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Evaluation of Recharge to the Skunk Creek Aquifer from a Constructed Wetland near Lyons, South Dakota

Water-Resources Investigations Report 02-4133

U.S. Department of the Interior
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Rapid City, South Dakota: 2002

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
acre	4,047	square meter
acre	0.4047	hectare
acre-foot	1,233	cubic meter
acre-foot	0.001233	cubic hectometer
cubic foot per second	0.02832	cubic meter per second
foot	0.3048	meter
foot per day	0.3048	meter per day
gallon per minute	0.06309	liter per second
gallon per day	0.003785	cubic meter per day
inch	2.54	centimeter
inch	25.4	millimeter
inch per day	2.54	centimeter per day
mile	1.609	kilometer
yard	0.9144	meter

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8$$

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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ABSTRACT

A wetland was constructed in the Skunk Creek flood plain near Lyons in southeast South Dakota to mitigate for wetland areas that were filled during construction of a municipal golf course for the city of Sioux Falls. A water-rights permit was obtained to allow the city to pump water from Skunk Creek into the wetland during times when the wetland would be dry. The amount of water seeping through the wetland and recharging the underlying Skunk Creek aquifer was not known. The U.S. Geological Survey, in cooperation with the city of Sioux Falls, conducted a study during 1997-2000 to evaluate recharge to the Skunk Creek aquifer from the constructed wetland.

Three methods were used to estimate recharge from the wetland to the aquifer: (1) analysis of the rate of water-level decline during periods of no inflow; (2) flow-net analysis; and (3) analysis of the hydrologic budget. The hydrologic budget also was used to evaluate the efficiency of recharge from the wetland to the aquifer. Recharge rates estimated by analysis of shut-off events ranged from 0.21 to 0.82 foot per day, but these estimates may be influenced by possible errors in volume calculations. Recharge rates determined by flow-net analysis were calculated using selected values of hydraulic conductivity and ranged from 566,000 gallons per day using a hydraulic conductivity of 0.5 foot per day to 1,684,000 gallons per day using a hydraulic conductivity of 1.0 foot per day. Recharge rates from the hydrologic budget varied from 0.74 to 0.85 foot per day, and averaged 0.79 foot per day.

The amount of water lost to evapotranspiration at the study wetland is very small compared to the amount of water seeping from the wetland into the aquifer. Based on the hydrologic budget, the average recharge efficiency was estimated as 97.9 percent, which indicates that recharging the Skunk Creek aquifer by pumping water into the study wetland is highly efficient.

Because the Skunk Creek aquifer is composed of sand and gravel, the “recharge mound” is less distinct than might be found in an aquifer composed of finer materials. However, water levels recorded from piezometers in and around the wetland do show a higher water table than periods when the wetland was dry. The largest increases in water level occur between the wetland channel and Skunk Creek. The results of this study demonstrate that artificially recharged wetlands can be useful in recharging underlying aquifers and increasing water levels in these aquifers.

INTRODUCTION

A wetland was constructed in the Skunk Creek flood plain near Lyons in southeast South Dakota (fig. 1) to mitigate for wetland areas that were filled during construction of a municipal golf course for the city of Sioux Falls. Following construction, the wetland was turned over to the Sioux Falls Water Department for management. The wetland was constructed on city-owned land. A water-rights permit was obtained to allow the city to pump water from Skunk Creek into the wetland during times when the wetland would otherwise be dry. The amount of water seeping through the wetland and recharging the underlying Skunk Creek aquifer was not known. The U.S. Geological Survey, in cooperation with the city of Sioux Falls, conducted a study during 1997-2000 to evaluate recharge to the Skunk Creek aquifer from the constructed wetland. The objectives of the study were to: (1) estimate recharge rates from the wetland to the Skunk Creek aquifer; (2) monitor all hydrologic input and output components for the constructed wetland to determine recharge rates and efficiency of recharge from the wetland to the Skunk Creek aquifer; and (3) determine the effect of the constructed wetland on ground-water levels in the wetland vicinity. The results of this study can be useful in the evaluation of effects of artificially recharged wetlands on underlying aquifers in other areas.

Purpose and Scope

The purpose of this report is to summarize the study results, which include estimates of recharge rates from the wetland to the Skunk Creek aquifer, estimates of the efficiency of recharge, and the effect of the wetland on ground-water levels in the underlying aquifer. Water-level data were collected during 1997-2000 for flow-net analyses. Data were collected for the components of the hydrologic budget during 1998-2000. Data collection was limited to the immediate vicinity of the wetland. During the data-collection period, data were not obtained during the parts of the year that the wetland site was inaccessible due to snow or flooding. Collection of data for the components of the hydrologic budget also was suspended during other time periods when the wetland was dry.

Description of the Study Area

The study area (fig. 1) is located in Minnehaha County in the northern part of the west half of the southeast quarter of section 7 in Township 103 North, Range 50 West. Apart from the depression of the constructed wetland, the study area is mainly flat to slightly sloping. The area immediately around the wetland is seeded in native grasses. Pasture is found west of the study area, and crops are grown on the other three sides. Skunk Creek is west of and adjacent to the study area and roughly parallels the wetland. The Skunk Creek aquifer is composed of sand and gravel and is hydraulically connected to Skunk Creek. Skunk Creek flows north to south, and the hydraulic gradient in the Skunk Creek aquifer is north to south and locally towards Skunk Creek (Ohland, 1990).

Description of the Wetland

The land in the study area was farmed prior to ownership by the city of Sioux Falls. The wetland was formed in 1997 by constructing a large berm across a natural drainageway to Skunk Creek in the Skunk Creek flood plain (fig. 2). The drainageway was reshaped somewhat to improve wildlife habitat. Within the berm, a 36-inch corrugated metal pipe was installed vertically to act in combination as a well casing and as a pumping wet well (fig. 3) for the Skunk Creek inlet. In the lower portion of the vertical pipe, a similar corrugated metal pipe extends horizontally to the southwest into a short (150-foot) drainage connected to Skunk Creek. In the upper part of the vertical pipe, another metal pipe extends horizontally to the northeast and has a flap gate into the wetland. A foam seal was installed on the flap gate to prevent leakage back into the wet well. This design allows water from Skunk Creek to flow by gravity into the wetland when the stage in Skunk Creek is higher than the wetland stage. During periods when the stage in Skunk Creek is lower than the wetland stage, the pump may be used to lift water from Skunk Creek into the wetland. After the wetland was constructed and this study initiated, two adjacent wetlands were constructed and connected to the study wetland with culverts. The smaller of the two (approximately 0.8 acre) is located southeast of the study area, and the larger (approximately 2.7 acres) is located southwest of the study area.

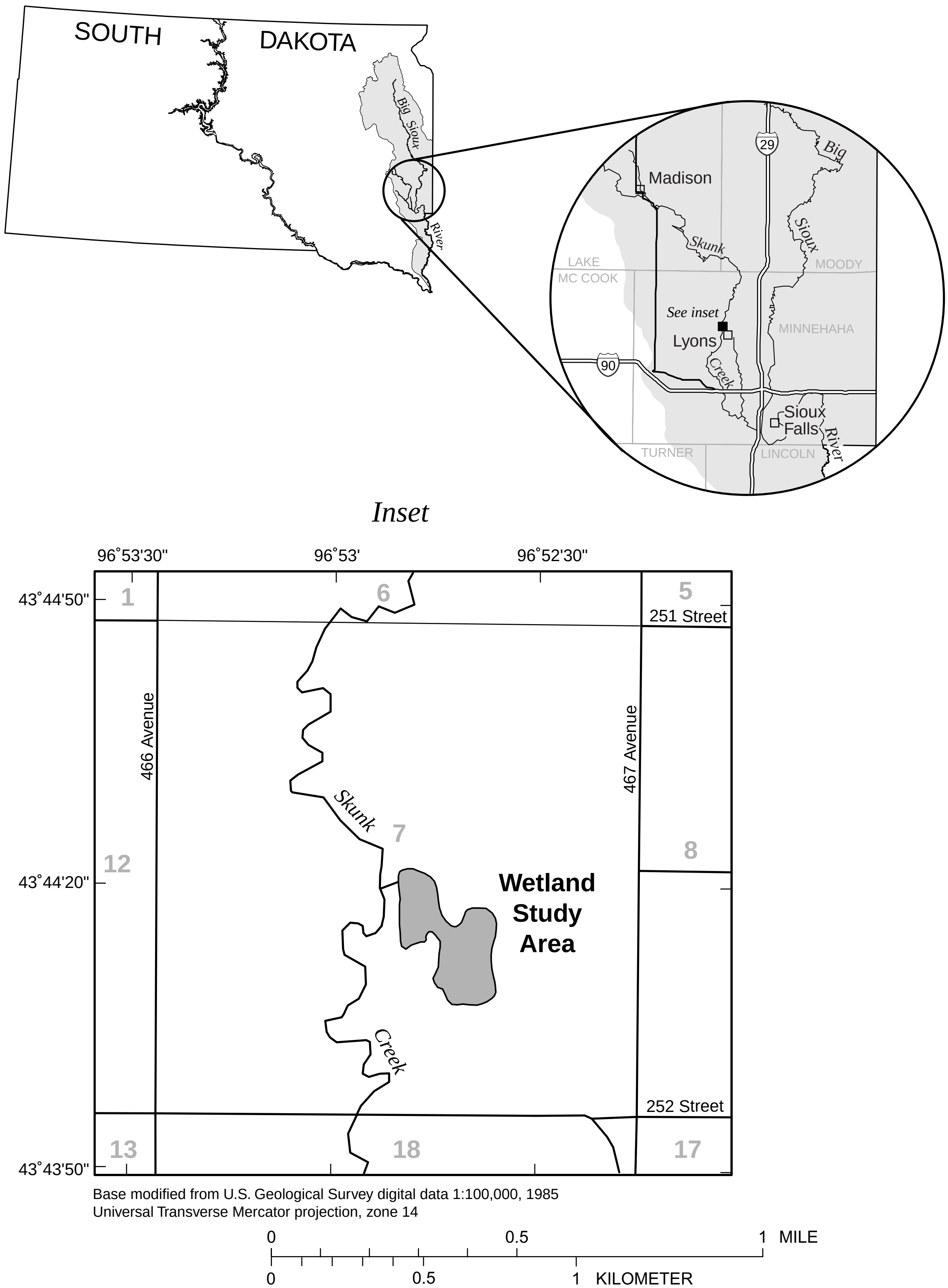


Figure 1. Location of study area.

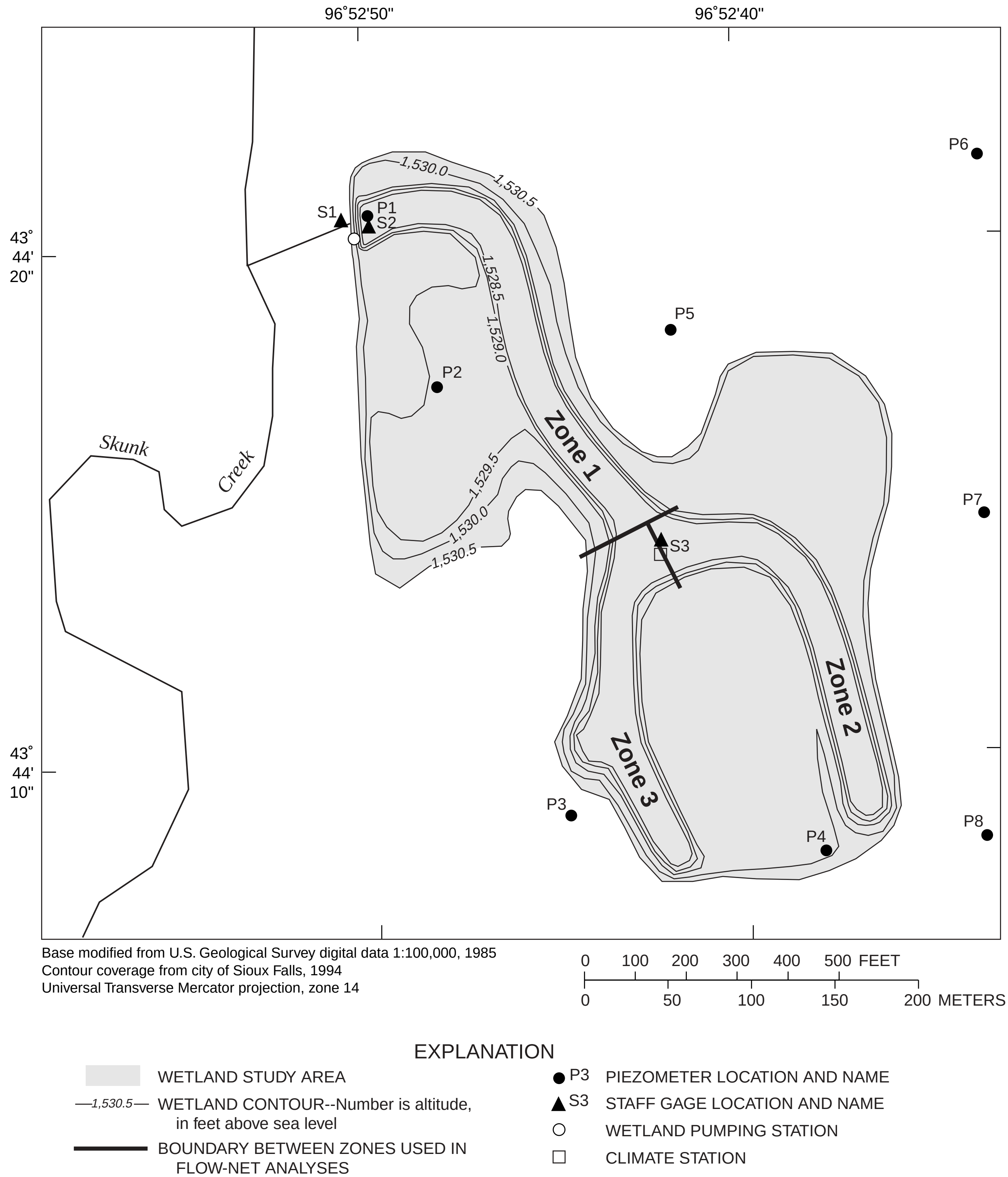


Figure 2. Wetland study area showing locations of piezometers, staff gages, pumping station, climate station, and zones used in flow-net analyses.

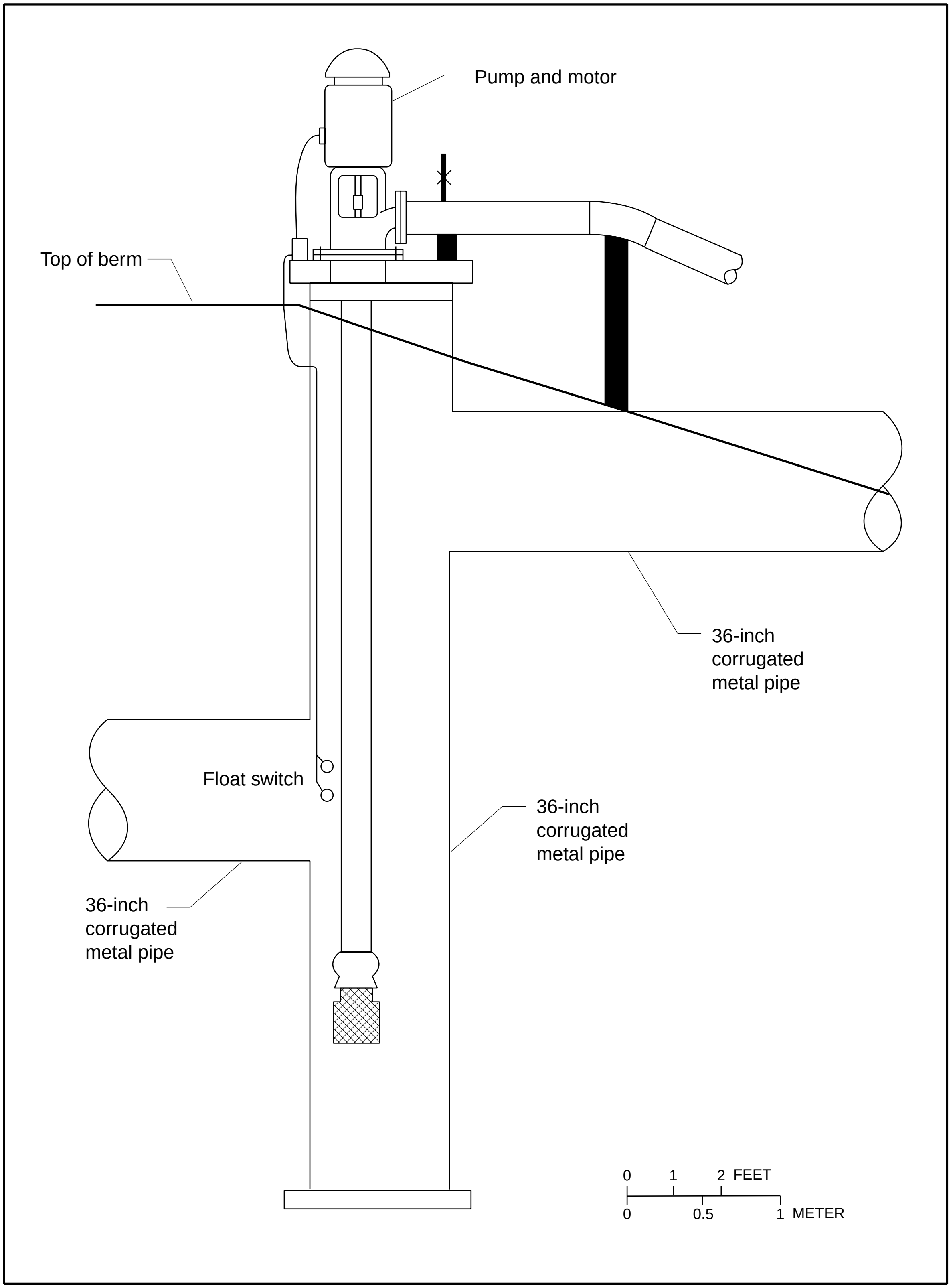


Figure 3. Detail of wetland pumping station.

During data-collection seasons 1997-2000, Skunk Creek never reached high enough stages to gravity flow into the wetland, and stages in the study wetland were never high enough to flow into the adjacent wetlands. In May 2001, the stage in Skunk Creek was high enough to gravity flow into both the study wetland and the adjacent wetlands. This also may have occurred during the springs of 1998-2000 before the instrumentation was in place for the data-collection season.

Piezometers were installed in the Skunk Creek aquifer at eight locations in and near the constructed wetland (fig. 2). Depths of the piezometers ranged from approximately 10 to 14 feet below land surface, and their water levels were assumed to represent the water table. Staff gages were installed in Skunk Creek and within the wetland. Staff gages also were installed in the adjacent wetlands so that any overflow from the study area could be measured. Altitudes of the staff gages and piezometers were determined using a reference mark established in the study area. Water levels in the piezometers and at the staff gages were periodically recorded by Sioux Falls Water Purification Plant staff.

Pump Operation

The pump (fig. 3) was installed in the wet well prior to each data-collection season sometime in late spring to early summer, when soil conditions at the wetland site were dry enough to allow access by the heavy vehicles required. High flows in Skunk Creek during spring often caused silting problems for the intake pipe of the pumping station. Pumping was then started after the silt was cleared. During the 1999 season, the pump was installed later in the year to allow soil conditions to become dry enough that portions of the wetland could be re-seeded with native grasses. The water-use permit allowing the city to pump water from Skunk Creek into the wetland stipulates that a minimum of 20 cubic feet per second of flow must remain in Skunk Creek for downstream users. Therefore, pumping was sometimes discontinued during periods of low flow. During the 1998 data-collection season, the city staff turned the pump on and off manually as required to maintain sufficient flow in Skunk Creek. A float switch was used during the 1999-2000 seasons to automatically operate the pump. The pump was removed at the end of each data-collection season sometime in late fall or early winter to avoid pump damage from ice formation.

EVALUATION OF RECHARGE

Recharge from the constructed wetland to the underlying Skunk Creek aquifer is evaluated in this section of the report. Three methods are presented that were used to estimate recharge. The efficiency of recharge from the wetland to the aquifer and the effects of the recharge on ground-water levels also are presented.

Methods

Background information, such as stage versus area and volume relations and evapotranspiration calculations, were needed to estimate recharge. Three methods were used to estimate recharge from the wetland to the aquifer: (1) analysis of the rate of water-level decline during periods of no inflow; (2) flow-net analysis; and (3) analysis of the hydrologic budget. The hydrologic budget also was used to evaluate the efficiency of recharge from the wetland to the aquifer.

Wetland Area and Volume

The methods involving analysis of water-level declines and analysis of the hydrologic budget both required wetland area and volume as inputs. The stage/area/volume relation for the study wetland was determined using the method described by Niehus and others (1999) for lake studies in northeast South Dakota. A set of construction plans showing the altitude and extent of the wetland was provided by the city of Sioux Falls. The contours on the plans were spot checked by using known altitudes at the staff gages and piezometers installed in and near the wetland. The contours were digitized to determine the wetland area at each contour. Because there is no standardized method for interpolating between known areas or for converting estimated areas to volumes, a set of equations was developed to relate stages, areas, and volumes. These equations were developed using a nonlinear least-squares regression of wetland stage versus area and wetland stage versus volume. Three shape coefficients were used to fit the equation to the data, beginning with the general equation of:

$$V(h) = V_{max}\left(ah' + \frac{(0.5(1-a)(1+b)(1-\cos(\pi h')))}{(1-b\cos(\pi h'))}\right)^{(c+1)} \qquad (1)$$

where

$V(h)$ = volume, in acre-feet at wetland stage h;
h = wetland stage, in feet above sea level;
V_{max} = maximum volume, in acre-feet;
h' = $(h - h_{min})/(h_{max} - h_{min})$, a standardized stage for $h' > 0$;
h_{min} = minimum (dry wetland bottom) stage, in feet above sea level;
h_{max} = maximum stage, in feet above sea level; and
a, b, and c = shape coefficients used to fit data for the wetland ($a > 0$, $b > -1$, and $c > 0$).

$V(h_{min}) = 0$, and $V(h)$ has positive first and second derivatives for $h > h_{min}$, which are conditions that must be satisfied by a valid volume function. The area equation obtained by differentiating $V(h)$ is:

$$A(h) = A_{max}\left(\frac{1 + \left(\frac{\pi}{2a}\right)(1-a)(1+b)(1-b)\sin(\pi h')}{(1-b\cos(\pi h'))^2}\right)\left(ah' + \frac{0.5(1-a)(1+b)(1-\cos(\pi h'))}{(1-b\cos(\pi h'))}\right)^{c} \qquad (2)$$

where

$$A(h) = \text{area, in acres at wetland stage } h;$$

and

$$A_{max} = \text{maximum area, in acres} = \frac{V_{max}a(c+1)}{(h_{max} - h_{min})}.$$

The parameters a, b, and c were fitted to known areas from the contours in figure 2 using nonlinear least-squares regression in S-Plus statistical and data analysis software (Lam, 1999). The minimum (dry wetland bottom) stage of 1,527.2 was estimated from the staff gage located a few feet from the low point in the wetland bottom. The value for h_{max} was taken as 1,530 feet, because the wetland stage never exceeded this value during the data-collection period. The fitted parameters of $a = 1.35839$, $b = -0.32577$, and $c = 1.77004$ provided an adequate fit to the data for stage versus area (fig. 4) and stage versus volume (fig. 5). The fitted parameters were used to estimate the area and volume of the wetland at various stages as required for the recharge estimates in a following section. Table 1 summarizes wetland stage, area, and volume values from the fitted equation at 0.1-foot intervals.

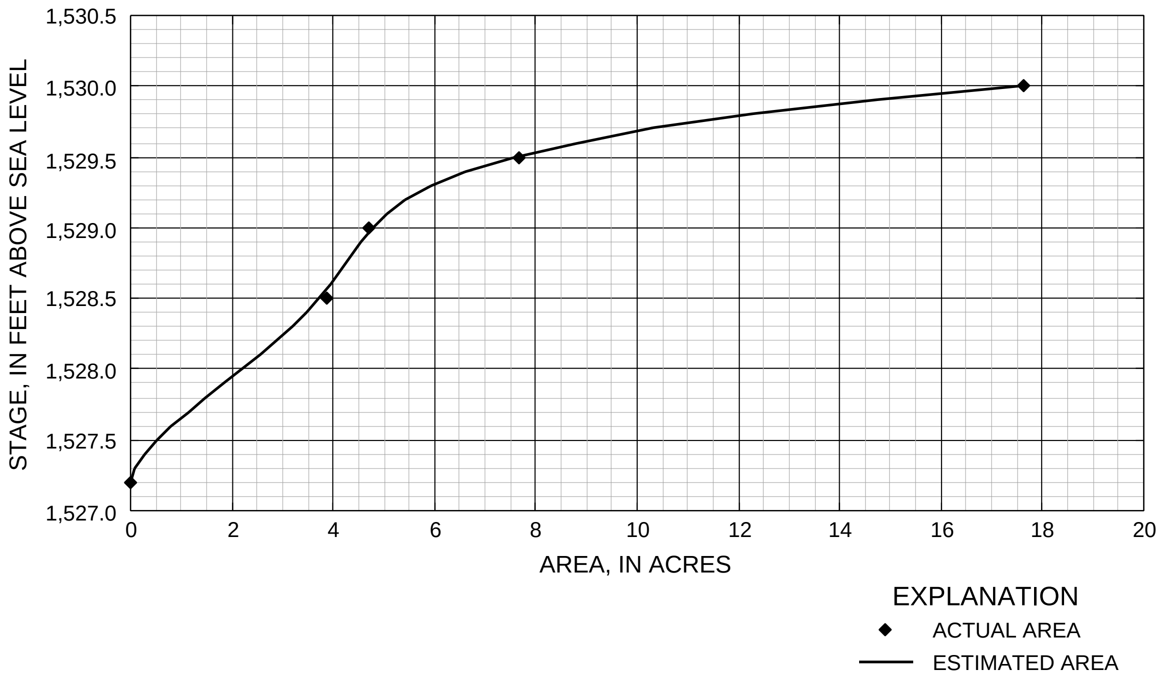


Figure 4. Wetland stage versus wetland area.

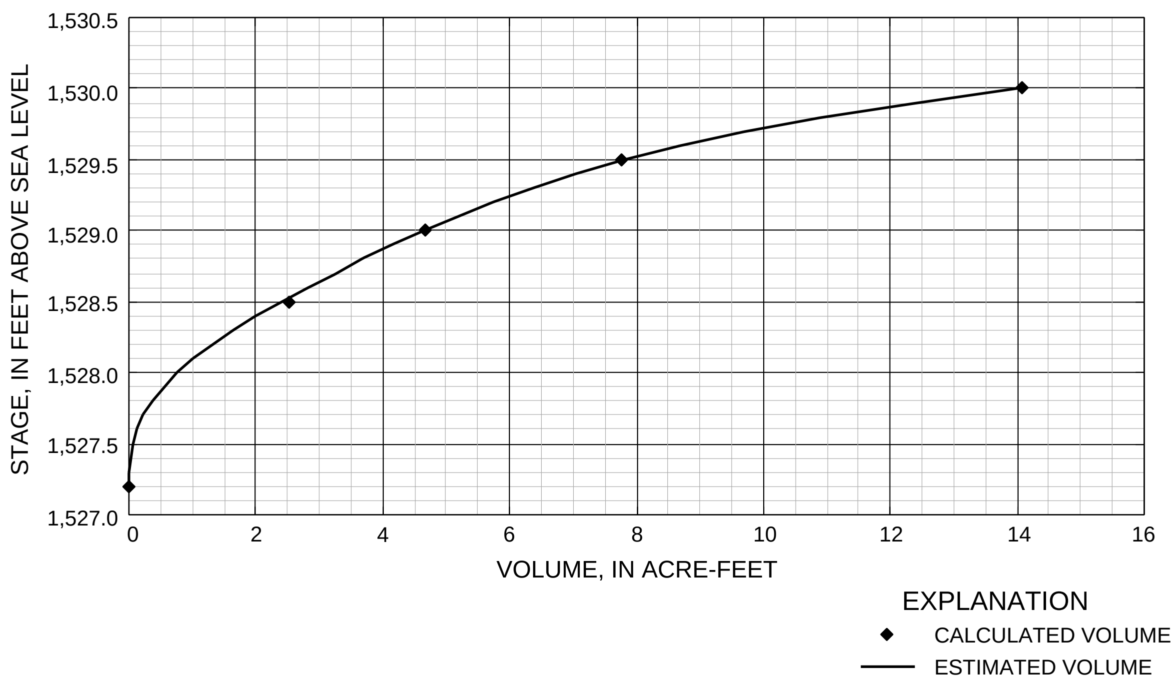


Figure 5. Wetland stage versus wetland volume.

Table 1. Wetland stage, area, and volume values from the fitted equation at 0.1-foot intervals

Stage (feet above sea level)	Area (acres)	Volume (acre-feet)
1,527.2	0	0
1,527.3	.079	.003
1,527.4	.259	.021
1,527.5	.506	.061
1,527.6	.802	.131
1,527.7	1.131	.235
1,527.8	1.482	.375
1,527.9	1.842	.553
1,528.0	2.201	.770
1,528.1	2.551	1.025
1,528.2	2.884	1.317
1,528.3	3.194	1.644
1,528.4	3.476	2.002
1,528.5	3.729	2.389
1,528.6	3.954	2.802
1,528.7	4.157	3.238
1,528.8	4.348	3.694
1,528.9	4.543	4.172
1,529.0	4.765	4.671
1,529.1	5.042	5.197
1,529.2	5.412	5.757
1,529.3	5.917	6.364
1,529.4	6.607	7.034
1,529.5	7.536	7.791
1,529.6	8.759	8.663
1,529.7	10.334	9.685
1,529.8	12.311	10.897
1,529.9	14.731	12.344
1,530.0	17.618	14.077

Evapotranspiration

Evapotranspiration losses were estimated using the Priestly-Taylor equation (Priestly and Taylor, 1972), which is an energy-balance method. The energy-balance method uses a horizontal layer with its lower boundary at land surface and its upper boundary above the wetland vegetation. Because evapotranspiration requires energy, evapotranspiration can be expressed as an energy flux with units of energy per unit time per unit area. In this report, the energy flux units are given in watts per square meter. The Priestly-Taylor equation is given as:

$$\lambda ET = \alpha\left(\frac{s}{s+\gamma}\right)(R-G) \qquad (3)$$

where
- λ = latent heat of vaporization of water;
- ET = evapotranspiration;
- α = best estimate of the Priestly-Taylor parameter, equal to 1.26;
- s = slope of saturation vapor pressure-temperature curve;
- γ = psychrometer constant;
- R = net radiation; and
- G = heat flux from the water surface down.

The parameters used to compute the flux terms were measured onsite at the wetland climate station (fig. 2). Net radiation, soil heat flux, water temperature, air temperature, relative humidity, rainfall, and wetland stage were each recorded using a data logger at one-half-hour time steps. An example of the evapotranspiration calculations for a 24-hour period is given in table 6 in the “Supplemental Information” section at the end of the report.

The total evapotranspiration for the 24-hour period listed in table 6 is equivalent to a rate of 0.19 inch per day over the wetland area. Pan evaporation for June 2000 expressed as a daily rate, was 0.19 inch per day at Brookings, South Dakota (approximately 38 miles north), and 0.26 inch per day at Pickstown, South Dakota (approximately 92 miles southwest) (National Oceanic and Atmospheric Administration, 2000).

Water-Level Declines

During the data-collection seasons of 1998-2000, near-constant pumping was required to maintain water in the wetland. At several periods throughout the data-collection phase, the pump was shut off for varying periods of time with different initial wetland stages. The rate of water-level decline in the wetland was recorded using a continuous-recording depth transducer at the wetland climate station (fig. 2). Using the stage/area/volume relations for the wetland, the quantity of water leaving the wetland over a given period of time can be estimated. By subtracting the quantity of water lost to evapotranspiration, a recharge rate can be estimated.

Flow-Net Analysis

Graphical construction of a flow net is a tool used in analysis of ground-water flow (Freeze and Cherry, 1979). A graphical flow net is essentially a cross-sectional view of an area where ground-water movement is occurring. On this cross-sectional view, a network of flow lines and equipotential lines are drawn, forming a net-like pattern. The space between flow lines sometimes is called a flow tube. The rules for graphical construction of a flow net in homogenous, isotropic media are relatively simple: (1) flow lines and equipotential lines must intersect at right angles; (2) equipotential lines must meet impermeable boundaries at right angles; (3) equipotential lines must parallel constant-head boundaries; and (4) if the flow net is drawn using rectilinear squares in one portion of the field, then rectilinear squares must be drawn throughout the rest of the field, except that partial flow tubes are allowed at the edge.

Once the flow net is drawn, the discharge per unit length of zone perpendicular to the flow net (Q) is described by the equation:

$$Q = \frac{mKH}{n} \qquad (4)$$

where

Q = discharge per unit length of zone perpendicular to the flow net;
m = number of flow tubes;
K = hydraulic conductivity of the media;
H = difference in hydraulic head; and
n = number of divisions of hydraulic head (equipotential lines).

Flow nets that involve both saturated and unsaturated flow are difficult to construct graphically. As evidenced by the field conditions and water-level data collected, the study wetland does, in fact, have regions of saturated and unsaturated flow. This type of flow net often is solved with computer models developed to solve finite-difference equations; however, such a model is beyond the scope of this study. Jeppson and Nelson (1970) discuss a mathematical model that is developed to allow regions of partially saturated flow. They state that using a saturated solution on a flow net that includes partially saturated conditions will underestimate the recharge rate, but for a sandy soil, the difference will be insignificant (Jeppson and Nelson, 1970). Because the study area is located in a flood plain, the soil is quite sandy, and it is underlain by the sand and gravel composing the Skunk Creek aquifer; thus, a standard flow net approach was used.

Hydrologic Budget

A hydrologic budget can be used to estimate recharge from the study wetland to the Skunk Creek aquifer. To estimate recharge in this way, the input and output components for the hydrologic budget of the wetland must be monitored. LaBaugh (1986) has described the following equation as the general-case hydrologic budget for lakes and streams:

$$\Delta S = PI + SI + GWI + NCI - ET - SO - GWO - NCO \qquad (5)$$

where

ΔS = change in storage;
PI = precipitation inflow;
SI = surface-water inflow;
GWI = ground-water inflow;
NCI = non-channelized inflow;
ET = evapotranspiration;
SO = surface-water outflow;
GWO = ground-water outflow; and
NCO = non-channelized outflow.

Equation 5 can be customized for the study wetland by adding a term representing pumped inflow:

$$\Delta S = QI + PI + SI + GWI + NCI - ET - SO - GWO - NCO \qquad (6)$$

where QI = pumped inflow from Skunk Creek to the wetland.

The change in storage in the wetland can be determined by relating differences in stage to the stage/area/volume relations of the wetland. Pumped inflow was determined using pump run time, the pump curve, stage in Skunk Creek, and estimated head losses in the pump's discharge pipe. Precipitation was measured using a tipping-bucket rain gage. As shown in figure 2, no streams drain into the wetland, so surface-water inflow is zero. Analysis of stage and rainfall data shows that non-channelized inflow is zero, except during high-intensity rainstorms or very wet antecedent conditions. Ground-water inflow can be assumed to be zero during periods when the stage in the wetland is greater than the water level in the underlying Skunk Creek aquifer. Thus, ground-water outflow (GWO) for these periods represents net recharge to the Skunk Creek aquifer and will be referred to as recharge in subsequent discussions and equations. Evapotranspiration is estimated using air temperature, relative humidity, water temperature, net solar radiation, and heat-flux data as previously described. Surface-water outflow is zero due to the foam seal on the one-way flap gate. Non-channelized outflow is zero because the wetland is a small closed basin.

Using the assumptions described above, several terms of equation 6 drop out to form equation 7:

$$\Delta S = QI + PI - ET - \text{Recharge} \qquad (7)$$

Equation 7 can be further simplified to equation 8 by selecting time periods that have no precipitation, and no net change in storage, as indicated by the same initial and final stage in the wetland:

$$QI = ET + \text{Recharge} \qquad (8)$$

Thus, by carefully selecting specific periods of time, recharge may be solved for as the residual. However, this does not take into account errors involved in the measurement of the remaining terms. In the study wetland, however, any errors in evapotranspiration estimates will be small relative to pumped inflow. Errors in the pumped inflow term can be minimized by carefully reading the pump curve and accounting for head losses in the pump's discharge pipe. Recharge then may be solved for as the residual, and the solution compared to the calculations from rate of water-level decline and to results of the flow-net analysis, as previously described.

Recharge Estimates

Analysis of water-level decline is a numeric method, flow-net analysis is a graphical estimation method, and the hydrologic budget involves measuring input and output components for the wetland. Estimated recharge rates from the study wetland to the Skunk Creek aquifer using each of three methods are presented in this section of the report.

Water-Level Declines

Periods of water-level decline with relatively steady antecedent stage and no recent heavy rainfall were chosen to avoid possible interference. Stage and rainfall graphs for the period of August and September 2000 show how rainfall can influence stage in the wetland (fig. 6). Early on August 4, the low stage in Skunk Creek activated the float switch, shutting off the pump. At midnight, rain began and by early the next morning, almost 2.5 inches had fallen. Direct precipitation and runoff increased the stage in the wetland and Skunk Creek by early on August 5, allowing the float switch to turn the pump back on. Similar but smaller events occurred on August 16, September 4, and September 9. On August 31, the float switch shut the pump off, and the wetland stage dropped rapidly, so that by the early morning of September 2, there was no water on the wetland stage transducer. Because the wetland stage had been relatively steady for several days prior to shut off, this event lends itself well to analysis of rate of water-level decline. Similar criteria were met for shut-off events on May 29, 1998, June 29, 2000, and October 10, 2000. Estimated recharge rates from these shut-off events are given in table 2. Because there were no climate data collected to calculate an evapotranspiration rate for the May 29 shut-off event, based on similar air temperatures, it was assumed that evapotranspiration losses were equal to the evapotranspiration losses during the 15.5-hour period beginning at 11:30 a.m. on June 20, 2000.

Recharge rates estimated by analysis of shut-off events ranged from 0.21 to 0.82 foot per day. The wide variation in these rates may be due to climatic variation influencing evapotranspiration or differences in the soil conditions of the wetland bottom, but this method of estimation also would be susceptible to errors associated with the area and/or volume calculations involved. Although figures 4 and 5 indicate that the equations fit the area and volume data rather well, there may be some error associated with using the wetland contours (fig. 2). The actual wetland contours may differ somewhat from the contours in the construction plans. Erosion or siltation from Skunk Creek flood events also may have caused errors that cannot easily be quantified without re-mapping the wetland. The 1998 shut-off event could potentially have the greatest susceptibility to errors in volume calculations. Because the storage change of the 1998 event was less than one-third as much as the other three events, any volume-related errors would have a proportionately larger affect on the recharge estimate from this event.

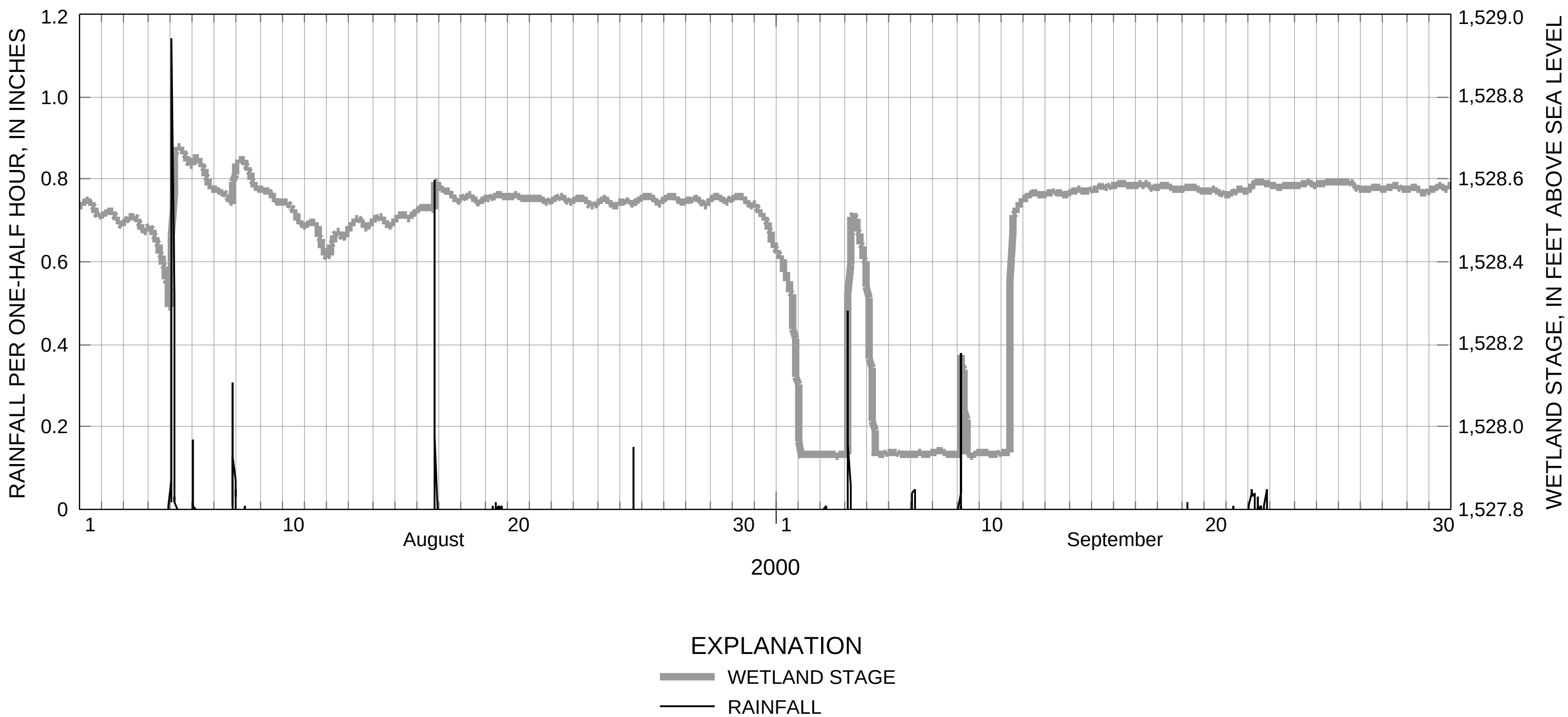


Figure 6. Stage and rainfall at the wetland climate station during August and September 2000.

Table 2. Estimated recharge rates from shut-off events

Beginning of water-level decline					End of water-level decline					Time elapsed (hour: minute)	Change in volume (acre-feet)	Evapo-transpi-ration losses (acre-feet)	Recharge[1]	
Date	Time	Stage (feet above sea level)	Area of wetland (acres)	Volume of wetland (acre-feet)	Date	Time	Stage (feet above sea level)	Area of wetland (acres)	Volume of wetland (acre-feet)				feet per day	gallons per day
May 29, 1998	1130	1,528.61	3.975	2.844	May 30, 1998	0300	1,528.48	3.681	2.310	15:30	0.534	[2]0.020	0.21	259,000
June 29, 2000	0200	1,528.51	3.753	2.430	June 30, 2000	1230	1,527.97	2.094	.701	34:30	1.729	.082	.39	373,000
Aug. 31, 2000	0200	1,528.56	3.867	2.634	Sept. 2, 2000	0200	1,527.96	2.058	.679	48:00	1.955	.068	.32	307,000
Oct. 10, 2000	1600	1,528.49	3.705	2.349	Oct. 11, 2000	0930	1,527.94	1.986	.635	17:30	1.714	.014	.82	760,000

[1]Recharge rate calculated by subtracting the evapotranspiration losses from the change in volume, then dividing by the average wetland area and the days of elapsed time.
[2]Climate data not available; evapotranspiration losses assumed equal to the 15.5-hour period beginning at 11:30 a.m. on June 20, 2000, based on similar temperatures.

Flow-Net Analysis

A series of flow-net analyses were performed to estimate recharge during different climatic conditions with adequate water-level data available; four different dates were used. The wetland was subdivided into three zones (fig. 2) for which a separate flow-net analysis was completed for each date. In this way, the flow net in each zone could be changed slightly to account for variations in the water table and depth of water in the wetland. Figure 7 is an example flow net representing zone 1 of the wetland on October 17, 1997. The flow-net parameters for each zone on each date are given in table 3. The recharge amounts for each zone were multiplied by the respective lengths of each zone (perpendicular to the flow net), then summed for each date to calculate the total recharge amount. By performing flow-net analyses from the available water levels collected during different seasonal conditions, a set of recharge rates was calculated. By using different values for *K*, it is possible to show the sensitivity of recharge rates to variations in hydraulic conductivity of the wetland bottom. Digital aquifer models for the Skunk Creek aquifer (Ohland, 1990) and the Big Sioux aquifer (Koch, 1982) used the streambed conductance values computed by Jorgensen and Ackroyd (1973) ranging from 0.4 to 1.0 foot per day.

The recharge per foot length of flow net was always greatest in zone 1, because the water table in the Skunk Creek aquifer generally slopes downward toward Skunk Creek and zone 1 is the closest to Skunk Creek. This results in a greater hydraulic head difference between the wetland stage and the Skunk Creek aquifer water table, and thus a greater recharge per unit length. Because the hydraulic gradient of the Skunk Creek aquifer is flatter at greater distances from Skunk Creek, the recharge per unit length in zones 2 and 3 are less than zone 1, but not substantially different from one another. Table 4 summarizes the recharge rates as determined by flow-net analysis (sums of rates for zones 1, 2, and 3) on the indicated dates using selected values of hydraulic conductivity.

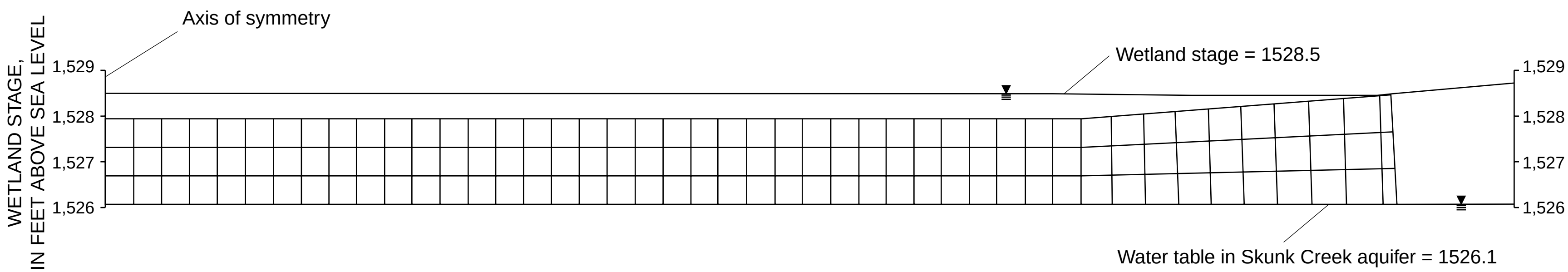
Table 3. Flow-net parameters for each zone on each date

[m, number of flow tubes; H, difference in hydraulic head, in feet; n, number of divisions of hydraulic head]

Flow-net zone	Length of zone (feet)	Oct. 17, 1997			Oct. 6, 1999			June 26, 2000			Sept. 25, 2000		
		m	H	n	m	H	n	m	H	n	m	H	n
1	941	88.4	2.4	3	175	1.7	3	147.8	1.6	2	145.6	1.7	2
2	728	89.2	2.0	3	68.4	2.7	3	177	1.8	4	91.1	2.5	3
3	728	65.8	2.6	3	87.8	2.8	4	92	2.3	3	104.7	2.8	4

Table 4. Recharge rates as determined by flow-net analyses on indicated dates using selected values of hydraulic conductivity

Hydraulic conductivity, *K* (feet per day)	Recharge rate (gallons per day) on indicated dates			
	Oct. 17, 1997	Oct. 6, 1999	June 26, 2000	Sept. 25, 2000
0.5	566,000	684,000	825,000	842,000
.8	906,000	1,094,000	1,320,000	1,347,000
1.0	1,132,000	1,368,000	1,650,000	1,684,000



Flow line (vertical)

Equipotential line (horizontal)

$$Q = \frac{mKH}{n}$$

m = 44.2 flow tubes; multiply by 2 to account for symmetry, so m = 88.4
K = 0.8 feet per day (assumed)
H = 2.4 feet of hydraulic head difference
n = 3 divisions of hydraulic head

$$Q = \frac{(88.4)(0.8)(2.4)}{3} = 56.6$$ cubic feet per day per foot length of zone perpendicular to the flow net

Figure 7. Example of flow net for October 17, 1997, representing zone 1.

Although one might expect similar recharge rates for the months of September and October, the recharge rates actually ranged from about 906,000 gallons per day to about 1,347,000 gallons per day at an assumed hydraulic conductivity of 0.8 foot per day. The large difference in recharge rates is probably due to hydraulic head differences rather than seasonal factors related to evapotranspiration. Any conditions that allow for a higher stage to be maintained in the wetland relative to the water table will increase recharge. This is because a higher wetland stage will increase the inundated area of the wetland, and will result in a higher number of flow tubes in the flow-net equation. Because flow-net analysis is dependant on hydraulic heads, seasonal fluctuations primarily will be limited to the effect they have on aquifer water levels and stream stage. Stream stage is perhaps the more significant of the two, because it determines whether there is any water available for pumping into the wetland.

Hydrologic Budget

Table 5 lists several periods during the 1998-2000 data-collection seasons that met the criteria described in the "Methods" section. These time periods also required that there be water in the wetland and that all sensors involved were functioning properly. Pumped inflow was iteratively calculated using the pump curve supplied by the manufacturer and taking into account the estimated head losses in the discharge pipe. Given the set of stages of Skunk Creek and the estimated head loss in the discharge pipe at the varying velocities involved, pumped inflow for the time periods shown in table 5 varied from 693 to 751 gallons per minute. Recharge rates for the same periods varied from 0.74 to 0.85 foot per day, and averaged 0.79 foot per day. This is close to the mean value of 0.93 foot per day reported by Thompson (1995) for a diversion canal adjacent to the Big Sioux River north of Sioux Falls.

The recharge rates resulting from the hydrologic budget analysis are more consistent than those calculated by analysis of water-level declines. The recharge rates calculated using equation 8 would not be subject to errors related to changes in volume because there is no net change in storage. A certain amount of variability in recharge rates is to be expected due to antecedent soil conditions and a buildup of bacteria within the soil matrix. However, given that the study wetland undergoes multiple wet-dry and freeze-thaw cycles each year, recharge rates as low as some of those in table 2 probably are not typical. Recharge rates estimated using flow-net analyses with a hydraulic conductivity of 0.8 foot per day (table 4) are similar to recharge rates estimated using the hydrologic budget analysis. Thus, approximately 0.8 foot per day appears to be a reasonable value for hydraulic conductivity in the study area.

Efficiency of Recharge

Recharge estimates derived using the hydrologic budget method previously described can be used to calculate the efficiency of recharge from the study wetland to the Skunk Creek aquifer. The amount of recharge to the aquifer is divided by the pumped inflow to the wetland to compute recharge efficiency. The date of the beginning of the analysis period, recharge rate, other data, and the indicated recharge efficiency are listed in table 5. The amount of water lost to evapotranspiration at the study wetland is very small compared to the amount of water recharging the aquifer from the wetland. Based on the hydrologic budget, the average recharge efficiency is estimated as 97.9 percent, which indicates that recharging the Skunk Creek aquifer by pumping water into the study wetland is highly efficient.

Effects on Ground-Water Levels

Based on data collected for this study, it is evident that the constructed wetland recharges a substantial amount of water to the Skunk Creek aquifer. Because the Skunk Creek aquifer is composed of sand and gravel, the "recharge mound" is less distinct than might be found in an aquifer composed of finer materials. However, water levels recorded from piezometers in and around the wetland do show a higher water table than periods when the wetland was dry. Figure 8 shows the water-table altitude in the constructed wetland area on September 30, 1997, during a time period when the wetland was dry. Figure 9 shows the water-table altitude in the constructed wetland area on October 17, 1997, after pumping had been initiated and the constructed wetland was recharging the Skunk Creek aquifer. The largest increases in water level occur between the wetland channel and Skunk Creek. However, smaller increases also occur upgradient of the wetland. The results from this study demonstrate that artificially recharged wetlands can be useful in recharging underlying aquifers and increasing water levels in these aquifers.

Table 5. Recharge during intervals with no precipitation and no net change in storage that occurred during the 1998-2000 data-collection seasons

[*QI*, pumped inflow from Skunk Creek to wetland; *ET*, evapotranspiration; --, not applicable]

Beginning of period		End of period		Time elapsed (hours)	Beginning and ending wetland stage (feet above sea level)	Wetland area (acres)	[1]*QI* (gallons per minute)	Total *QI* (gallons)	Total *ET* (gallons)	Total recharge (gallons)	Recharge		Recharge efficiency (percent)
Date	Time	Date	Time								feet per day	gallons per day	
1998													
July 9	1415	July 12	0715	65:00	1,528.55	3.84	733	2,859,000	67,000	2,792,000	0.82	1,031,000	97.7
July 12	1215	July 14	1145	47:30	1,528.56	3.87	725	2,066,000	47,000	2,019,000	.81	1,020,000	97.7
July 16	1700	July 18	1830	49:30	1,528.53	3.80	719	2,135,000	59,000	2,076,000	.81	1,007,000	97.2
July 24	1700	July 29	0500	108:00	1,528.56	3.87	705	4,568,000	85,000	4,483,000	.79	996,000	98.2
1999													
Sept. 11	0830	Sept. 13	0400	43:30	1,528.59	3.93	751	1,960,000	28,000	1,932,000	.83	1,066,000	98.6
Sept. 20	0730	Sept. 21	2200	38:30	1,528.55	3.84	751	1,735,000	27,000	1,708,000	.85	1,065,000	98.4
Sept. 24	0730	Sept. 25	2230	39:00	1,528.55	3.84	751	1,757,000	24,000	1,733,000	.85	1,066,000	98.6
2000													
June 16	1930	June 19	0730	60:00	1,528.55	3.84	699	2,516,000	53,000	2,463,000	.79	985,000	97.9
June 22	0600	June 23	1200	30:00	1,528.56	3.87	699	1,258,000	24,000	1,234,000	.78	987,000	98.1
June 25	2230	June 27	1900	44:30	1,528.54	3.82	706	1,885,000	43,000	1,842,000	.80	993,000	97.8
July 4	1030	July 6	1000	47:30	1,528.57	3.89	707	2,015,000	44,000	1,971,000	.79	996,000	97.8
July 12	2030	July 15	0530	57:00	1,528.66	4.08	715	2,445,000	68,000	2,377,000	.75	1,001,000	97.2
July 15	1230	July 17	1500	42:30	1,528.66	4.08	708	1,805,000	61,000	1,744,000	.74	985,000	96.7
July 20	1730	July 24	2330	102:00	1,528.64	4.04	701	4,290,000	90,000	4,200,000	.75	988,000	97.9
July 26	1530	July 30	1200	92:30	1,528.61	3.98	694	3,891,000	99,000	3,792,000	.76	984,000	97.5
Aug. 13	0400	Aug. 15	0100	45:00	1,528.54	3.82	696	1,879,000	46,000	1,833,000	.79	978,000	97.6
Aug. 19	2130	Aug. 23	1100	85:30	1,528.59	3.93	695	3,565,000	39,000	3,526,000	.77	990,000	98.9
Aug. 26	0030	Aug. 30	1030	106:00	1,528.59	3.93	693	4,407,000	70,000	4,337,000	.77	982,000	98.4
Average	--	--	--	--	--	--	--	--	--	--	.79	1,007,000	97.9

[1]Pump discharge from pump curve based on difference in head between Skunk Creek and pump discharge pipe, and estimated head losses in discharge pipe.

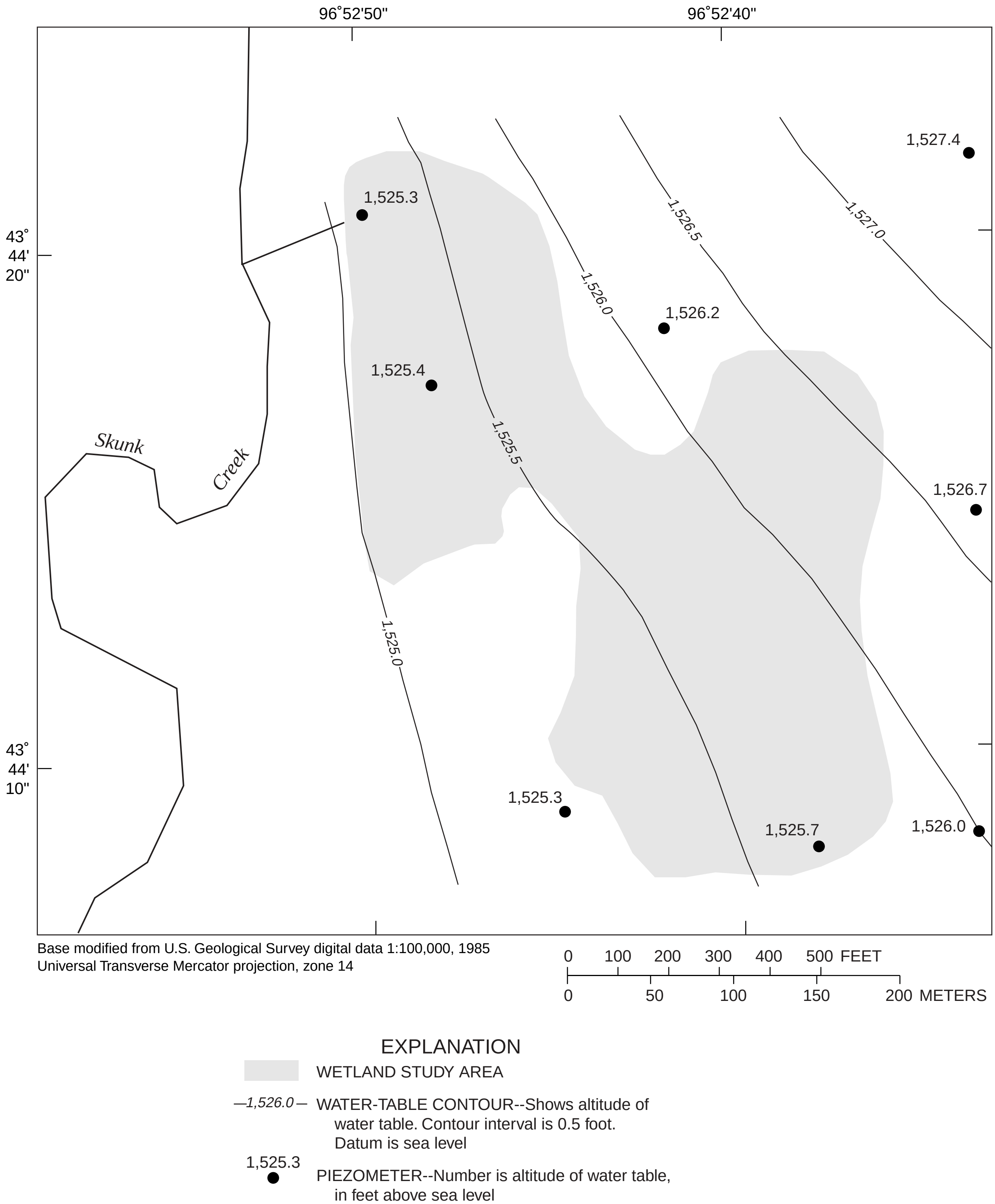


Figure 8. Water table on September 30, 1997, when wetland was dry.

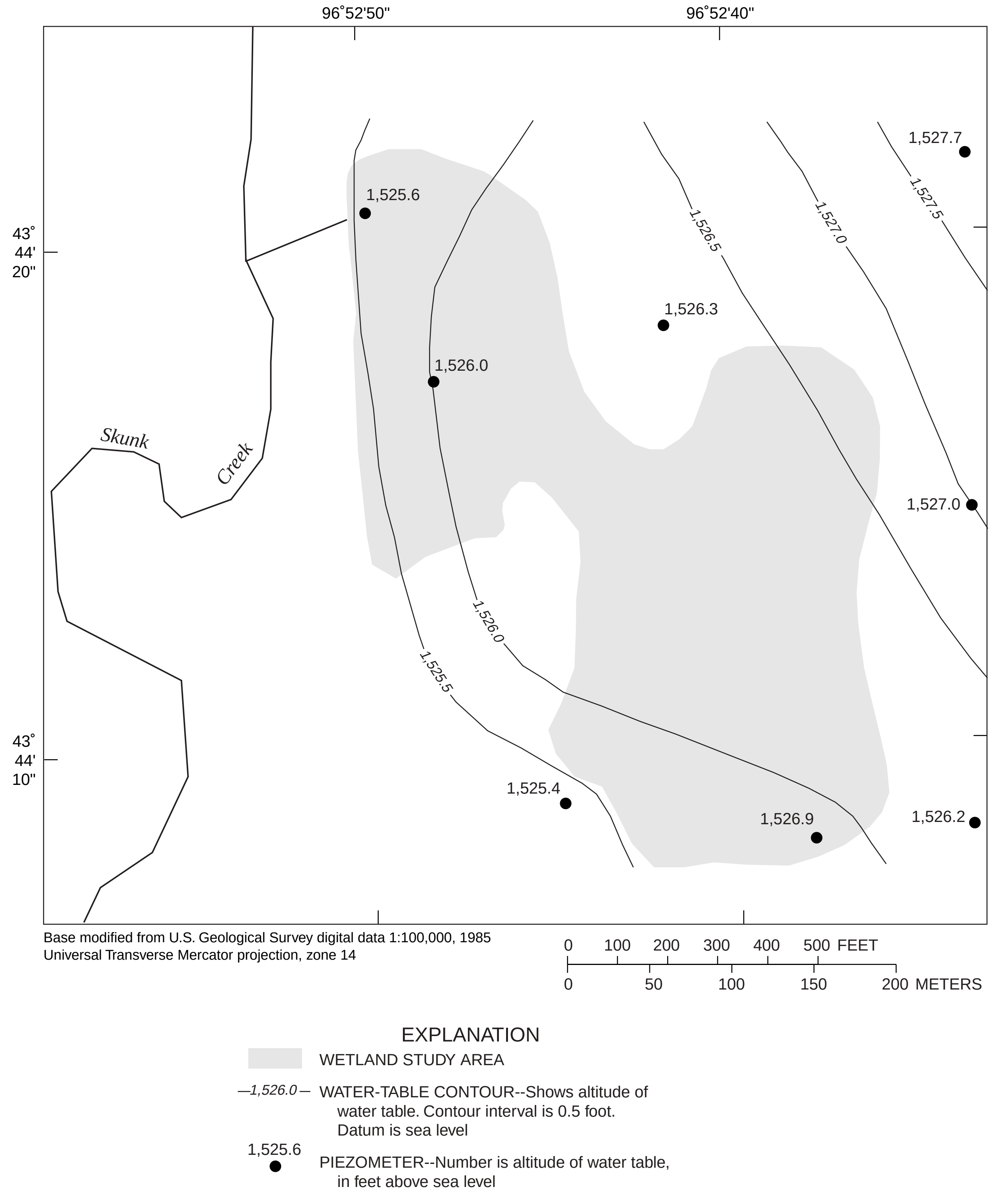


Figure 9. Water table on October 17, 1997, when wetland was active.

SUMMARY

A wetland was constructed in the Skunk Creek flood plain near Lyons in southeast South Dakota, to mitigate for wetland areas that were filled during construction of a municipal golf course for the city of Sioux Falls. A water-rights permit was obtained to allow the city to pump water from Skunk Creek into the wetland during times when the wetland would be dry. The amount of water seeping through the wetland and recharging the underlying Skunk Creek aquifer was not known. The U.S. Geological Survey, in cooperation with the city of Sioux Falls, conducted a study during 1997-2000 to evaluate recharge to the Skunk Creek aquifer from the constructed wetland.

Three methods were used to estimate recharge from the wetland to the aquifer: (1) analysis of the rate of water-level decline during periods of no inflow; (2) flow-net analysis; and (3) analysis of the hydrologic budget. The hydrologic budget also was used to estimate the efficiency of recharge from the wetland to the aquifer. Recharge rates estimated by analysis of shut-off events ranged from 0.21 to 0.82 foot per day (259,000 to 760,000 gallons per day) but these estimates may be influenced by possible errors in volume calculations. Recharge rates determined by flow-net analysis were calculated using selected values of hydraulic conductivity and ranged from 566,000 gallons per day using a hydraulic conductivity of 0.5 foot per day to 1,684,000 gallons per day using a hydraulic conductivity of 1.0 foot per day. Recharge rates from the hydrologic budget varied from 0.74 to 0.85 foot per day (985,000 to 1,066,000 gallons per day), and averaged 0.79 foot per day (1,007,000 gallons per day). Recharge rates estimated using flow-net analyses with a hydraulic conductivity of 0.8 foot per day are similar to recharge rates estimated using the hydrologic budget analysis. Thus, approximately 0.8 foot per day appears to be a reasonable value for hydraulic conductivity in the study area.

The amount of recharge to the aquifer was divided by the pumped inflow to the wetland to compute recharge efficiency. The amount of water lost to evapotranspiration at the study wetland is very small compared to the amount of water seeping from the wetland into the aquifer. Based on the hydrologic budget, the average recharge efficiency is estimated as 97.9 percent, which indicates that recharging the Skunk Creek aquifer by pumping water into the study wetland is highly efficient.

Because the Skunk Creek aquifer is composed of sand and gravel, the “recharge mound” is less distinct than might be found in an aquifer composed of finer materials. However, water levels recorded from piezometers in and around the wetland do show a higher water table than periods when the wetland was dry. The largest increases in water level occur between the wetland channel and Skunk Creek. However, smaller increases also occur upgradient of the wetland. The results from this study demonstrate that artificially recharged wetlands can be useful in recharging underlying aquifers and increasing water levels in these aquifers.

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SUPPLEMENTAL INFORMATION

Table 6. Sample evapotranspiration calculations for June 16, 2000

[°C, degrees Celsius; RH, relative humidity; %, percent; λ, latent heat of vaporization; γ, psychrometer constant; *G*, soil-heat flux; *ET*, evapotranspiration; --, not applicable]

Date	Time	Top temperature[1] (°C)	Bottom temperature[2] (°C)	RH (%)	Air temperature[3] (°C)	Net radiation[4] (watts per square meter)	Heat flux[5] (watts per square meter)	[6]λ (joules per gram)	[7]γ (kilopascals per °C)
6-16-00	0000	15.4	15.6	94.9	13.9	-52.7	-14.51	2467.4	0.05294
6-16-00	0030	15.2	15.4	96.6	13.5	-58.2	-15.55	2468.4	.05292
6-16-00	0100	15.0	15.2	97.8	13.2	-56.6	-16.84	2469.0	.05290
6-16-00	0130	14.9	15.1	98.1	12.9	-60.1	-17.84	2469.7	.05288
6-16-00	0200	14.7	14.9	97.3	12.6	-62.1	-18.48	2470.6	.05286
6-16-00	0230	14.5	14.7	98.0	12.2	-60.7	-19.27	2471.5	.05284
6-16-00	0300	14.3	14.6	99.6	11.7	-57.9	-20.19	2472.6	.05281
6-16-00	0330	14.2	14.4	99.9	11.5	-55.0	-21.22	2473.0	.05280
6-16-00	0400	14.1	14.4	98.6	11.8	-32.1	-21.50	2472.4	.05282
6-16-00	0430	14.0	14.2	98.5	11.7	-50.4	-20.84	2472.6	.05281
6-16-00	0500	13.8	14.1	99.3	11.3	-53.6	-21.82	2473.6	.05279
6-16-00	0530	13.8	14.0	99.4	11.4	-18.2	-21.60	2473.2	.05280
6-16-00	0600	13.8	14.0	99.8	11.5	-9.3	-20.55	2473.1	.05280
6-16-00	0630	13.8	14.0	99.7	11.8	1.1	-19.27	2472.3	.05282
6-16-00	0700	13.8	14.0	99.5	12.0	7.1	-17.82	2471.9	.05283
6-16-00	0730	13.9	14.1	95.9	12.2	23.5	-15.55	2471.5	.05284
6-16-00	0800	14.0	14.2	95.9	12.0	41.4	-13.79	2471.8	.05283
6-16-00	0830	14.2	14.3	92.7	12.6	96.3	-9.35	2470.5	.05287
6-16-00	0900	14.5	14.7	83.3	12.7	180.6	-4.46	2470.1	.05287
6-16-00	0930	15.1	15.1	77.1	13.4	281.7	.93	2468.6	.05291
6-16-00	1000	15.8	15.6	75.3	13.5	350.1	10.36	2468.3	.05292
6-16-00	1030	16.9	16.4	71.5	14.4	430.8	23.36	2466.2	.05297
6-16-00	1100	17.8	17.3	69.7	14.8	485.1	37.01	2465.2	.05300
6-16-00	1130	18.8	18.2	67.7	15.1	535.7	47.13	2464.5	.05302
6-16-00	1200	19.5	18.9	68.2	15.1	511.8	51.63	2464.6	.05301
6-16-00	1230	20.9	20.0	65.6	15.5	586.1	61.38	2463.5	.05304
6-16-00	1300	21.8	20.9	64.2	15.8	563.0	71.00	2463.0	.05305
6-16-00	1330	22.4	21.5	64.2	15.9	606.7	73.50	2462.6	.05306
6-16-00	1400	22.8	22.1	62.4	15.7	437.9	72.50	2463.1	.05305
6-16-00	1430	23.6	22.9	59.4	16.5	723.0	75.80	2461.2	.05310
6-16-00	1500	23.6	23.0	58.5	16.5	480.4	75.50	2461.2	.05310
6-16-00	1530	23.9	23.3	58.8	16.7	508.8	71.20	2460.8	.05311
6-16-00	1600	23.6	23.1	56.3	16.9	416.2	65.04	2460.3	.05312

[8]ΔS_{soil} (watts per square meter)	[9]ΔS_{water} (watts per square meter)	[10]G (watts per square meter)	Net radiation -G	Saturation vapor pressure[11] (kilopascals)	Slope of saturation vapor pressure curve[12]	[13]$s/(s+\gamma)$	[14]λET	[15]ET (grams per square meter per second)	[15]ET (gallons per acre per one-half hour)
-4.89	-77.97	-97.37	44.7	1.584	0.1029	0.660	37.2	0.01506	28.30
-4.31	-71.06	-90.93	32.7	1.543	.1006	.655	27.0	.01094	20.56
-4.03	-66.52	-87.38	30.8	1.517	.0991	.652	25.3	.01024	19.26
-4.89	-77.60	-100.33	40.3	1.487	.0974	.648	32.9	.01331	25.02
-5.75	-84.39	-108.62	46.5	1.453	.0954	.643	37.7	.01526	28.68
-4.60	-77.60	-101.47	40.8	1.416	.0933	.638	32.8	.01327	24.95
-4.03	-62.38	-86.59	28.7	1.373	.0908	.632	22.8	.00924	17.37
-2.01	-29.10	-52.33	-2.6	1.360	.0900	.630	-2.1	0	0
-4.02	-64.71	-90.24	58.2	1.381	.0912	.633	46.4	.01878	35.30
-3.74	-60.15	-84.73	34.3	1.374	.0908	.632	27.3	.01106	20.78
-1.44	-20.02	-43.28	-10.3	1.334	.0885	.626	-8.1	0	0
-.86	-13.35	-35.81	17.6	1.349	.0894	.629	13.9	.00564	10.60
.29	6.66	-13.60	4.4	1.355	.0897	.630	3.5	.00140	2.62
.57	11.10	-7.59	8.7	1.384	.0914	.634	6.9	.00281	5.28
1.15	19.95	3.28	3.8	1.402	.0924	.636	3.1	.00124	2.33
2.01	33.20	19.67	3.8	1.417	.0933	.639	3.1	.00123	2.32
5.46	90.76	82.43	-41.1	1.405	.0926	.637	-32.9	0	0
9.49	155.95	156.09	-59.8	1.458	.0957	.644	-48.5	0	0
12.94	217.63	226.11	-45.5	1.470	.0964	.646	-37.0	0	0
13.80	263.43	278.15	3.5	1.534	.1001	.654	2.9	.00118	2.23
23.58	425.02	458.96	-108.9	1.547	.1008	.656	-89.9	0	0
26.16	397.82	447.34	-16.5	1.637	.1060	.667	-13.9	0	0
25.88	433.18	496.07	-11.0	1.686	.1087	.672	-9.3	0	0
19.84	302.30	369.27	166.4	1.715	.1104	.676	141.7	.05748	108.04
30.48	535.33	617.44	-105.6	1.712	.1102	.675	-89.9	0	0
25.30	387.11	473.79	112.3	1.764	.1131	.681	96.3	.03911	73.51
18.98	294.73	384.70	178.3	1.788	.1145	.683	153.5	.06233	117.16
16.68	197.31	287.49	319.2	1.806	.1155	.685	275.6	.11190	210.33
21.56	353.44	447.50	-9.6	1.784	.1142	.683	-8.3	0	0
5.17	39.14	120.12	602.9	1.876	.1194	.692	525.8	.21363	401.57
7.76	112.34	195.61	284.8	1.877	.1195	.692	248.4	.10094	189.73
-5.75	-111.97	-46.52	555.3	1.900	.1207	.695	485.9	.19748	371.20
6.32	129.20	200.57	215.6	1.924	.1221	.697	189.3	.07695	144.65

Table 6. Sample evapotranspiration calculations for June 16, 2000—Continued

[°C, degrees Celsius; RH, relative humidity; %, percent; λ, latent heat of vaporization; γ, psychrometer constant; *G*, soil-heat flux; *ET*, evapotranspiration; --, not applicable]

Date	Time	Top temperature[1] (°C)	Bottom temperature[2] (°C)	RH (%)	Air temperature[3] (°C)	Net radiation[4] (watts per square meter)	Heat flux[5] (watts per square meter)	[6]λ (joules per gram)	[7]γ (kilopascals per °C)
6-16-00	1630	23.9	23.3	52.8	17.4	444.9	59.74	2459.0	0.05316
6-16-00	1700	24.1	23.4	50.8	18.1	504.2	65.40	2457.4	.05320
6-16-00	1730	23.6	23.3	52.5	17.9	331.2	55.58	2458.0	.05318
6-16-00	1800	23.0	22.8	54.6	17.7	275.3	40.97	2458.5	.05317
6-16-00	1830	22.3	22.2	54.9	17.5	192.8	29.84	2458.8	.05316
6-16-00	1900	21.5	21.6	57.5	16.9	100.6	20.89	2460.2	.05313
6-16-00	1930	21.0	21.1	59.5	16.7	68.0	12.19	2460.7	.05311
6-16-00	2000	20.2	20.4	64.4	15.9	3.7	4.99	2462.7	.05306
6-16-00	2030	19.6	19.8	73.5	14.7	-2.6	-2.89	2465.6	.05299
6-16-00	2100	19.0	19.3	73.4	14.4	-23.7	-7.50	2466.3	.05297
6-16-00	2130	18.4	18.8	79.5	13.6	-31.3	-11.11	2468.1	.05292
6-16-00	2200	18.0	18.3	79.9	13.1	-57.5	-14.06	2469.2	.05290
6-16-00	2230	17.3	17.7	89.8	11.4	-68.5	-18.89	2473.2	.05280
6-16-00	2300	16.7	17.2	97.3	10.3	-59.5	-23.72	2475.9	.05273
6-16-00	2330	16.3	16.7	99.9	9.8	-45.7	-26.97	2477.2	.05270
6-17-00	0000	15.8	16.4	99.8	9.7	-39.2	-28.92	2477.3	.05269
Total	--	--	--	--	--	--	--	--	--

[1]Water temperature at the water surface.

[2]Water temperature at the wetland bottom.

[3]Air temperature above the wetland.

[4]Algebraic sum of all incoming and outgoing short- and long-wave radiation, measured with a net radiometer.

[5]Flux of heat flowing downward through the wetland bottom, measured with a heat-flux plate.

[6]Calculated from equation $\lambda = 2{,}500.25 - 2.365 *$ air temperature.

[7]Calculated from equation $\gamma = 0.00066 *$ air pressure $* (1 + 0.00115 *$ air temperature).

[8]Change in energy stored in soil above the soil heat flux sensor plate, calculated from equation ΔS_{soil} = (1000*(soil temperature at the end of the measurement interval – soil temperature at the beginning of measurement interval)*volumetric heat capacity of soil above heat flux plate*depth of plate)/time length of measurement interval.

[9]Change in energy stored in water, calculated from equation ΔS_{water} = (1,000*(water temperature at the end of the measurement interval – water temperature at the beginning of the measurement interval)*volumetric heat capacity of water*depth of water)/time length of measurement interval.

[10]Heat flux from water surface down, calculated from equation G = heat flux + $\Delta S_{soil} + \Delta S_{water}$.

[11]Calculated from Lowe's (1976) polynomial.

[12]Calculated by Lowe (1976).

[13]Slope of the saturated vapor pressure curve / (slope of the saturated vapor pressure curve + psychrometer constant).

[14]Latent heat of vaporization*evaportranspiration, calculated from equation $\lambda ET = 1.26*(s/(s+\gamma))*$(net radiation – heat flux), as given by Priestly and Taylor (1972).

[15]Negative evapotranspiration values are assumed to be zero evapotranspiration.

[8]ΔS_{soil} (watts per square meter)	[9]ΔS_{water} (watts per square meter)	[10]*G* (watts per square meter)	Net radiation -*G*	Saturated vapor pressure[11] (kilopascals)	Slope of saturated vapor pressure curve[12]	[13]$s/(s+\gamma)$	[14]λET	[15]*ET* (grams per square meter per second)	[15]*ET* (gallons per acre per half hour)
3.45	68.91	132.10	312.8	1.990	0.1257	0.703	277.0	0.11266	211.76
-4.31	-150.49	-89.40	593.6	2.077	.1306	.710	531.4	.21625	406.48
-14.38	-236.09	-194.88	526.1	2.045	.1288	.708	469.1	.19085	358.75
-16.10	-274.72	-249.85	525.2	2.018	.1273	.705	466.7	.18984	356.84
-18.69	-296.18	-285.03	477.8	2.000	.1263	.704	423.7	.17233	323.92
-14.66	-229.65	-223.42	324.0	1.928	.1223	.697	284.6	.11569	217.47
-19.55	-317.12	-324.48	392.5	1.901	.1208	.695	343.5	.13960	262.40
-16.96	-260.98	-272.95	276.6	1.803	.1153	.685	238.7	.09694	182.22
-14.95	-235.31	-253.14	250.5	1.667	.1077	.670	211.5	.08579	161.25
-13.80	-215.34	-236.64	212.9	1.636	.1059	.667	178.8	.07250	136.28
-14.95	-211.78	-237.84	206.5	1.554	.1012	.657	170.9	.06923	130.13
-17.83	-280.70	-312.58	255.1	1.508	.0986	.651	209.2	.08472	159.25
-14.09	-220.70	-253.68	185.2	1.351	.0895	.629	146.8	.05934	111.55
-12.36	-192.52	-228.61	169.1	1.251	.0836	.613	130.7	.05277	99.19
-10.35	-169.27	-206.59	160.9	1.207	.0811	.606	122.9	.04960	93.23
-7.47	-111.61	-148.00	108.9	1.204	.0809	.605	83.0	.03352	63.01
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