Thermal response of a horizontal subsurface flow wetland in a cold temperate climate

Scott D. Wallace* and Jaime A. Nivala**

***** North American Wetland Engineering LLC, 20 North Lake Street, Suite 210, Forest Lake, MN 55025 USA
(E-mail: swallace@nawe-pa.com)
** The University of Iowa, Department of Civil and Environmental Engineering, 4105 Seamans Center, Iowa City, IA 52242
(E-mail: jnivala@engineering.uiowa.edu)

Abstract

The thermal response of an insulated horizontal subsurface flow treatment wetland located in Marine on St. Croix, Minnesota, USA was studied between July 2000 and April 2002. An energy balance over this time period indicates that net solar radiation is the primary energy gain during the summer months, and drives a variety of energy loss mechanisms, most notably evapotranspiration. Net solar radiation also warms the water as it flows through the wetland, resulting in elevated effluent temperatures during the summer. During the winter months, the most important energy input is heat associated with the influent flow, followed by heat transferred from ground storage. Measurement of soil temperatures under the wetland cell indicate that the maximum rate of ground heat transfer was approximately 100 $kJ/m^2 \cdot d$. During the winter months, both energy gains and losses are minimized and exhibit little change, resulting in stable effluent temperatures. During the winter of 2000-2001, effluent temperatures averaged 1.0°C, whereas during the winter of 2001-2002, effluent temperatures averaged 2.7°C. The higher average effluent temperatures of the 2001-2002 winter season can be attributed to greater influent flows and warmer air temperatures. Thermal performance of this system illustrates that insulated subsurface flow wetlands can successfully be used for wastewater treatment in cold climates.

INTRODUCTION

Subsurface flow constructed wetlands are the most common type of wetland used to treat small wastewater flows. In cold climates, these wetlands are typically designed to operate without an exposed water surface. Keeping the water within the bed media provides resistance against freezing during winter conditions. Plants and plant detritus also provide insulation, helping to stabilize the subsurface thermal environment (Brix, 1994; Smith et al., 1997). In very cold climates, insulation may have to be added to the system to prevent freezing (Mæhlum et al., 1995). Experience with subsurface flow wetlands in the cold climate of Minnesota indicates that systems without a mulch insulating layer can freeze during winters with little snow cover (Henneck et al., 2001). The amount of mulch insulation required to prevent freezing is highly dependent on the timing and amount of snow fall (Kadlec, 2001) since snow cover is a significant insulator. Use of different mulch materials for insulation has lead to an understanding of how mulch composition affects treatment performance (Wallace et al., 2001). As a result of these developments, subsurface flow wetlands in cold regions of North America are now often constructed with a mulch insulation layer of peat or yard waste compost to prevent system freezing.

In this study, the thermal response of horizontal subsurface flow constructed wetland located in Marine on St. Croix, Minnesota, USA (Lat 45.1°N, elevation 256 m) was evaluated from July 14, 2000 to April 23, 2002. This system, located in a residential development (Jackson Meadow), was designed to serve 32 single-family homes at a design flow of 21 m^3/d. During the period of this study, new homes were being added to the development and the flow rate gradually increased from 3.3 m^3/d to 12.2 m^3/d.

The Jackson Meadow wetland is designed to provide treatment of wastewater prior to a soil infiltration system. Wastewater receives primary treatment in a series of settling tanks (37.8 m^3 total volume). Secondary treatment is completed in the subsurface flow wetland. The area of the wetland cell is 650 m^2, with a 45 cm-thick gravel bed (d_{10} of 5.8 mm, uniformity coefficient of 1.8). The system is insulated with 15 cm of peat mulch, and the water level in the wetland bed is 5 cm below the base of the peat layer. This 5-cm "air gap" provides an additional layer of insulation to the system. To aid in nitrification and in the removal of carbonaceous biological oxygen demand (BOD_5), the wetland cell is equipped with an internal aeration system (Wallace, 2001).

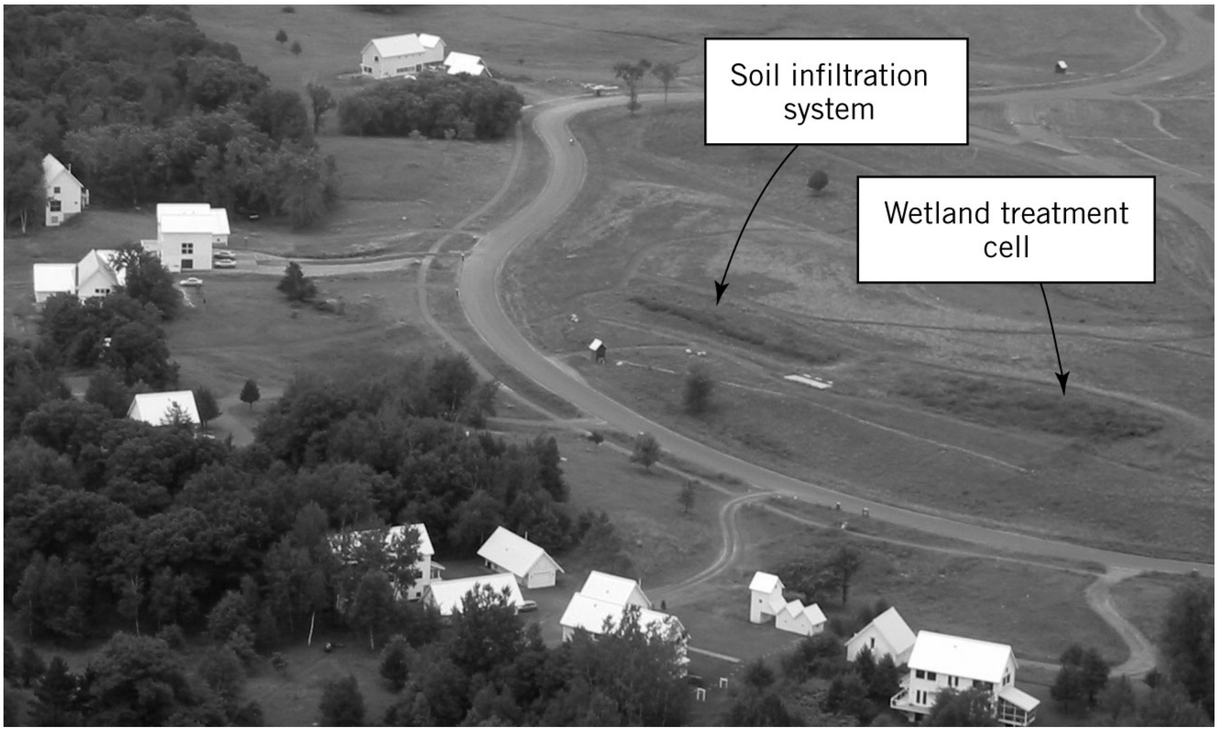

Figure 1. Aerial photo of Jackson Meadow horizontal subsurface flow wetland system at Marine on St. Croix, Minnesota.

METHODS

Flow into the wetland cell was measured based on elapsed time meters that were connected to the influent pumps. Temperatures at the inlet and outlet of the wetland cell were measured using Stowaway Tidbit temperature data logging sensors (Onset Computer Corporation, Massachusetts, USA) that were programmed to record temperatures on a 6-hour interval. A four-channel HOBO H8 data logging recorder (Onset Computer Corporation, Massachusetts, USA) was used in conjunction with thermocouple probes to record the air temperature 1.5 m above the wetland cell as well as temperatures in the soil 7.5 cm, 15 cm, and 22.5 cm below the bottom of the lined wetland cell. Precipitation at the site was recorded using a tipping bucket recorder (Rainwise Inc., Maine, USA) connected to a HOBO H7 event logger (Onset Computer Corporation, Massachusetts, USA).

Energy inputs and outputs from the wetland system were determined. For ease of comparison, this paper uses the same nomenclature as *Treatment Wetlands* (Kadlec and Knight, 1996). In the

Jackson Meadow wetland, net solar radiation, R_N, and heat associated with the influent flow, U_{in}, were considered to be energy gains. Evapotranspiration, $\lambda\rho ET$, and heat associated with the effluent flow, U_{out}, were considered to be energy losses. Ground storage heat transfer, G, and heat transfer to the air, E_{loss}, are two-way mechanisms. For the purposes of this paper, G was classified as an energy gain and E_{loss} was classified as an energy loss as this reflects the winter condition, which is the most important time period in terms of thermal design. Changes in energy storage were not considered. This results in the following energy balance equation:

$$R_N + U_{in} + G = \lambda\rho ET + E_{loss} + U_{out}$$

Where:

R_N = net solar radiation, $\mathrm{MJ}/\mathrm{m}^2\cdot\mathrm{d}$

U_{in} = energy entering with water, $\mathrm{MJ}/\mathrm{m}^2\cdot\mathrm{d}$

G = ground storage heat transfer, $\mathrm{MJ}/\mathrm{m}^2\cdot\mathrm{d}$

λ = latent heat of vaporization of water, 2.453 MJ/kg @ 20°C

ρ = density of water, kg/m^3

ET = evapotranspiration, m/d

E_{loss} = energy transfer to air, $\mathrm{MJ}/\mathrm{m}^2\cdot\mathrm{d}$

U_{out} = energy leaving with water, $\mathrm{MJ}/\mathrm{m}^2\cdot\mathrm{d}$

Net solar radiation, R_N, was determined using the approach outlined in *Treatment Wetlands* (Kadlec and Knight, 1996). Monthly average values for the wetland albedo, α, and solar radiation, R_S, were obtained from NASA's surface meteorology and solar energy website (NASA, 2004). Monthly average values for percent daily sunshine, S, were calculated using average percent daylight cloud cover data (NASA, 2004) where S = 1 – (average percent daylight cloud cover). Since monthly average values were used for these terms, the calculated net solar radiation, R_N, was also an average monthly value. This approach represents R_N as a step function in Figure 5 instead of a smooth sinusoidal curve, which also impacts evapotranspiration in Figure 6. Energy associated with the influent wastewater, U_{in}, was measured directly through influent flows and temperatures. Effluent flows and temperatures were used to measure energy leaving the system in the treated effluent, U_{out}. Ground storage heat transfer, G, was determined using thermocouple data to determine thermal gradients and an assumed soil thermal conductivity of 44.9 kJ/m·d·°C (Kadlec and Knight, 1996). Energy losses to the air, E_{loss}, were calculated using the measured differential between the effluent water temperature (which assumes the majority of the wetland is at the balance point) and the air temperature and the thermal conductivity of the mulch, which was assumed to be 5.2 kJ/m·d·°C (Kadlec and Knight, 1996). Evapotranspiration energy losses, $\lambda\rho ET$, were used to close the energy balance.

RESULTS AND DISCUSSION

Data collected at the Jackson Meadow site provides a detailed portrait as to how horizontal subsurface flow constructed wetlands respond to energy gains and losses under both summer and winter conditions in a cool temperate climate. Figure 2 illustrates influent and effluent temperatures compared to air temperatures over a 22-month period:

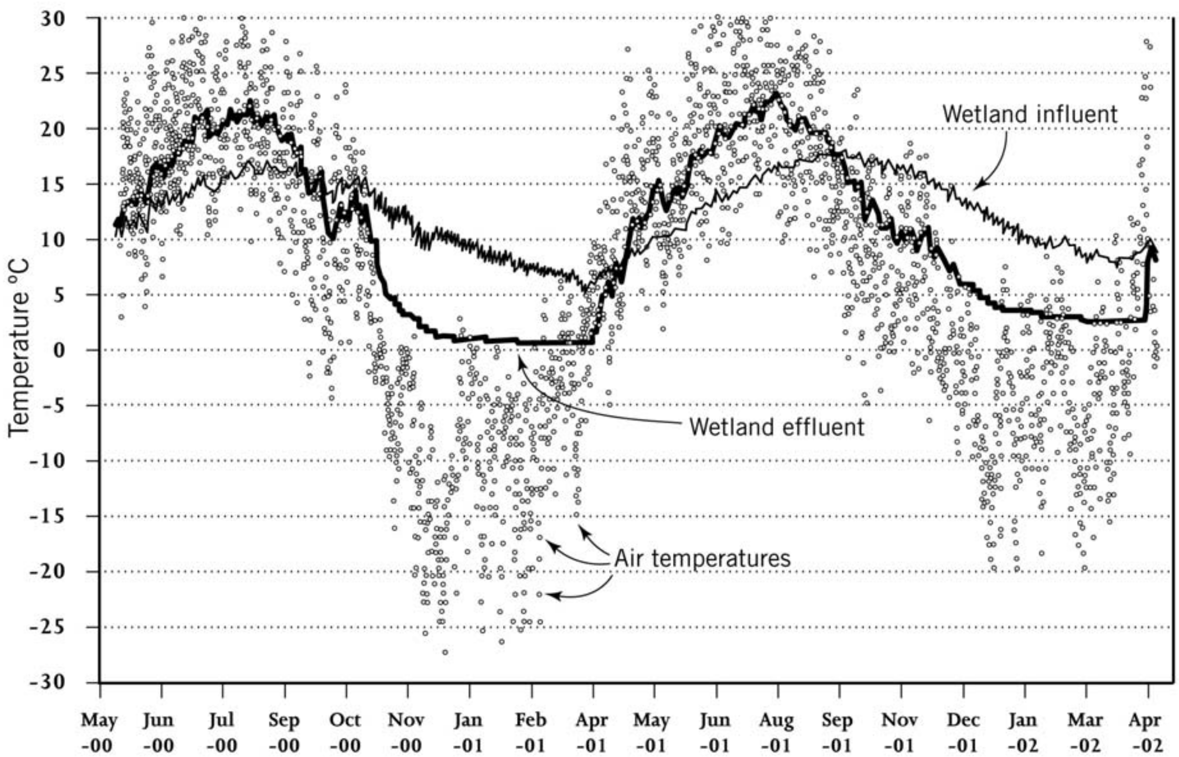

Figure 2. Influent, effluent and air temperatures for the Jackson Meadow wetland system.

During the summer months, effluent temperatures exceed influent temperatures as shown in Figure 2, indicating the water is being warmed as it passes through the wetland. During late summer, effluent temperatures exceeded 20°C, and were often 5°C warmer than the influent.

Under winter conditions (corresponding from November through snow-melt in April in this region of the northern hemisphere) both energy gains and losses are minimized and exhibit little change, resulting in stable effluent temperatures. During the winter of 2000-2001, this balance point was reached at an effluent temperature of 1.0°C, whereas during the winter of 2001-2002, the balance point temperature was 2.7°C. The higher average effluent temperature of the 2001-2002 winter season can be attributed to greater influent flows and warmer air temperatures. Average daily air temperatures of -20 to -25°C were common during the winter of 2000-2001, while during the winter of 2001-2002, the coldest air temperatures ranged from -15 to -20°C.

Determining the amount of insulation required for a specific wetland system requires some knowledge of the energy input from ground storage, G. During freezing conditions, ground storage energy inputs are particularly important during periods of zero flow. No-flow events, especially at night, are common in very small treatment systems. To determine G, soil temperatures were measured at three depths beneath the wetland cell, as indicated in Figure 3:

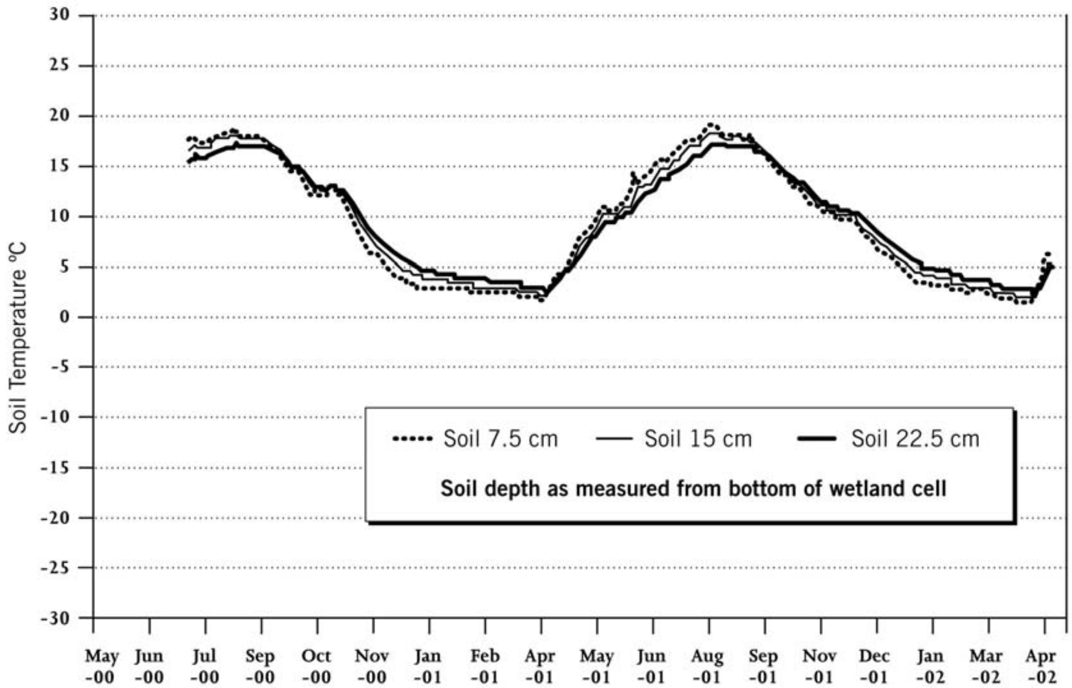

Figure 3. Soil temperatures below Jackson Meadow wetland system.

As seen in Figure 3, the shallowest soil temperatures are the warmest during summer months, indicating that the wetland acts as an energy sink (e.g. some of the incoming solar radiation, R_N, is used to warm the soil underneath the wetland cell). During the winter months, the underlying soil is warmer than the wetland cell and the energy flow is reversed. In this manner the ground storage heat transfer can be likened to an "energy flywheel", storing and releasing heat energy. For the Jackson Meadow system, this ground storage heat transfer is shown in Figure 4:

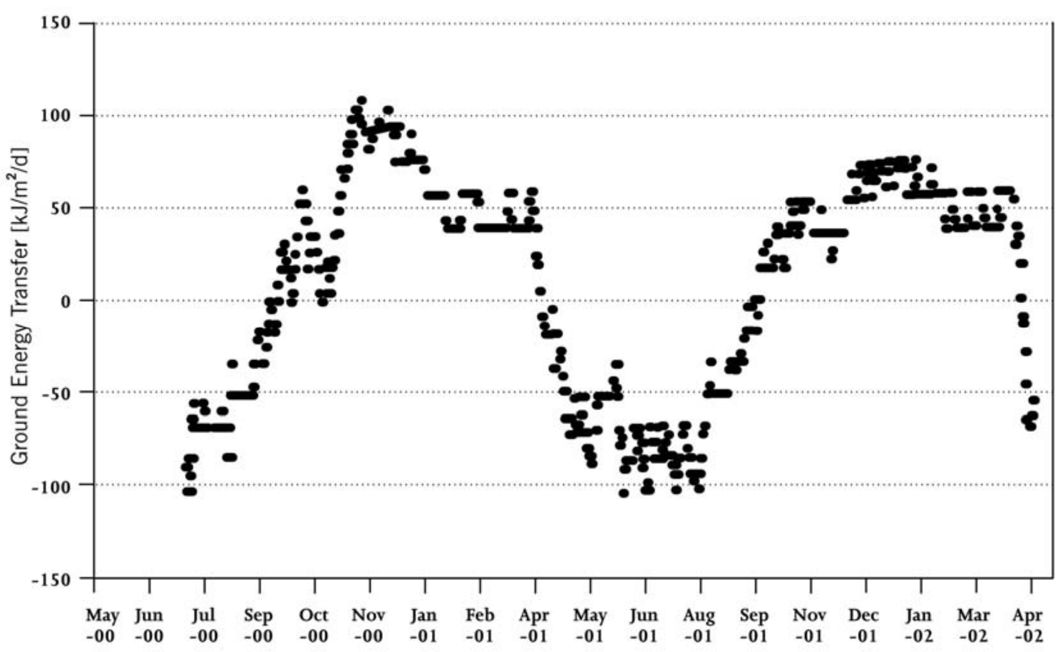

Figure 4. Ground energy transfer at the Jackson Meadow wetland system.

The maximum rate of ground storage heat transfer observed in this system was approximately 100 $kJ/m^2 \cdot d$. This is somewhat lower than rates observed at other subsurface flow wetlands in Minnesota. The Grand Lake wetland system (Lat 46.8°N) had a measured rate of 200 $kJ/m^2 \cdot d$ (Kadlec, 2001), while a similar system at Lutsen (Lat 47.5°N) had an estimated peak transfer rate of 320 $kJ/m^2 \cdot d$ (Wallace et al., 2001). The ground storage heat transfer, while important during winter months, is still small relative to other energy gains to the wetland system, as shown in Figure 5:

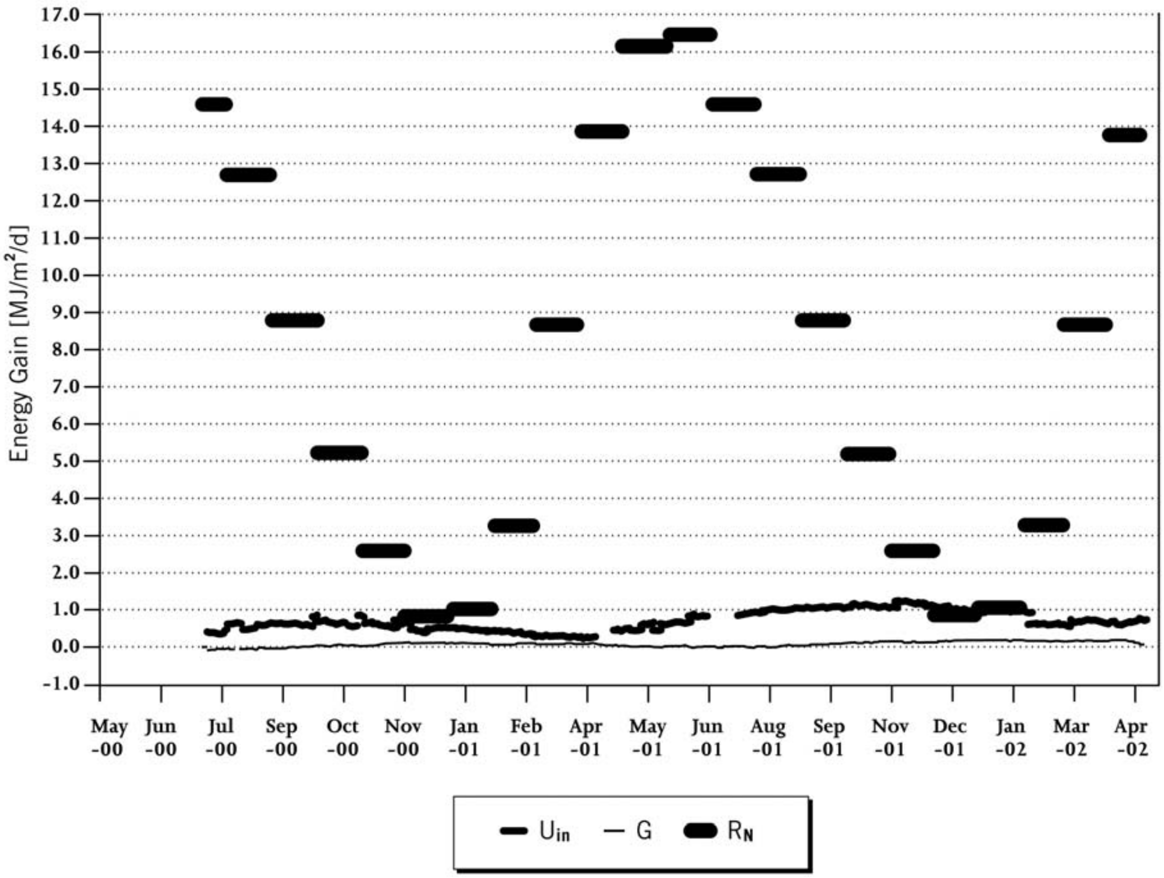

Figure 5. Energy gains at the Jackson Meadow wetland system.

As shown in Figure 5, the dominant energy input is the net solar radiation, R_N, during summer months. This energy input greatly exceeds that of the influent wastewater U_{in}, or the ground heat transfer, G. This large solar radiation input during the summer months drives three processes:

1. Transferring heat to ground storage, G.
2. Warming the water as it passes through the wetland, increasing U_{out}.
3. Driving evapotranspiration in the wetland, increasing $\lambda\rho ET$.

Of these three processes of summer energy loss, the heat lost through evapotranspiration, $\lambda\rho ET$, is by far the greatest, as illustrated in Figure 6:

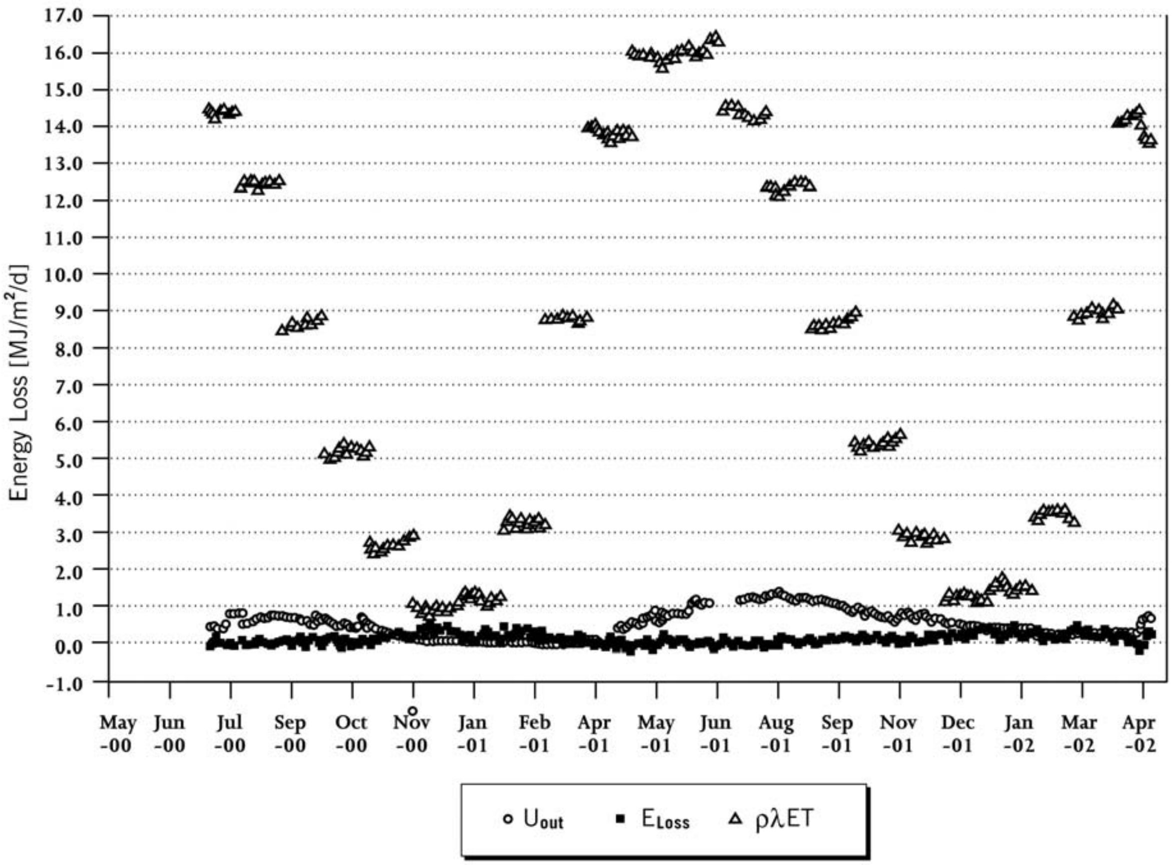

Figure 6. Energy losses at the Jackson Meadow wetland system.

As shown in Figure 6, energy losses are clearly dominated by evapotranspiration in the summer months. As effluent temperatures increase throughout the summer months, the energy exported in the effluent flow, U_{out}, also increases. Energy transfer to the atmosphere is minimized under both summer and winter conditions due to the presence of the insulating layer of peat mulch. The aeration system used at the wetland may serve to increase evapotranspiration losses, $\lambda\rho ET$, during the winter months due to the low relative humidity of the input air.

CONCLUSIONS

The Jackson Meadow wetland data further illustrates that water temperatures in horizontal subsurface flow wetlands are driven by energy inputs and outputs. Net solar radiation, R_N, drives a variety of processes during the summertime, of which evapotranspiration, $\lambda\rho ET$, is the most significant. During winter months, the primary energy inputs are the heat of the influent wastewater, U_{in}, and the heat recovered from ground storage, G. In the winter, temperatures within the wetland can be successfully managed with an insulation layer that minimizes energy losses to the atmosphere, E_{loss}. This approach results in a "balance point" temperature that prevents system freezing, as illustrated by the 2000-2001 and 2001-2002 winter events at Jackson Meadow.

REFERENCES

Brix H. (1994) Functions of macrophytes in constructed wetlands. *Water Science and Technology* 29(4), 71-78.

Henneck J., Axler R., McCarthy B., Monson-Geerts S., Heger S., Anderson J., Crosby J. (2001) Onsite treatment of septic tank effluent in Minnesota using SSF constructed wetlands: Performance, costs, and maintenance. pp. 650-662. St. Joseph, Michigan, United States, American Society of Agricultural Engineers.

Kadlec R.H. (2001) Thermal environments of subsurface treatment wetlands. *Water Science and Technology* 44(11/12), 251-258.

Kadlec R.H., Knight R.L. (1996) Treatment Wetlands. Boca Raton, Florida, United States, CRC Press.

Mæhlum T., Jenssen P.D., Warner W.S. (1995) Cold climate constructed wetlands. *Water Science and Technology* 32(2), 95-102.

NASA (2004) Surface meteorology and solar energy (release 5). *http://eosweb.larc.nasa.gov/sse/* .

Smith I., Bis G., Lemon E., Rozema L. (1997) A thermal analysis on a subsurface vertical flow wetland. *Water Science and Technology* 35(5), 55.

Wallace S.D. (2001) System for removing pollutants from water. (6,200,469 B1). Minnesota, United States. [Patent]

Wallace S.D., Parkin G.F., Cross C.S. (2001) Cold climate wetlands: Design and performance. *Water Science and Technology* 44(11/12), 259-266.