Water Balance of a Stock-Watering Pond in the Flint Hills of Kansas

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Abstract

Small ponds are often the main source of drinking water for grazing livestock. The hydrology of these ponds must be understood so impoundments can be located, designed, and managed to avoid water shortages during dry weather. A study was conducted to measure the water balance of a stock-watering pond in the Flint Hills region of east-central Kansas from June 2005 to October 2006. The 0.35-ha pond supplied water to 250-kg yearling steers in a 65-ha pasture of native tallgrass prairie. Evaporation, depth change, and cattle consumption were measured continuously using meteorological sensors, depth recorders, and water meters. Seepage, transpiration, and inflow were measured periodically or modeled. Evaporation was also predicted from weather data using forms of the Penman and Priestley-Taylor models. Evaporation accounted for 64% of the total water loss annually, while seepage, cattle consumption, and transpiration accounted for 31%, 3%, and 2%, respectively. The greatest water loss was observed in July, with total monthly losses over 358 mm and peak daily losses sometimes exceeding 18 mm $\cdot$ d^{-1}. Cattle consumption averaged 30 L $\cdot$ day^{-1} $\cdot$ animal^{-1} with peak usage of 46 L $\cdot$ day^{-1} $\cdot$ animal^{-1}. On average, the Priestley-Taylor and Penman evaporation models estimated monthly evaporation to 3% and 5%, respectively. Thus, evaporation, the main form of loss, can be predicted with simple models using data from weather station networks. Inflows from runoff proved difficult to predict and were highly dependent on antecedent soil water content. Results showed that losses from ponds can be measured or predicted with reasonable accuracy. These data could be incorporated into catchment-scale hydrology models to provide site-specific designs for stock-watering ponds and livestock-watering strategies.

Resumen

Los pequeños estanques son a menudo la principal fuente de agua potable para el ganado de pastoreo. La hidrología de estos estanques debe entenderse de manera que los embalses pueden ser ubicados, diseñados, manejados para evitar la escasez de agua durante la temporada seca. Se realizó un estudio para medir el balance hídrico de un estanque en la región de las colinas de Flint en la región central del este de Kansas a partir de junio del 2005 hasta octubre del 2006. El estanque de 0.35 ha suministró agua a bueyes menores de 1 año y 250 kg en una pradera de 65 ha pastos altos nativos. La evaporación, el cambio de profundidad, y el consumo del ganado, se midieron de forma continua utilizando sensores meteorológicos, sensores de profundidad, y de agua. La filtración, transpiración, y el flujo de agua se midieron periódicamente o se modelaron. La evaporación también se predijo de datos meteorológicos utilizando formas de los modelos de Penman y Priestley-Taylor. La evaporación representó el 64% del total de la pérdida de agua anual, mientras que la filtración, el consumo de ganado, y la transpiración representó el 31%, 3%, y 2%, respectivamente. La mayor pérdida de agua fue observada en Julio, con un total de las pérdidas mensuales de más de 358 mm y con un volumen máximo de pérdidas diarias a veces superior a 18 mm $\cdot$ d^{-1}. El consumo de ganado promedió 30 L $\cdot$ día^{-1} $\cdot$ animales^{-1} con un pico de uso de 46 L $\cdot$ día^{-1} $\cdot$ animales^{-1}. En promedio, los modelos de evaporación Priestley-Taylor y Penman estimaron la evaporación mensual entre el 3% y 5%, respectivamente. Por lo tanto, la evaporación, la principal forma de pérdida, puede predecirse con modelos simples utilizando datos de redes de estaciones meteorológicas. Las afluencias a partir de la escorrentía fueron difíciles de predecir y dependieron en gran medida del contenido previo de agua en el suelo. Los resultados mostraron que las pérdidas de los estanques se pueden medir o predecir con una exactitud razonable. Estos datos podrían incorporar a modelos hidrológicos a escalas de cuencas para proveer diseños propios de captación para los estanques de reserva y estrategias de provisión de agua para ganado.

Key Words: evaporation, hydrology, runoff, seepage, tallgrass prairie, water consumption

INTRODUCTION

The performance of grazing livestock is strongly affected by access to quality drinking water. Studies have shown that a large fraction of grazing occurs within 365 m of water (Gerrish and Davis 1997), and forcing livestock to travel long distances between grass and water decreases performance. Also, any factor that decreases water quality affects weight gain (Wells 1995). Thus, watering of livestock has long been a crucial and sometimes limiting aspect of ranching. In areas with adequate precipitation and some relief in topography, water for gazing livestock is often provided by small constructed ponds that are fed by runoff, seeps, or springs. The Flint Hills of eastern Kansas is one such area where earthen ponds are the primary source of livestock water. The Kansas Agricultural Statistics Service reported approximately 1.5 million head of cattle grazed the 1.4 million ha in the Kansas Flint Hills in 2005.

The annual consumption from an individual pond is dependent on the stocking rate, size of the pasture(s) being served by the pond, and stocking duration. Ponds must be

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Manuscript received 5 September 2007; manuscript accepted 4 December 2007.

Table 1. Factors affecting the pond water balance (see Equation 1).

Weather and watershed	*I, P, E, T*	Radiation, wind, humidity, temperature, precipitation, pond area, drainage area, vegetation type and size, antecedent soil moisture, soil type, slope, and topography
Stocking management	*C*	Stocking density, cattle size, breed, forage quality, and weather
Pond design	*S, O*	Pond area, water depth, soil liner properties, degree of sedimentation, and water table depth

designed to collect and store enough water to meet all the consumptive demands of the livestock as well as all other forms of water loss. Essentially, water inputs to the pond must be equal to or exceed all losses; otherwise the depth of the pond will decrease over time and eventually dry up. In many areas of the country, including the Flint Hills of Kansas, the ponds are primarily filled and replenished by runoff from precipitation. According to the Natural Resource Conservation Service ([NRCS] 2005), a pond that is replenished by runoff should have a minimum depth of 1.5 m at the deepest point and a minimal area of 46.5 m^2. However, these are general guidelines and mainly address the geotechnical aspects of pond construction. The more difficult question is how the pond should be designed and managed to minimize the probability that the pond will go dry when serving as the primary water source for grazing livestock. Hauling or pumping water to pastures with dry ponds increases costs, increases demands on labor and equipment, and can decrease livestock performance if cattle are forced to travel greater distances to water, all of which decrease profits. Thus, there is merit to studying the water balance of livestock ponds closely to optimize new pond construction and prevent the need to haul water under all but the most severe droughts. Furthermore, the supply capacity of existing ponds could be more closely approximated so that fenced areas and stocking rates could be properly sized for a given pasture-pond combination.

The water balance of a stock-watering pond can be expressed as

$$I + P = E + T + C + S + O + \Delta D, \quad [1]$$

where I is inflow into the pond, P is the precipitation falling directly on the pond, E is evaporation, T is transpiration from surrounding vegetation, C is cattle consumption, S is seepage, O is overflow out of the pond, and ΔD is the rate change in depth, with all terms expressed as mm · day^{-1}. This equation represents the conservation of mass for a control volume, inputs = outputs + the change in storage, where I and P are inputs, and the right-hand side represents losses and storage term (i.e., depth change). Unfortunately the factors affecting the water balance are complex; Table 1 lists over 20 site-specific variables that could alter pond hydrology, factors that include weather, watershed properties, pond characteristics, and grazing regime. Predicting runoff into a pond is especially complex but has been the subject of considerable modeling work (e.g., TR-55 small watershed hydrology model; NRCS 2002). In this paper we will focus on the main forms of water loss, namely E, C, and S, as represented on the right-hand side of Equation 1.

In the Great Plains annual evaporation from open water can range from 1.2 to 1.8 m (Sophocleous 1998) and probably represents the largest form of water loss for most ponds. Unfortunately, evaporation from ponds has received minimal attention because most studies have focused on larger lakes and reservoirs. Evaporation from stock-watering ponds is complex because the air flowing over the pond never reaches equilibrium with the water surface. Furthermore, the surrounding vegetation and landforms can strongly affect wind flow, a factor that controls the aerodynamic conductance of water vapor between the surface and atmosphere. Measuring and modeling evaporation from small water bodies was evaluated by Ham (1999) when studying the water balance of animal waste lagoons. The modeling approaches based on formulas proposed by Penman (1948) and Priestley and Taylor (1972) are the most common ones applied to ponds (e.g., Steward and Rouse 1976; De Bruin 1978; Ham 1999).

Transpiration from trees and vegetation surrounding a pond could be a significant source of water loss at certain locations. For example, during hot summertime conditions a large cottonwood tree can transpire up to 500 L · d^{-1} (Schaeffer et al. 2000), a value equal to the water consumption of 15 head of cattle. Unfortunately, modeling the water loss from trees and brush around a pond also is challenging. However, methods developed for modeling transpiration from trees in riparian areas could be applied to ponds (e.g., Goodrich et al. 2000). Ponds with small areas or those with shapes that have a small area-to-perimeter ratio (i.e., small isoperimetric quotient) will be most affected by shoreline vegetation.

Seepage losses from ponds also have received little study. Ham (2005) measured seepage from 20 animal waste lagoons in Kansas and found an average seepage rate of 1.1 mm · d^{-1} (0.4 m · yr^{-1}). Although animal waste lagoons are different from ponds, they are a reasonable choice for comparison based on size and depth. Because most ponds do not have a compacted clay liner, we might expect seepage from ponds to be larger than that from lagoons. However, Ham (2005) found that lagoons with no constructed liner still had seepage rates less than 3 mm · d^{-1}. Also, stock ponds are typically shallower than lagoons, so there is less pressure head to drive seepage. In summary, we might expect seepage from many stock-watering ponds to range from 0.9 to 3 mm · d^{-1} or 0.3–1.0 m annually.

The importance of stock-watering ponds to grazing cattle merits additional study of factors affecting pond hydrology on rangelands. In this study methods similar to those used by Ham (1999, 2005) and Ham and DeSutter (1999) were used to estimate or measure the water balance of a stock-watering pond in the Flint Hills of eastern Kansas. Several meteorological models of pond evaporation also were tested. Results show which components of the water balance are most important and provide background information for an improved design framework for ponds on rangeland. Ultimately a hydrology-based, site-specific model of stock-watering ponds could help determine the supply capacity of existing impoundments and improve the design and management of new ponds.

METHODS

Site Description

The pond was located in the Rannells Flint Hills Prairie Preserve approximately 9 km south of Manhattan, Kansas (lat 39°08′N, long 96°32′W, ~340 m above mean sea level). Historical aerial photographs show the pond was built prior to 1971 (Jantz et al. 1975). The vegetation in the surrounding pasture is dominated by C4 grasses, including big bluestem (*Andropogon gerardii* Vitman) and indiangrass (*Sorghastrum nutans* [L.] Nash), and has been annually burned each spring for the last several decades. Historically the pasture had been grazed by stocker cattle in the spring and summer months (May to early October). The soil is classified as a silty clay loam (Benfield series: fine, mixed, mesic, Udic Agriustolls) with slopes of 5%–20% and has a loamy upland range site classification. The 30-yr average annual precipitation is 880 mm, with 540 mm received between May and September, and Sophocleous et al. (1998) report 1 470 mm of potential evaporation for the region.

The pond and watershed were mapped with global positioning systems (AgGPS 132 and AgGPS 710, Trimble Navigation Limited, Sunnyvale, CA); areas and slopes were computed using Arcview (9.1; ESRI, Redlands, CA). When full, the pond had an area of 0.35 ha and was 2.2 m at the deepest point. The pond captured drainage from approximately 25 ha, with the highest point at 425 m and elevation of the pond was 390 m. The average slope (i.e., *y*-slope) of the drainage was 4.7°. The 65-ha pasture that encompassed the pond was stocked with yearling steers between May and October. In 2005 grazing livestock were comprised of 12 head of Black Angus (*Bos taurus*) and 36 head of Brahma (*Bos indicus*) cattle with an average initial weight of ~250 $kg \cdot steer^{-1}$ and ~180 $kg \cdot steer^{-1}$, respectively. In 2006, 37 head of Black Angus grazed the pasture with an average initial weight of ~250 $kg \cdot steer^{-1}$.

The cattle were fenced off from the pond, and drinking water was supplied to the cattle by a 4.5 m^3 circular watering trough that was positioned outside the fence below the dam. Routing pond water to a trough located some distance away from the shoreline is becoming common practice to improve water quality (Ohlenbusch et al. 1995). The watering trough was supplied from a 1.9-m^3 storage tank positioned on the dam. The storage tank was kept full by a solar-powered pump in the pond that was activated by a float switch. Two flow meters, one analog and one digital (FTB-6205 and FTB-4707; Omega Engineering, Inc., Stamford, CT), were installed between the solar pump and supply tank to record the volume of water diverted to the stock tank for cattle use.

Water Balance Measurements and Calculations

Evaporation from the pond was measured using the approach of methods of Ham (1999). A meteorological raft (1.5 m × 2.0 m) was positioned at the center of the pond and carried an infrared thermometer (4000.4ZL; Everest Interscience Inc., Tucson, AZ) for measuring surface temperature, a three-cup anemometer (0301-L; Campbell Scientific Inc., Logan, UT), and an air temperature and humidity probe (HMP35-A; Campbell Scientific), all positioned 1 m above the water. Additional instrumentation on the bank of the pond included a tipping bucket rain gauge (TE-525W; Campbell Scientific), a pyranometer (LI200; Li-Cor Inc., Lincoln, NE), and a micrologger (CR10X; Campbell Scientific) for data acquisition.

Hourly evaporation was estimated using the methods of Ham (1999):

$$E' = C_e U_r \rho (q_s{*} - q_r), \quad [2]$$

where E' is evaporation rate ($kg \cdot m^{-2} \cdot s^{-1}$), C_e is the bulk aerodynamic transfer coefficient for vapor (2.8×10^{-3} dimensionless), U_r is the average wind speed at 1 m ($m \cdot s^{-1}$), ρ is air density ($kg \cdot m^{-3}$), q_s* is the saturated specific humidity at the water surface, and q_r is the specific humidity of air at 1 m ($kg \cdot kg^{-1}$). Summing E' over 24 h yields daily evaporation required in Equation 1.

Depth change in the pond was measured using a float-based recorder described by Ham and DeSutter (1999). A linear displacement transducer (LX-PA 50, Unimeasure Inc., Corvallis, OR) with a retractable leader was used to sense changes in water level based on float travel inside a stilling well. The recorder, when logged with the CR10X, had a resolution of 0.24 mm and a full scale range of 1.27 m.

Pond seepage was determined as the difference between depth change and evaporation, providing *I, P, C,* and *O* can be eliminated from the water balance equation:

$$S = \Delta D - E. \quad [3]$$

Ham (1999, 2002) demonstrated that the resolution of seepage calculations can be improved when integrating over long time periods (7–10 d) during cold weather when *E* is small. Therefore, seepage was estimated during lengthy dry periods in the winter of 2006 when no cattle were present and no water was entering the pond or passing through the spillway. Seepage calculations for the rest of the year were scaled by pond depth following the approach of Ham (2002, 2005) assuming the hydraulic conductivity of the soil liner did not change over time.

Cattle consumption, expressed in terms of pond depth, was estimated as

$$C = \frac{V - E_{pan}}{A}, \quad [4]$$

where *C* is cattle water consumption ($mm \cdot d^{-1}$), *V* is the volume pumped from the pond and delivered to the watering tank ($m^3 \cdot d^{-1}$), E_{pan} is the evaporation from the watering tank ($m^3 \cdot d^{-1}$), and *A* is pond area (m^2).

Evaporation from the surface of the water trough was assumed to be equal to that from a Class-A evaporation pan. Ham (2005) showed that ratio between lagoon and pan evaporation was variable but typically between 0.7 and 0.8 for summer months ($E{:}E_p \approx 0.75$). Thus E_{pan} was computed from estimates of pond evaporation from Equation 2, assuming a pan coefficient of 0.75, and adjusting for the area of the watering trough. Because E_{pan} is much smaller than *V*, errors associated with estimating E_{pan} have little effect on *C* and the overall water balance.

Transpiration from vegetation on the edge of the pond was difficult to approximate. The grasses were thought to have little effect because a zone of bare soil bordered the periphery of the pond. However, there were two mature cottonwood trees (*Populus*) growing on the dam that most likely obtained most of their water directly from the pond. During a low water period, large roots were observed running over the bottom of the lagoon. Using sap flow gauges, Schaeffer et al. (2000) showed that transpiration from large cottonwood trees growing in riparian areas in an arid climate was typically 0.2–0.5 $m^3 \cdot d^{-1}$. Assuming that the maximum water use from the tree at the pond was 0.5 $m^3 \cdot d^{-1}$ and coincided with the maximum evaporation from the pond, T from a single tree in terms of pond depth can be roughly approximated as

$$T=\frac{0.5 \cdot E}{A \cdot E_{max}}, \quad [5]$$

where E_{max} was the maximum daily pond evaporation observed during the growing season, 10 and 15 $mm \cdot d^{-1}$ for 2005 and 2006, respectively. Transpiration was calculated only between May and September when the tree was fully foliated. Although this approach is simplistic, it is a rational choice given the available data and is better than neglecting T altogether.

On-site instrumentation and supporting calculations provided estimates of most water balance terms, including P, E, S, C, T, and ΔD. Precipitation in the summer of 2006 was below normal and provided long periods when no overflow occurred ($O = 0$). There were three heavy rain events in 2006 that allowed the calculation of inflow from runoff, I, from the residual from Equation 1. Basically, the volume of water entering the pond was calculated from the sudden increase in pond depth and area after a rain storm. Given the land area draining into the pond was known, the percentage of precipitation that entered the pond from runoff could be calculated.

Stocker beef cattle are sensitive to heat stress and therefore increase their daily water consumption rates to alleviate the stress (Bicudo and Gates 2002, equation 7; Osborne 2003). Maximum daily air temperature and relative humidity data were used from a nearby weather station, located at the headquarters of the Konza Prairie Biological Station, to compute a temperature humidity index (THI) for the grazing steers:

$$\mathrm{THI}=0.8t_{db}+\mathrm{RH}(t_{db}-14.4)+46.4, \quad [6]$$

where t_{db} is the dry-bulb air temperature (°C), and RH is the relative humidity in decimal form. The THI is often used as a heat stress warning system and provides the producer with values to monitor cattle heat stress. Heat stress levels occur at index values greater than 65 and become more dangerous as the values reach or exceed 70. Comparisons of THI to water consumption were made on a daily basis to study the response of the grazing cattle during the grazing period.

Modeling Pond Evaporation

One goal of the project was to determine if evaporation from the pond could be estimated using data from a weather station network. The closest weather station was located at the headquarters of the Konza Prairie Biological Station located 7 km west of the pond. Average daily wind speed, air temperatures, and vapor pressure deficits (VPDs) at the pond were compared to the same data collected from the weather station. Data from the weather station were used to calculate daily evaporation using the Penman equation (Penman 1948) and the Priestley-Taylor model of Stewart and Rouse (1976). The Penman formula was a form of the FAO-56 equation for reference crop evaportranspiration (Allen et al. 2005) that had been modified for open water. After removing the canopy resistance term and using a roughness length of 0.1 cm for a pond-sized water body, the resulting equation took the following form:

$$E=\frac{0.408\Delta(R_n)+\gamma\frac{418}{T+273.15}u_2(e_s-e_a)}{\Delta+\gamma}, \quad [7]$$

where E is the reference evapotranspiration ($mm \cdot d^{-1}$), R_n is the net radiation ($MJ \cdot m^{-2} \cdot d^{-1}$), T is air temperature at 2 m (°C), e_s is the saturation vapor pressure at air temperature (kPa), e_a is the vapor pressure of air (kPa), u_2 is the wind speed at 2 m ($m \cdot s^{-1}$), Δ is the slope of the vapor pressure curve at air temperature ($kPa \cdot C^{-1}$), and γ is the psychometric constant ($kPa \cdot C^{-1}$). Details on calculating E using the modified Penman and the Priestley-Taylor formulas are provided in Jensen et al. (1990) and Allen et al. (1998).

RESULTS

Weather and Evaporative Demand

In the temperate climate of the central United States, a large fraction of the annual precipitation and runoff occurs in spring and early summer. In Manhattan, Kansas, long-term records show the months of May, June, and July account for 56% of annual precipitation. Thus, stock-watering ponds tend to fill to capacity during the spring and early summer and then are depleted by cattle consumption, evaporation, and seepage during late summer and early fall. In 2005 near-record precipitation of almost 300 mm fell in June so the pond was filled to capacity at the start of the study (Fig. 1). For the remainder of the 2005 grazing season, precipitation was near normal, and reference ET was within 2% of the historical average (Fig. 1). The pond at the study site and those in the region had a good supply of water during the summer, and there was no threat of water shortage in 2005. In 2006 precipitation in May and June was 179 mm (83 vs. 262 mm) below normal, and spring runoff was insufficient to fill the pond going into the grazing season. Comparisons of reference pond ET in 2006 to the historical average showed that evaporative and reference ET exceeded rainfall by 50 cm. Because of high evaporative demand and below-normal precipitation, water levels in stock-watering ponds in the region tended to decline significantly during the summer of 2006 and water shortages were a major concern. However, in August 236 mm of precipitation fell within 20 d (Fig. 1), which refilled the pond.

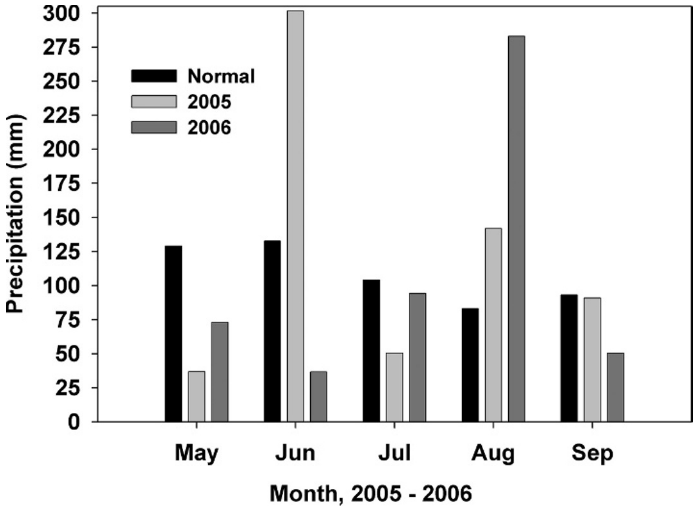

Figure 1. Comparison of precipitation during 2005 and 2006 to the 30-yr (1971–2001) average for Manhattan, Kansas.

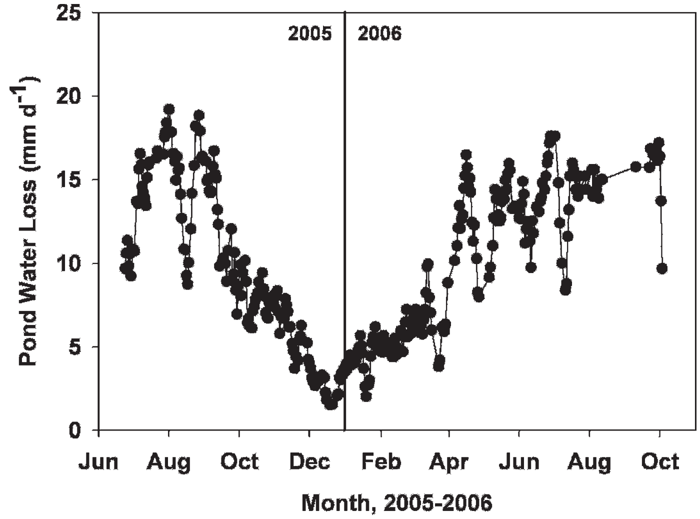

Figure 3. Total daily pond water losses for the entire study as measured by the floating depth recorder. The graph represents the change in pond depth, or the combined losses from *E, T, C,* and *S* over time.

Pond Depth Changes and Runoff

Pond depth fluctuated over 1.5 m during the 490-d record (Fig. 2). Large runoff events filled the pond to its maximum capacity of 2.2 m in the spring of 2005 and midsummer of 2006, while the low-water mark of 0.6 m occurred in August 2006 at the end of a summer drought. Because rainfall events in the High Plains are infrequent and episodic, there were periods between inflow events that showed a steady decline in depth. The largest of these drawdown periods, a 0.8-m decline, occurred between 14 June and 13 August 2006, when the pond got so low the water supply for the cattle was almost disrupted. Filtering out the few instances of precipitation, runoff, and overflow during the study allowed calculation of daily water losses ($S+E+T+C$) solely from the change in depth measurements (Fig. 3). Data show an annual cycle of water loss with peak values near 17 mm $\cdot$ d^{-1} during both years. Average summer (21 June to 22 September) loss rates were 14.2 and 14.6 mm $\cdot$ d^{-1} for 2005 and 2006, respectively. There was a rapid decline in the rate of water loss starting in October 2005 with lowest values of 1.5 mm $\cdot$ d^{-1} occurring during an unusually cold December in 2005. Rates of water loss increased steadily during the winter and spring of 2006 and varied from 8 to 18 mm $\cdot$ d^{-1} throughout the summer depending on weather conditions. In 2006 the rate of loss during September was greater than during July, even though evaporative demand was greater in July. This suggested that the increase in depth and area following the August rains may have increased losses from *S* and possibly *T*. Despite the weather-induced variability in Figure 3, these data show the utility of simple depth measurement when addressing pond hydrology. If depth time series were collected for several years in multiple ponds in a region, it would be possible to derive a good "rule of thumb" estimate of daily and monthly loss rates, numbers that might aid pond design and management.

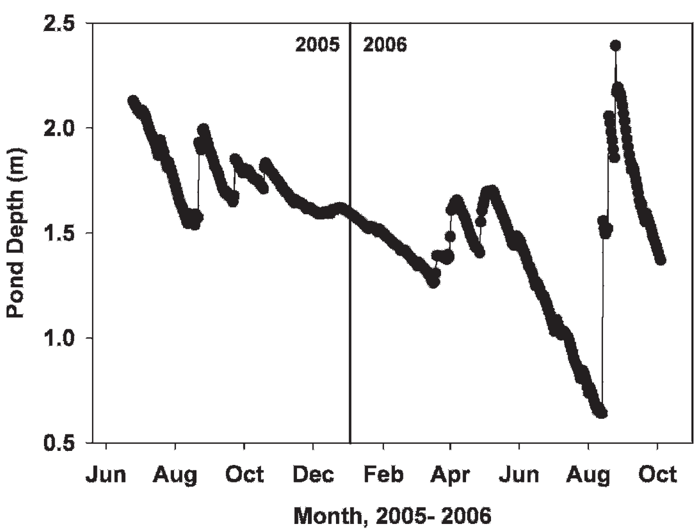

Figure 2. Depth of the pond at the deepest point as measured by the depth recorder in 2005 and 2006.

Three heavy rains received during mid-to-late August 2006 caused significant runoff and provided a good opportunity to see how well pond inflow could be predicted with a simple model. Actual runoff from these events was measured from pond depth changes and surface area (Q_{meas}), while runoff also was modeled using the NRCS curve number method (Q_{mod}) (Table 2). Prior to the first runoff event, the region had received minimal precipitation resulting in a drier than normal soil moisture profile. On 14 August, 81.9 mm of rain was received over 7.5 h. Modeled runoff from this event was 26.5 mm, while only 8 mm of runoff was measured by pond measurements. Results from event 2 were more comparable at 8.0 and 6.8 mm for Q_{meas} and Q_{mod}, respectively. Event 3 resulted in slightly lower similarity with 10.7 mm measured and 6.8 mm modeled. Calculations showed that dry soils retained nearly 60% ($I/P = 0.6$) of the precipitation that fell on the initial heavy rain on 14 August and explain the dissimilarity between Q_{meas} and Q_{mod} during the first event. Initial abstraction (I_a), the runoff curve number model parameter that accounts for infiltration and capture before runoff begins, is highly variable and depends on antecedent soil moisture and soil cover (NRCS 2002). Measured and modeled runoff from events 2 and 3 may

Table 2. Comparison of the measured pond inflow to modeled runoff using the Natural Resources Conservation Service curve number method.[1]

Event	Period (DOY)	P (mm)	ΔD (mm)	$A_{P\ ave}$ (m^2)	Q_{meas} (mm)	Q_{mod} (mm)	I_{fitted} (mm)	I/P (mm)
1	226	81.5	936.6	1 561.1	8	26.5	50.4	0.6
2	230–231	46.3	550	2 635.3	8	6.8	15.3	0.3
3	237	44.9	716.5	2 722.5	10.7	6.8	8.1	0.2

[1]Data shown are from three separate precipitation events that occurred during middle-to-late August 2006, where P = precipitation, ΔD = change in depth, $A_{P\ ave}$ = average pond area, Q_{meas} = measured runoff into the pond, Q_{mod} = modeled runoff from curve number, I_{fitted} = initial abstracted precipitation, and I/P = percentage of P abstracted by the landscape. DOY indicates day of year.

have been more similar than event 1 because of the increase in soil water content from the first precipitation event. Results in Table 2 suggest it will be challenging to estimate runoff and pond inflow in the Flint Hills of Kansas with any accuracy unless antecedent soil water content is included in the modeling framework.

Seepage

The seepage rate from a pond is dependent on the liner permeability, liner thickness, and hydraulic head. All of these parameters can vary spatially and with pond depth as the submerged area changes. The apparent whole-pond seepage rate was calculated during a 20-d study in December and January of 2005–2006. Winter is the best time to conduct the test because Ham (2002) showed that the uncertainty seepage estimate is lowest during periods of low evaporation. Also, there was no inflow or outflow from the pond during this period so that the change in depth was solely from evaporation and seepage (Ham 1999). Figure 4 shows cumulative depth change and total evaporation over the 20-d study, the difference in the two totals representing seepage. The calculated seepage rate was $2.6\ mm \cdot d^{-1}$, a value is consistent with the minimum winter-time rate change in depth data observed in Figure 3. Assuming an apparent liner thickness of 30 cm and an average pond depth of 1.5 m, the whole-pond hydraulic conductivity was computed as $7.59 \times 10^{-7}\ cm \cdot s^{-1}$ following the procedures of Ham (2005). Although the thickness of the liner was not known, it was important to parameterize the seepage in terms of permeability so that seepage could be scaled during the rest of the study as the depth of the pond changed. Figure 5 shows the calculated seepage rate for the entire study period as calculated from hydraulic conductivity and pond depth. On average, seepage was $2.6\ mm \cdot d^{-1}$, but ranged from 3.7 to $1.4\ mm \cdot d^{-1}$. These seepage rates and the ponds hydraulic conductivity are about three times higher than those from earthen basins with compacted soil or clay liners (Ham 2002).

Evaporation

Evaporation was highly variable but demonstrated clear seasonal trends (Fig. 6). The average evaporation rate for the summer (21 June to 22 September) was 5 and $7\ mm \cdot d^{-1}$ for 2005 and 2006, respectively. Lower VPDs and wind speeds in 2005 resulted in less evaporative demand compared to drier and windier conditions in 2006. Peak evaporation rates of $17\ mm \cdot d^{-1}$ occurred in July 2006 when wind speeds were over $5\ m \cdot s^{-1}$ and air temperatures exceeded 38°C. Advection of sensible heat from the surface boundary layer provided extra energy for evaporation. Examination of the 2006 grazing period (May to October) showed a midseason trend in which evaporative demand decreased after 8 August. Between 15 June and 8 August, 490 mm of evaporation was recorded as compared to 247 mm for the latter half of the study. This pattern was caused by a change in weather patterns that

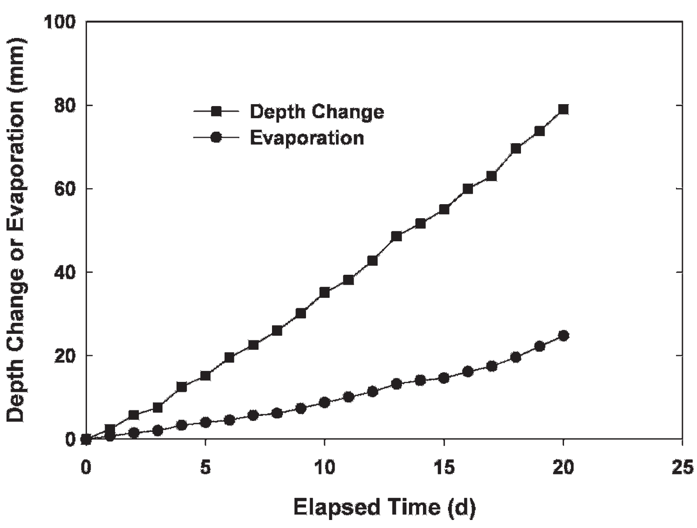

Figure 4. Change in depth and evaporation from the pond during a 20-d seepage test between 27 December 2005 and 15 January 2006. Seepage rate was calculated as the difference between total depth change and cumulative evaporation over time. The apparent seepage rate for the test was $2.6\ mm \cdot d^{-1}$.

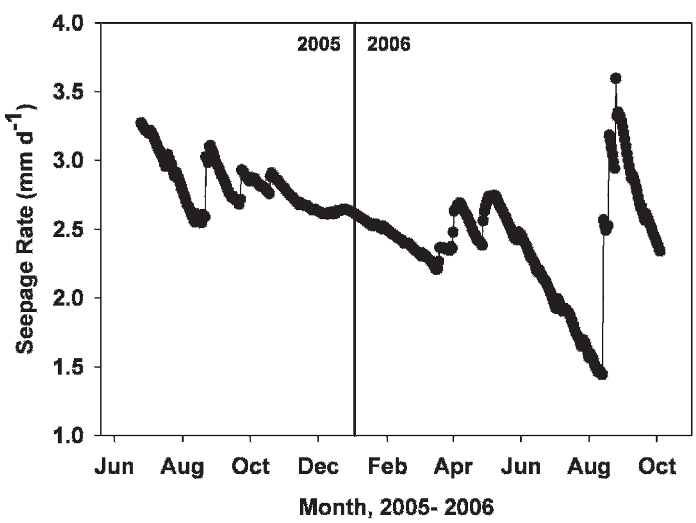

Figure 5. Fluctuations in the apparent seepage rate for the stock pond over the entire study period. Because seepage is influenced by hydraulic head pressure at the soil liner, seepage rates fluctuate as pond depth changes.

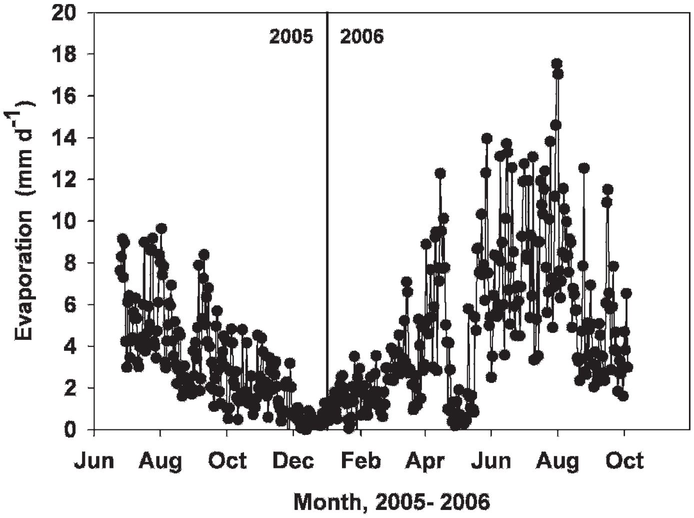

Figure 6. Evaporation from the stock-watering pond during the grazing period of the study. Evaporation was measured using instrumentation on the meteorological raft floating on the center of the pond.

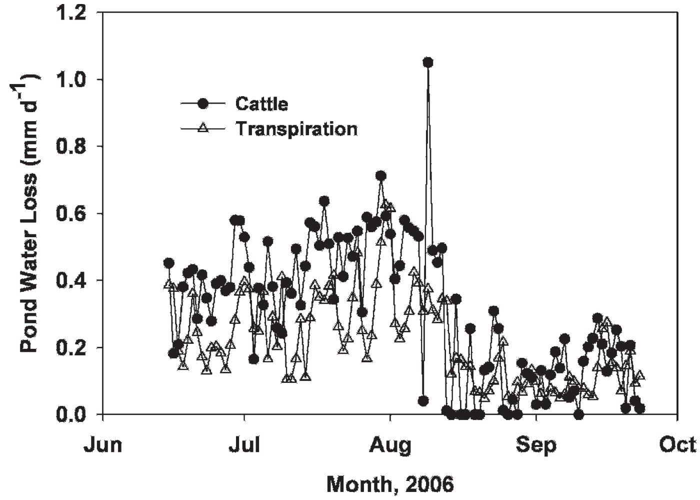

Figure 7. Cattle consumption and transpiration from the pond during the 2006 grazing season. Data are expressed in terms of pond depth.

decreased evaporative demand (Fig. 1). Examination of a full year of data (October 2005 to October 2006) gave an annual evaporation of 1 472 mm, which was comparable to Penman open-water evaporation of 1 448 mm calculated from long-term weather records for this region of Kansas (Sophocleous 1998). Rainfall during the same period was 708 mm.

Cattle Consumption and Transpiration

Consumption of water by cattle and transpiration were components of the pond water balance between May and October, a period that covered both the grazing season and the time of active plant growth (i.e., green leaves). Results show that both *C* and *T* were less than 1.0 mm $\cdot$ d^{-1} and were very small components of the water balance (Fig. 7). Both decreased significantly after 14 August 2006 when heavy rains caused ponding of water at other locations in the pasture and the cattle drank from multiple sources. Evaporative demand also decreased during this period.

The cattle consumed between 12 and 46 L $\cdot$ d^{-1} $\cdot$ $animal^{-1}$ during the first part of the 2006 grazing season when the pond was the only source of drinking water. On average, consumption was 30 L $\cdot$ d^{-1} $\cdot$ $animal^{-1}$, which was comparable to values in the literature for cattle of this weight (Gerrish and Davis 1997; Bicudo and Gates 2002; Osborne 2003). Water consumption was only loosely correlated with THI. Regression of consumption vs. THI (Equation 6) resulted in the equation $C = 45.6 + 1.1 \times \text{THI}$, $r^2 = 0.39$. Therefore, factors other than THI were governing water consumption. One controlling factor may have been the forage water content (Bartholomew et al. 2001). Lack of precipitation likely decreased forage water content and thus increased drinking water consumption needed to meet the water demand of the cattle.

Partitioning Water Losses During the Grazing Season

A summary of the monthly water losses by component over the 5-mo grazing season in 2005 and 2006 showed that evaporation was main source of water loss, accounting for 57%–77% of the total (Table 3). On average, evaporation was 64% of the total water loss, seepage was 31%, and cattle consumption and transpiration accounted for the remaining 5%. July was the month with the greatest water loss in both years, 277 and 358 mm in 2005 and 2006, respectively. Even during these months, cattle consumption still accounted for only 4% of the total loss. Because evaporation was such a large fraction of the water balance, management practices that might reduce losses from the pond are limited. In this case one option would be to dewater the basin and excavate to create greater depth and install a compacted soil liner. A deeper pond would provide more storage without increasing the surface area for evaporation. Although increasing depth will raise hydraulic head and increase seepage, installation of a compacted clay liner would moderate this effect and likely still reduce seepage rates to about one half or one third of those observed in Table 3 (Ham 2002).

Evaporation Modeling

Another goal of the study was to determine if data from local weather stations could be used to estimate the monthly evaporation from the stock-watering ponds. One question was how comparable weather conditions at the pond were to those at a weather station located kilometers away. Weather conditions at the pond were compared to data from the nearby Konza Prairie Biological station from June through August, the three months with the greatest evaporative loss. On average, air at the pond was about 2.0°C cooler, and the VPD was 0.2 kPa lower at the pond (Table 4). Cooler and more humid conditions at the pond are not surprising considering the latent heat flux from the water and the higher soil moisture contents in the lowland landscape surrounding the pond. Surprisingly, wind speeds at the pond were only about 10% lower than the weather station data even though the Konza weather station was in an upland location and the pond was at the bottom of the catchment (Table 4). A funneling effect from drainage landforms may have amplified wind speeds at the pond and compensated for its lowland location. Assuming radiation was identical between the two sites, sample calculations of reference evaporation (Equation 7) using weather data from the pond and Konza stations showed that average evaporative demand

Table 3. The total monthly losses of water from the stock-watering pond during the 2005 and 2006 grazing periods.

Date	Evaporation (mm); (%)	Seepage (mm); (%)	Cattle (mm); (%)	Transpiration (mm); (%)	Total (mm)
June 2005	153 (58)	96 (36)	12 (5)	3 (1)	264
July 2005	169 (61)	94 (33)	11 (4)	3 (2)	277
August 2005	127 (57)	86 (39)	8 (3)	3 (1)	224
September 2005	121 (56)	85 (41)	3 (2)	3 (1)	212
May 2006	138 (61)	81 (36)	4 (2)	3 (1)	226
June 2006	223 (74)	61 (21)	10 (3)	6 (2)	300
July 2006	279 (77)	56 (16)	14 (4)	9 (2)	358
August 2006	214 (71)	74 (24)	8 (3)	6 (2)	302
September 2006	132 (60)	82 (37)	3 (2)	3 (1)	220
Average	173 (64)	79 (31)	8 (3)	4 (2)	265

was 6 mm · d^{-1} and 7 mm · d^{-1} at the pond and Konza station, respectively, for the months of June through August.

Comparisons of the weather data indicated adequate agreement between data collected from the pond and weather station (Table 4), which permitted the use of meteorological models to estimate evaporation from the pond. Relatively good agreement was observed between evaporation measured by the pond instrumentation and that calculated from the Penman and Priestley-Taylor models using data from Konza as input. Compared to measured values, both models overestimated evaporation in the summer of 2005 and underestimated evaporation during the hottest months of 2006 (Fig. 8). When only the grazing season was considered, May to October, the Penman and Priestley-Taylor models underestimated evaporation by 13% and 14%, respectively, in 2006, and overestimated evaporation by similar amounts in 2005. Conditions in 2006 were warmer and windier compared to 2005 (Table 4). The Priestley-Taylor model does not use wind speed or VPD as inputs, and neither model accounts for horizontal advection, a factor that could significantly increase evaporation from small water bodies (Webster and Sherman 1995). During the fall and winter, the Penman model produced slightly higher estimates for evaporation than the Priestley-Taylor formula and was typically in better agreement with the measured data during this period. Using the pooled monthly evaporation data from 2005 and 2006, there was good agreement among the measure and modeled values (Fig. 9). Regression of monthly measured and modeled evaporation from both years yielded an R^2 of 0.81 and 0.86 for the Priestley-Taylor and Penman formulas, respectively. The slopes from both models ($0.97E_{Priestley\text{-}Taylor}$ and $0.95E_{Penman}$) were slightly less than unity and can be used as pond-specific coefficients (i.e., much like crop coefficients for *ET*) to make predictions of actual pond evaporation from calculated values of reference evaporation (e.g., Equation 7).

DISCUSSION

The study demonstrated that it is possible to monitor the water balance of the stock water pond for extended periods. Results showed that evaporation accounted for 64% of the total loss of water during the grazing period. Peak evaporation rates of 10–17 mm · d^{-1} were common in the months of July and August. Unfortunately there is little that can be done from a management perspective to decrease evaporation from stock ponds other than perhaps making ponds deeper with less surface area. Floating synthetic covers, like those used on some waste lagoons, might be cost effective for ponds in remote, arid locations. Seepage was the next most critical form of loss, accounting for 31% of the total. Seepage losses from this pond could likely be reduced by one-half to one-third of the current rate with the installation of a compacted clay liner. However, the cost benefit ratio of such an investment would need to be considered. Cattle water consumption was only 3% of average loss from the pond and reached a peak of 46 L · d^{-1} · animal^{-1} during July 2006. In this case the pond could have supported a much larger number of cattle. Although transpiration ranked last in the amount of water lost, it was just slightly lower than cattle consumption at this pond. Large phreatophytes, like the *Populus* trees, and other surrounding woody vegetation could be removed for that reason to increase the amount of potential water use for livestock.

Table 4. Monthly weather parameters recorded from the weather station located at the Konza Prairie Station (KZ) and the stock-watering pond (Pond). Shown in the table are the average air temperature, vapor pressure deficit, and wind speed for three months of the pond study.

	Temperature (°C)		Vapor pressure deficit (kPa)		Wind speed (m · s^{-1})	
Date	KZ	Pond	KZ	Pond	KZ	Pond
June 2005	24.3	24.1	1.1	0.9	3.6	2.8
July 2005	26.1	25.4	1.4	1.1	2.8	2.1
August 2005	25.3	24.4	1.1	0.9	2.4	1.9
June 2006	23.9	21.2	1.3	1.1	2.9	2.9
July 2006	28	24.6	1.8	1.5	2.8	2.9
August 2006	26.3	22.7	1.3	1	2.6	2.6
Average	25.7	23.7	1.3	1.1	2.8	2.5

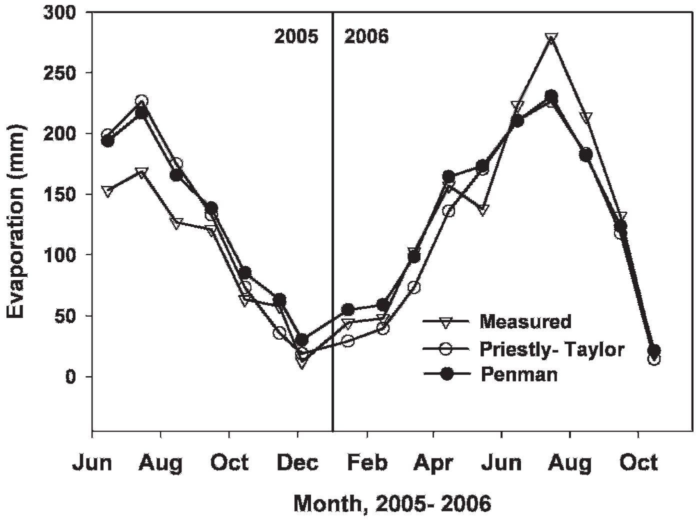

Figure 8. Comparison of monthly evaporation measured from pond instrumentation to estimated evaporation derived from the Priestley-Taylor and Penman models using local weather data from the Konza Prairie Biological Station.

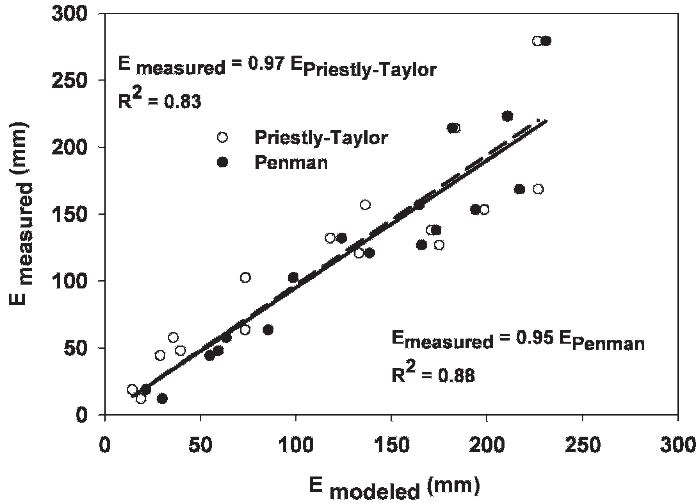

Figure 9. The correlation between measured evaporation using the bulk transfer equation to the Priestley-Taylor (—) and the Penman (-) evaporation models. Modeled values are from weather data obtained from the Konza Biological Station, and measured values are from the actual evaporation measured from raft instrumentation on the pond.

Although not the focus of this study, predicting inflow into a pond in convoluted, hilly terrain like the Flint Hills of Kansas continues to be a challenge. Most of the inflow from runoff occurred during a few infrequent storms. As expected, inflow in the pond was highly dependent on soil moisture conditions at the time of precipitation. The NRCS curve number method for modeling of runoff did not provide accurate estimates of inflow to the pond when soil conditions were dry at the start of precipitation. Modeling approaches that include the impact of antecedent soil water content on runoff will be required in a comprehensive model of pond hydrology (Silveira et al. 2000).

A goal of this research was to determine if pond evaporation could be modeled using data from weather station networks. Monthly comparisons of average air temperature, VPD, and wind speed between the stock-watering pond and the Konza weather station had sufficient similarity to allow use in meteorological modes. On average, the Priestley-Taylor and Penman equations slightly overestimated evaporation by 3% and 5%, respectively. These models can be used to compute reference pond evaporation and then multiply the result by a "pond coefficient" to estimate actual pond evaporation. Results showed that the Penman model with a multiplier of 0.95 would have predicted evaporation to within $\pm$ 6% for any month over the grazing season (May to October).

IMPLICATIONS

Ultimately the goal is to locate and design ponds for a given pasture and grazing regime that can provide season-long drinking water in all but perhaps the driest of years. This study showed that evaporation can be modeled and other forms of loss quantified with a relatively simple set of measurements. A clear need is to collect pond water balance data at multiple locations throughout a region to quantify the site-to-site variation. One interesting finding was that much could be learned solely from the time series of pond depth (e.g., Fig. 2). Because inflow events tend to be episodic in the Great Plains, it was possible to quantify the rate of loss (the sum of *E, S, C,* and *T*) for most of the year from the slope of the depth vs. time curve. Furthermore, during the winter, the rate change in depth provided an approximation of seepage. Finally, the sudden increases in depth following a rainfall provided a measure of runoff. Thus, depth measurements alone coupled with a few other measures of catchment area, pond dimensions, etc., provide the researcher with detailed knowledge of site-specific pond hydrology. Thus, if multiple ponds in a region were equipped with high-resolution depth recorders and recording rain gauges, much could be learned about pond hydrology with minimal expense and effort. This research as well as the combined findings from many other research projects clearly demonstrates that adequate technology and knowledge is available to provide site-specific designs for stock-watering ponds and livestock-watering strategies in the Great Plains. In areas where livestock drinking water often becomes limited, having properly designed and managed stock-watering ponds could have significant economic benefits.

ACKNOWLEDGMENTS

Technical support was provided by F. W. Caldwell. A GIS analysis of catchment containing the pond was provided by P. I. Coyne.

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