied little with varying precipitation or runoff.

Effect of Starting Stage

Starting stage was defined as the water level in the pond at the start of the annual simulation (1 January). Annual seepage volumes and average annual seepage rates increased linearly with increasing starting stage. Increasing the starting stage from 0 to 250 cm caused a 200% increase

Table 3. Effect of varying annual precipitation from 50 annual simulations for each year and sludge period combination with randomly selected starting stages

Sludge Accumulation Period (yrs)	Date	Annual Precip (cm)	Seepage Volume (m^3/y)			Average Seepage Rate (cm/day)			Average Stage (cm)	Volume of Other Losses (m^3/y)		
			Whole	Bottom	Sidewalls	Whole	Bottom	Sidewalls		Evap	Pumpage	Overflow
0	1984	69	33900	17000	16900	1.12	1.12	1.13	175	9500	0	0
0	1988	44	21500	14900	6600	1.11	1.09	1.16	68	7100	0	0
0	1993	96	34800	16300	18600	1.11	1.12	1.12	197	8300	13000	550
1	1984	69	25800	10600	15200	0.93	0.70	1.31	139	8800	0	0
1	1988	44	22800	10300	12600	0.86	0.65	1.36	113	9600	0	0
1	1993	96	34300	12700	21600	0.97	0.80	1.28	204	8800	5500	160
5	1984	69	26600	6900	19600	0.80	0.40	1.34	172	10300	0	0
5	1988	44	18300	6100	12200	0.66	0.35	1.41	104	10100	0	0
5	1993	96	28900	7000	21900	0.80	0.41	1.35	190	9000	19900	2700
22	1984	69	21000	5400	15600	0.53	0.20	1.47	127	12200	0	0
22	1988	44	13900	4800	9100	0.41	0.18	1.80	65	12400	0	0
22	1993	96	17700	5100	12600	0.48	1.64	0.19	101	9400	27500	5700

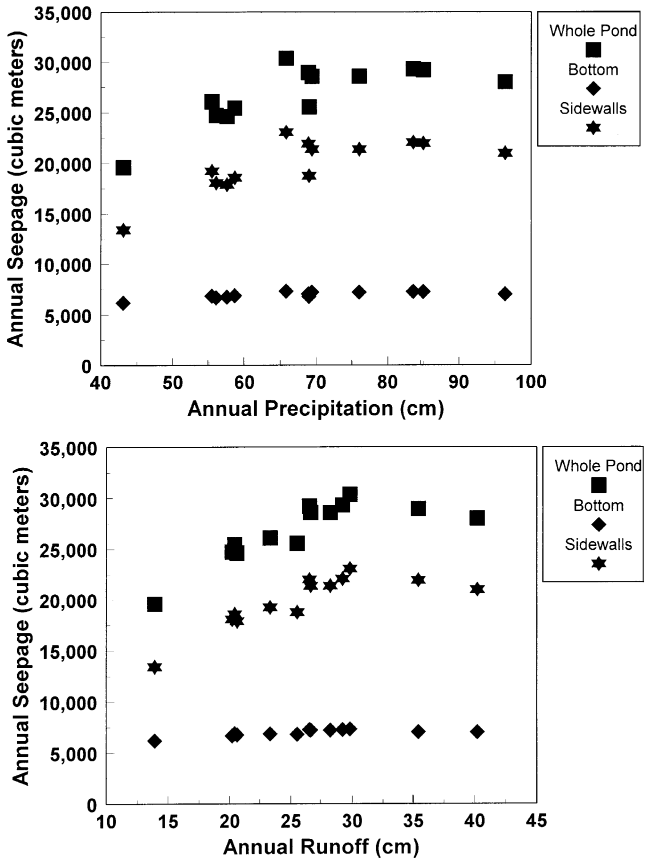

Figure 5–Graphs for the 5-year sludge accumulation period showing how seepage volumes increase with increasing annual precipitation and annual runoff. Seepage rates varied little with precipitation or runoff.

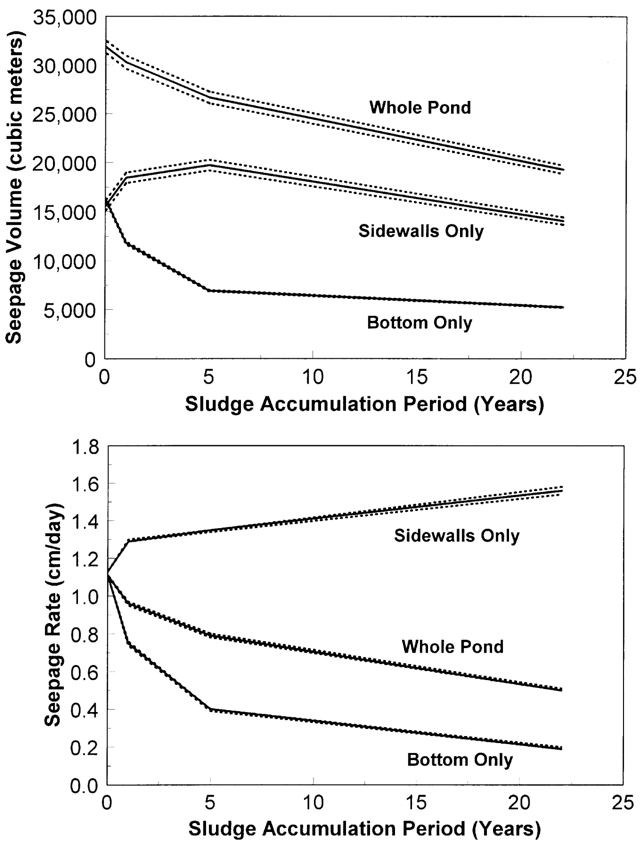

Figure 6–Effect of sludge accumulation on annual seepage volumes and rates. Broken lines represent 95% confidence intervals.

in annual seepage volume, yet only a 20% increase in average annual seepage rate.

EFFECT OF SLUDGE THICKNESS ON SEEPAGE

Annual seepage volume for the whole pond and the pond bottom decreased as the sludge thickness increased (fig. 6). However, the volume of seepage from the sidewalls increased up to the 5-year sludge condition before decreasing at the 22-year sludge condition. One reason for this occurrence is that the average annual stage increased up to the 5-year condition, a result of less liquid seeping through the pond bottom which resulted in a slower drop in stage, and thus a larger wetted perimeter causing more seepage from the sidewalls. As the sludge thickness increased to the 22-year period, the maximum stage decreased dramatically, which caused the average stage to decrease, resulting in less seepage from the sidewalls. Also, the ratio of sidewall to bottom area decreased as the sludge thickness increased. Summary statistics for the 2,000 simulations are presented in table 4.

COMPARISON OF SEEPAGE FROM BOTTOM AND SIDEWALLS

The ratio of sidewall to bottom seepage volumes varied depending on precipitation and stage. As average annual stage increased, the volume of seepage from the sidewalls also increased, causing greater sidewall to bottom seepage ratios. The percentage of seepage volume from the sidewalls ranged from 49% of the total seepage volume for the 0-year (no sludge) condition to 73% of the total seepage volume for the 22-year sludge condition (table 4). At the 22-year sludge condition, the volume of seepage from the sidewalls was almost three times that from the

Table 4. Effect of sludge thickness from 500 simulations for each sludge period with randomly selected annual weather records and randomly selected starting stages

Sludge Accumulation Period (yrs)	Sludge Depth (cm)	Seepage Volume (m^3/y)			Average Seepage Rate (cm/day)			Average Stage (cm)	Volume of Other Losses (m^3/y)			Rainfall Volume on Pond (m^3/y)	Feedlot Runoff Volume (m^3/y)	Reduction in Annual Storage in Pond (m^3/y)*
		Whole	Bottom	Sidewalls	Whole	Bottom	Sidewall		Evap	Pumpage	Overflow			
0	0.0	31900	16300	15600	1.11	1.11	1.13	162	9700	600	30	9600	26000	6630
1	6.8	30300	11800	18500	0.96	0.75	1.29	172	10400	700	40	9600	26200	5640
5	34.0	26600	6900	19700	0.79	0.40	1.35	173	11000	2100	100	9700	26500	3600
22	150.0	19280	5220	14060	0.50	0.19	1.56	114	12550	5930	630	9700	26100	2590

* Reduction in annual storage was calculated by subtracting volume of liquid outputs from volume of liquid inputs to the pond.

pond bottom. For the 0-year (no sludge) condition, the volume of seepage from the sidewalls and pond bottom was similar.

VARIABILITY IN ANNUAL SEEPAGE RATES AND SEEPAGE VOLUMES

Because of the variability in the inputs, there was variability in the modeling results. This variability can be visually observed in figure 7, which shows frequency histograms for annual seepage volume (whole pond) and average annual seepage rate (whole pond) for the 22-year sludge conditions, along with the normal probability density functions. The normal distribution appears to adequately describe the distributions for seepage rates and annual seepage volumes.

The coefficient of variation (CV) ranged from 22 to 26% for annual seepage volumes, and from 0.4 to 14% for average seepage rates (table 5). If CVs were relatively constant between different feedlots, then a person could estimate probabilities of exceedence for a given mean seepage rate or volume assuming normally distributed data. However, we still could not use the normal distribution to predict probabilities near the tails of the distribution (at probabilities of exceedence less than 2% or greater than 98%), as the error becomes greater near the boundaries.

Table 5. Results showing variation in seepage volume and seepage rate predictions at four sludge accumulation periods

Sludge Accumulation Period (years)	Sludge Depth (cm)	Annual Seepage Volume			Average Seepage Rate		
		Mean (m^3/y)	Standard Deviation (m^3/y)	Coefficient of Variation	Mean (cm/d)	Standard Deviation (cm/d)	Coefficient of Variation
0	0.0	31910	7170	0.22	1.11	0.005	0.004
1	6.8	30290	7730	0.25	0.96	0.085	0.088
5	34.0	26660	6850	0.26	0.79	0.095	0.12
22	150.0	19280	4790	0.25	0.50	0.068	0.14

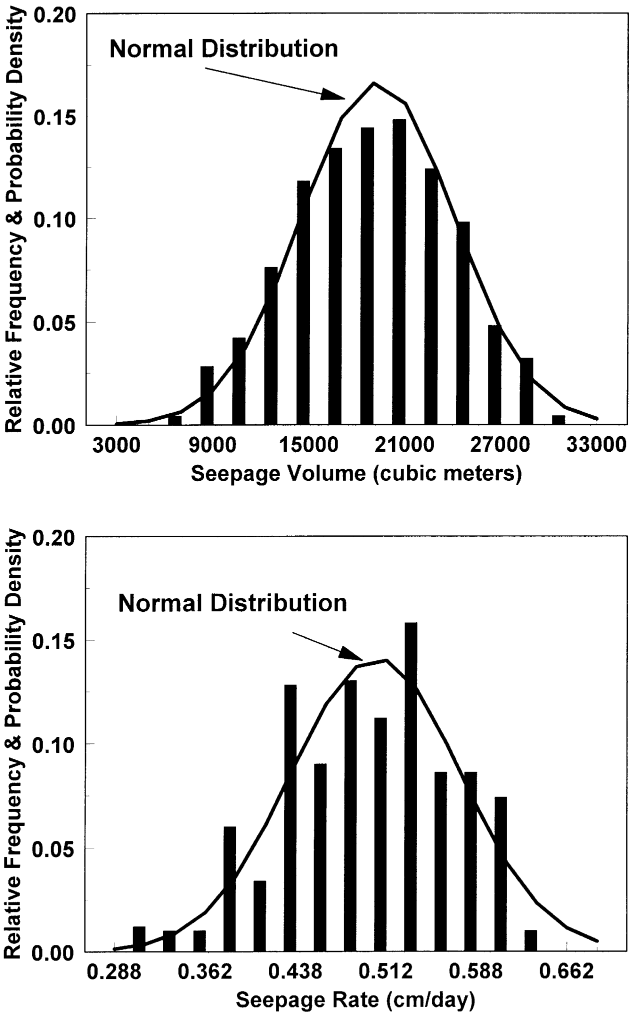

Figure 7–Normal probability distribution function superimposed over frequency histograms for seepage volume and seepage rate for the 22-year sludge accumulation simulation.

EVALUATION OF POND SIZE

The size of the modeled pond was compared to USDA guidelines (USDA, 1992) for sizing of feedlot runoff storage ponds. For ponds with a watershed and no spillway, the USDA recommends that feedlot runoff storage ponds have adequate capacity to hold (1) twice the 25-yr, 24-h storm event runoff volume from the watershed, (2) runoff during the storage period, which was taken as the 180-day period from November-April, (3) precipitation less evaporation on the pond surface, and (4) manure and solids during the storage period, which varies depending on the time between solids removal.

For this site, we calculated a liquid storage requirement of 28 400 m^3 according to the USDA design criteria, which compares to combined pond volumes of 37 200 m^3 for the 0-year sludge accumulation period and 28 300 m^3 for the 22-year sludge accumulation period. At the 22-year sludge accumulation period, the combined pond capacity was slightly less than that recommended, indicating the need for sludge removal to maintain adequate capacity. As it was originally designed, the pond was adequately sized. Thus, the pond configurations modeled in this research appear to be representative of the sizes recommended in the USDA design criteria.

COMPARISON TO STATE REGULATIONS

At the time of this research, the State of Nebraska allowed a seepage rate of 0.63 cm/day from feedlot storage ponds (NDEQ, 1989). The 0.63 cm/day guideline is still in effect in early 1999 (NDEQ, 1995). Assuming a linear relationship between seepage rates at the 5- and 22-yr sludge accumulation periods, we determined that the pond had a mean seepage rate of 0.63 cm/day after about 14 years of sludge accumulation. If the mean annual seepage rate is used as the comparative standard, then in its present condition (22-year sludge) the pond meets the criteria outlined in Nebraska's regulations. If the sludge should ever be removed from the pond, then the pond would possibly exceed the allowable seepage rate. This poses an interesting issue for other unlined storage ponds which rely on accumulated sludge to reduce seepage. It may be appropriate to never completely remove all of the sludge from these ponds, but rather remove only enough to satisfy storage requirements while leaving some to prevent seepage.

We calculated average annual seepage rates by averaging the daily seepage rates when there was water in the pond. Had the days when the pond was empty been included in the average seepage rate calculations, the average annual seepage rate would have been less. Most regulations give a maximum seepage rate, but do not state whether the rate is based on days in which water is in the pond, or all 365 days in the year. They also do not state whether seepage rates pertain to average annual, short term, or instantaneous seepage rates.

CONCLUSIONS

1. Average annual seepage rates and annual seepage volumes for the whole pond decreased with increasing sludge thickness. Seepage rates from the pond bottom decreased as the sludge depth increased, while seepage rates from the sidewalls increased.
2. The percentage of seepage volume from the sidewalls increased with sludge accumulation, from 49% of total pond seepage at the no-sludge condition (0-year sludge accumulation period), to 73% of the total pond seepage volume at the 1.5 m sludge condition (22-years of sludge accumulation).
3. Annual seepage volumes increased as much as 50% when annual precipitation increased from 44 to 96 cm/y. Average annual seepage rates varied little with varying annual precipitation. Increasing the pond stage from 0 to 250 cm at the beginning of the simulations caused a 200% increase in annual seepage volumes, yet only a 10% increase in annual seepage rates.
4. Seepage losses ranged from 50 to 76% of total liquid losses from the pond. Seepage losses were as much as 3.2 times as great as evaporation losses. Annual seepage volumes ranged from 19 300 to 31 900 m^3/y, while annual evaporation volumes ranged from 9700 to 12 500 m^3/y. The average annual runoff volume was 26 300 m^3/y, and the annual rainfall volume on the pond surface averaged 9600 m^3/y.
5. Based on the modeling results, we concluded that 14 years of sludge accumulation were necessary before the average annual seepage rate from this unlined feedlot storage pond was below the state of Nebraska's allowable seepage rate of 0.63 cm/day.

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