Evapotranspiration crop coefficients for two constructed wetland macrophytes : cattail and bulrush
by Brett William Towler

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering
Montana State University

Abstract:
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APPROVAL

of a thesis submitted by

Brett William Towler

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ABSTRACT

In recent years, a great deal of research has been directed at using constructed wetlands (CW) for wastewater treatment. Because this technology has shown so much promise, a need exists for a better understanding of the water demands for macrophytes typically used in CW design. An energy-based combination evapotranspiration (ET) model has been adapted for two wetland plant species: cattail and bulrush. Actual evapotranspiration (ET_C) has been correlated with Penman's equation for potential evapotranspiration (ET_O) in order to quantify crop coefficients for these two species in a controlled greenhouse environment. Analysis of daily ET_C/ET_O ratios over a six month period support peak crop coefficients of 1.7 and 1.4 for cattail and bulrush, respectively. These results should benefit both the design and performance analysis of constructed wetlands in semi-arid environments such as Montana.

1.0 INTRODUCTION

In the past twenty-five years, a dramatic turnaround has occurred in the world view of the importance of wetland ecosystems. The role they play in biological habitat, flood attenuation and water quality is significant and further magnified by the fact that nearly half of the pre-settlement wetland areas in the U.S. have been destroyed in the past 200 years (Mitsch et al. 1993). Replacement is often impossible due to development; yet artificially created wetlands provide a mitigating solution. Because many wetland ecosystems experience a high rate of biological productivity, they have shown a remarkable potential for waste amelioration. As such, a great deal of research has been directed at using constructed wetlands (CW) for wastewater treatment. Because this technology has shown so much promise, a need exists for a better understanding of the CW water balance.

The quantification of evapotranspiration (ET) from wetland hydrophytes is crucial in the development of a CW water budget. Preliminary studies have shown that actual evapotranspiration from wetland plants can exceed potential evapotranspiration (Boyd 1987). Clearly then, ET from plant species typically used in CW design (i.e. cattail, bulrush, sedge) represents a significant water pathway. ET plays a substantial role in the expression of CW performance indicators and failure to consider ET would lead to misuse of concentration-based treatment goals.

Evapotranspiration models can be separated into three general classes: empirical, theoretical, or combination equations. Combination equations are a compromise between the accuracy of theoretical models and the utility of empirical relationships. The Penman combination equation (Penman 1948, 1963) is based on the physical concepts of available energy, diffusivity and an empirical aerodynamic wind function. Its accuracy, versatility and foundation in the fundamental physical processes controlling ET, make it a likely candidate for the development of constructed wetland crop coefficients.

Goals and Objectives

This research was designed to contribute to the understanding of the water requirements of wetland plant species in semi-arid climates. Measurements of water usage by wetland plants in an existing CW have been correlated with environmental factors such as temperature, humidity, and net solar radiation. This has allowed the adaptation of an energy-based combination ET model to wetland plant species. The results have provided insight on the water requirements for a constructed wetland, contributed to the development of crop coefficients for *Typhia sp.* and *Scirpis sp.*, and allowed for the evaluation of CW treatment performance on a mass basis. This information will benefit the design of CW systems throughout the Rocky Mountain States of the U.S.

2.0 LITERATURE REVIEW

Evapotranspiration

Evapotranspiration is a term first used by Warren Thornwaite (Monteith 1985) to describe the total amount of water loss due to evaporation from a soil surface and transpiration by plants. Evaporation is the process of water changing state from a liquid to a vapor. The rate of evaporation from any surface is largely dependent upon environmental factors such as available energy and the rate at which water vapor can diffuse into the atmosphere (Shuttleworth 1993). Transpiration is the process by which water is transported from the soil, through plant tissues to the plant surface and finally into the atmosphere as water vapor. Transpiration, like evaporation, is similarly affected by environmental factors as well as biological processes controlled by the plant. Measuring these terms separately is unnecessary; irrigation practices and hydrologic studies are concerned with the total water loss from a system only. Therefore, evaporation and transpiration are often combined as one term, evapotranspiration or ET.

A variety of models exist for estimating evapotranspiration. Most can be placed into one of three categories: empirical, theoretical, or combination equations. Empirical models are, by far, the most common. They provide simple, often accurate, estimates of evapotranspiration using readily available information such as average daily temperature and solar radiation (e.g. Hargreaves et al. 1985). The drawbacks of these models are that they have no theoretical foundation and their application is often limited to the region or time for which they were developed. Theoretical approaches are based on the fundamental physical processes controlling evapotranspiration such as available energy and mass transfer. While this approach can be highly accurate, it may require large amounts of information to completely define the system of interest. As such, theoretical models are often time-consuming, expensive and ill-suited for use by the layperson. Combination equations are just that; they utilize the accuracy of a theory-based model, making empirical substitutions where expedient.

Potential Evapotranspiration

Potential evapotranspiration (ET_o) is defined as the rate at which available water is removed from the plant and soil surface. It is commonly reported as an equivalent depth of water per unit area. Historically, this is calculated in two ways; as evaporation from a large open water body or as evapotranspiration from an extensive land surface having some reference crop (i.e. short grass) that is actively growing, fully canopied, and not water stressed (Doorenbos and Pruit, 1977). Because of this ambiguity, the latter is often referred to as reference crop evapotranspiration (ET_r).

Crop Coefficients

Most ET formulae provide estimates of potential evapotranspiration not actual crop evapotranspiration. The exceptions are resistance models (e.g. Penman-Montieth) that are calibrated to a specific crop. Crop evapotranspiration (ET_c), then, is estimated from potential evapotranspiration and a crop coefficient;

$$ET_c = K_c ET_o \quad \text{or} \quad ET_c = K_c ET_r \tag{2.1}$$

where ET_c is crop evapotranspiration in mm/day; ET_o and ET_r are the potential evaporation or reference crop evapotranspiration in mm/day respectively; and K_c is the dimensionless crop coefficient.

Clearly, K_c is a complex factor. It is an experimentally determined coefficient that accounts for specific plant physiology and the degree of crop cover. Furthermore, K_c represents the peak value of ET_C/ET_O ratios as the plant progresses from seed to senescence. The time dependent ET_C/ET_O ratio is referred to as the basal crop coefficient. In addition, because crop coefficients are derived from the ratio of ET_c to ET_o (or ET_r), care must be taken in applying them only to the potential evapotranspiration model against which they were calibrated. While referred to as a crop coefficient, it is important to note this term includes evaporation from the soil surface as well as transpiration. Potential evapotranspiration is greatly affected by soil moisture and water availability in the root zone. Basal crop coefficients can be adjusted to account for these factors as well.

Energy Budget Method

Energy budget methods seek to model the physical processes involved in evapotranspiration by performing an energy balance on a control volume. Taken as a closed system, the control volume includes the plant canopy, surrounding atmosphere, root system and surrounding soil. Fluxes to this system are then quantified:

$$R_n + G + H + A_n + LE + P = \Delta S \tag{2.2}$$

where R_n is net solar radiation; G is the soil heat flux; H is the sensible heat flux; A_n is the advective heat loss; LE is the latent heat of vaporization of water; P is the change in biochemical photosynthetic energy; ΔS is the change in energy storage.

Radiation is the dominant factor affecting evapotranspiration (Shuttleworth 1993). Indeed, radiation alone is often a good predictor of water loss. However, only a fraction of the extraterrestrial short wave radiation reaching the earth strikes the surface (plant or soil). Much of the energy in this spectrum, .3 to 3μm, is disrupted by atmospheric gases, clouds and dust. The fraction of energy reaching the surface as diffuse radiation can be as little as 15% on a clear day or nearly 100% on an overcast day (Shuttleworth 1993). A significant portion of the total incoming short wave radiation is reflected at the earth's surface. This reflection or albedo (α) effect is dependent on the angle of incidence, the fraction of diffuse radiation, and the type of land cover (i.e. vegetation, water, snow). Thus, the net short wave solar radiation is the sum of incident short wave and diffuse radiation not reflected at the earth's surface.

$$S_n = S_t (1 - \alpha) \tag{2.3}$$

where S_n net incoming short wave radiation; S_t is the total incoming short wave radiation; α is the reflection coefficient.

The surface and the atmosphere also emit long wave radiation in the range of 3μm to 100μm. This tends to result in a net loss of energy as, on average, the earth's surface is warmer than the atmosphere.

$$L_n = L_i - L_o \tag{2.4}$$

where L_n is the net long wave radiation; L_i is the total incoming long wave radiation; L_o is the total outgoing long wave radiation.

Net radiation (R_n), the first term in this energy balance equation, is the sum of net short wave solar radiation and net long wave radiation. It is the flux of radiant energy into the control volume and is easily measured with a net radiometer.

$$R_n = S_n + L_n \tag{2.5}$$

Soil heat flux (G) is the second term in this energy budget (eqn. 2.2). Energy movement occurs by conduction and is strongly affected by the density of plant cover (Shuttleworth 1984). As density of the crop increases, the amount of radiation reaching the surface diminishes thus limiting the amount of heat transferred to the soil over the day.

Radiant energy will also warm the air surrounding the plant canopy. This results in a temperature change which can be sensed or measured, and is therefore referred to as the *sensible heat flux* (*H*). Sensible heat flow moves downward to the surface during the night when long wave radiation is lost to the atmosphere. The direction of this heat flux during the day is dependent on conditions at the surface. Typically, it is a loss from the system but in instances when the canopy is wet and evaporative demand is high, it can be an input into the system (Shuttleworth 1993).

Advective energy (A_n) is associated with the movement of air masses across the canopy or control volume. Wind imparts energy to the system as heat which can greatly affect ET rates at the boundary of a crop or water body. The quantity of heat transferred to the system drops quickly as the air mass moves from the boundary to interior portions of the control volume. For this reason, the effects of advection become insignificant for extensive areas and this term is often ignored. For small systems, such as isolated stands of wetland hydrophytes, advective energy can play a greater role in evapotranspiration (Anderson and Idso 1987).

Two additional terms play a small role in evaporative loss, *photosynthetic energy* (P) and *storage* (ΔS). Photosynthetic energy refers to that portion of the incoming energy that fuels biochemical processes within the plant. Typically this loss is insignificant, but 2 % of the incoming net solar radiation is a reasonable approximation (Stewart 1973). Due to the lack of thermal mass in most agricultural and wetland plants, a stored energy term is unnecessary in all but forest systems (Stewart 1973).

By quantifying all other terms in this energy budget, the final component, *latent energy* (LE), can be isolated by rearranging the equation:

$$LE = \Delta S - R_n - A_n - P - H - G \tag{2.6}$$

Ignoring ΔS and P, and using the convention that a loss from the system is positive the equation becomes:

$$LE = R_n - A_n - H - G \tag{2.7}$$

Thus, the potential evapotranspiration or latent heat of vaporization of water remains a function of net solar radiation, soil heat flux and advective and sensible heat losses.

$$ET_o = R_n - G - (A_n + H) \qquad (2.8)$$

Penman Model

The Penman equation (1948, 1963) is widely regarded as an accurate method of predicting potential evapotranspiration (ET_o) for periods of one month to one day (Burman 1980). It incorporates a reduced energy balance with evaporation's dependence on diffusivity (McCuen 1989). Dalton's diffusivity law describes the mass transfer of water from a liquid to a vapor, stating that the rate of evaporation is proportional to the vapor pressure deficit.

$$E = c[g(v)(e_s - e_a)] \qquad (2.9)$$

where E is evaporation from a water surface; e_a is the actual vapor pressure; e_s is the saturation vapor pressure for the temperature at which e_a was measured; c is a mass transfer coefficient; v is the windspeed; and $g(v)$ is an empirically derived aerodynamic wind function. The Penman equation is essentially an energy budget, combined with Dalton's Law, and supplemented by an empirical wind function. For this reason it is often referred to as a "combination equation". It takes the general form

$$ET_o = [\Delta/(\Delta+\gamma)](R_n - G) + [\gamma/(\Delta+\gamma)]f(u)(e_a - e_s) \qquad (2.10)$$

where ET_o is potential evapotranspiration in mm/day; Δ is the slope of the saturation vapor pressure-temperature curve in mbar/K; γ is the psychometric constant in mbar/K; R_n is the net solar radiation in mm/day; G is the heat flux into the soil in mm/day; e_a is the actual vapor pressure in mbar; e_s is the saturation vapor pressure at the dew point temperature in mbar; u is the windspeed in m/day; and $f(u)$ is an empirically derived aerodynamic wind function. Penman's work predated accurate net radiometers and thus, R_n was estimated as a function of incident short-wave solar radiation. The wind function (Allen 1986) is defined as

$$f(u) = a_w + b_w u \qquad (2.11)$$

where u is the wind speed in m/s at 2 m elevation; and a_w and b_w are empirical coefficients that are calibrated to a specific location and set of conditions. Penman suggested values of $a_w = 0.263$ and $b_w = 0.141$ for short grass. Wright (1982), working in Kimberly, Idaho, developed equations for a_w and b_w based on the day of the year. More theory-based wind functions have also been suggested (Businger 1956; Monteith 1965). Penman's original equation (1948) neglected the soil heat flux term, G. Later studies have suggested that soil heat flux term can be neglected for any cyclic period where the soil temperature is the same at the start and end of the cycle. Wright (1982) estimated G as

$$G = (T_a - T_p)C_S \tag{2.12}$$

where T_a is the mean daily temperature in K; T_p is the mean daily temperature for the preceding three days in K; and C_S is an empirical soil specific heat coefficient in mm/day/K. An empirical formula for soil heat flux model, based on R_n and a leaf area index, was proposed by Choudhury et al. (1987).

The Penman method (eqn. 2.10) has evolved considerably since its inception in 1948, including modifications made by Penman, himself, in 1963. The empiricism of this method has fueled the evolution of several sibling equations. The Penman-Monteith (Monteith 1965) equation is a widely used variant that includes a stomatal and aerodynamic resistance model. Wright (1982) has adjusted the original Penman equation for the semi-arid conditions in Idaho. Others have done similar regional tuning of the wind function (Doorenbos 1977). While its applicability is limited due to the extensive data requirements, the Penman equation, including modifications, is generally accepted as the most accurate method of estimating ET (Amatya 1995, Kotsopoulos 1997).

Evapotranspiration by Wetland Vegetation

In general, the effect of vegetation on wetland evapotranspiration rates is unclear. Numerous studies have resulted in conflicting ET_c/ET_o ratios in naturally occurring wetlands. Two schools of thought exist; the presence of extensive vegetation may retard evaporation beyond contributions due to plant transpiration, or hydrophytic plant species may act as "water pumps" that move water from the root zone into the atmosphere at a rate greater than evaporation from the soil (Kadlec et al. 1998). An examination of prairie potholes in North Dakota found ET rates to be ten percent less in vegetated potholes than in non-vegetated ones. Other studies (Brown 1981, Heimburg 1984) have yielded similar results for other naturally occurring wetlands. In contrast, bogs and fens in New Hampshire, Minnesota and Germany have demonstrated ET rates well in excess of open water evaporation for all or part of the year (Mitsch 1993). Extremes in hydrologic or environmental conditions and variations in plant species may explain the ambiguous results reported by these large-scale field studies.

Species-specific studies appear more conclusive. Otis (1914) reported water use by cattails as nearly three times that of open water evaporation. Young and Blaney (1942) recorded ET_c/ET_o ratios for cattail of approximately 1.4. Others have reported values within this range (Snyder et al. 1986). Allen et al. (1992) compared ET_c rates to an alfalfa reference crop, yielding crop coefficients of 1.6 and 1.8 for cattail and bulrush, respectively. Anderson and Idso (1987) suggest that the ET rates reported by Otis, which represent the upper extreme of literature values, may be due to advective energy contributions. Excluding the Otis (1914) study, most reported values for wetland plants lie between 1.4 and 1.8. It seems likely then, that this variability is due to different definitions of potential evapotranspiration and errors in experimental design.

3.0 METHODS AND MATERIALS

Constructed Wetland Cell Design

Eight constructed wetland cells have been operating in an environmentally controlled greenhouse in Montana State University's Plant Growth Center (PGC). Figure 3.1 shows a generalized design plan for each of the eight cells. The walls of each cell are made of 5/8" thick polypropylene sheeting sealed with a polypropylene bead and silicone caulking to form a rectangular box. Each box (or cell) is 60 inches long, 30 inches wide and 22 inches high. The cells are filled to a depth of 18 inches with a washed ¾ inch bedding gravel. Flow through the cell is in the longitudinal direction. An inflow nipple is placed at a height of 17 inches above the base at the center of the front end. This connects to a one inch diameter polyvinylchloride (PVC) manifold also centered 17 inches above the cell base. The gravel size is partitioned such that two areas (4 inches in length) of higher conductivity exist at the ends of each cell. This was done to promote plug flow. Sampling ports exist at the center of each quadrant and a removable sampling basket was placed in the center of the box. Outflow boxes are attached to each cell at the back end. The outflow boxes are 9 inches wide, 9 inches long and 22 inches high. Water enters the outflow box through plastic tubing at a height of 17 inches. This maintains the water level 1 inch below the gravel of this sub-surface flow wetland (SSW).

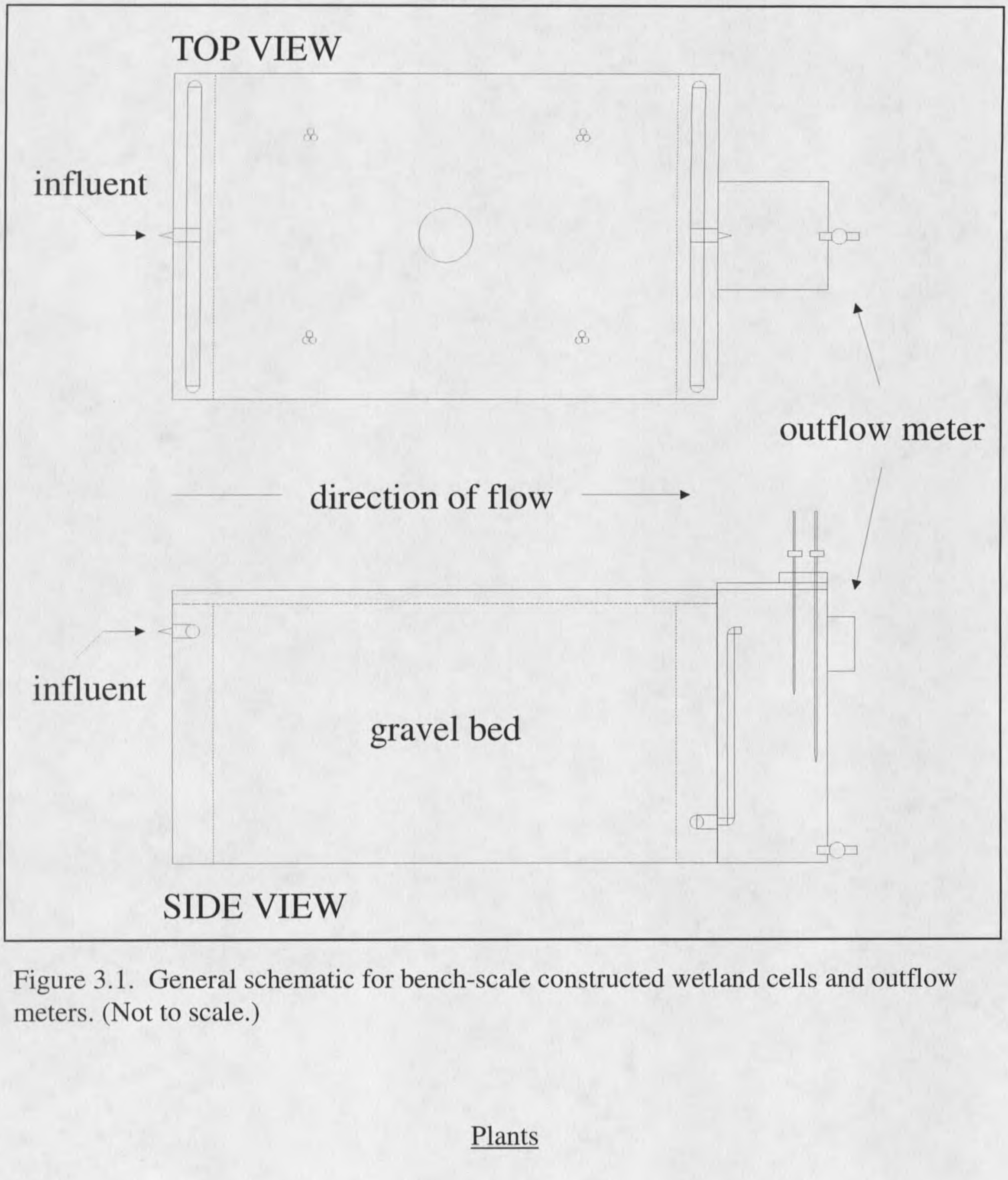

Figure 3.1. General schematic for bench-scale constructed wetland cells and outflow meters. (Not to scale.)

Plants

Three CW cells were planted with cattail, three with bulrush, and two were left as unplanted controls. Cattails are characterized by long crescent-shaped leaves growing in masses of a dozen or more. The leaves range in length from 3 to 6 feet and 1 to 2 inches in width. Typically, they are light green in color and are grouped around a large seed head. Bulrush are dark green, tube-like in shape and terminate in small seed heads. The stalks are approximately ½ inch in diameter and range from 2 to 6 feet in height. Both plants were transplanted to the greenhouse as rhizomes from native stands found outside the Missouri Headwaters State Park, Montana in 1995. Figures 3.2 and 3.3 show photographs of these two wetland macrophytes.

Figure 3.2. Typical appearance of bulrush cells during mid-spring (April, 1998).

Figure 3.3. Typical appearance of cattail cells during mid-spring (April, 1998).

Wastewater Supply

The wastewater supply is a soluble synthetic mixture intended to represent domestic wastewater entering secondary treatment. The composition of this synthetic waste is detailed in Table 3.1.

Table 3.1. Chemical composition of synthetic wastewater used in bench-scale CW.

Type	Description	Chemical formula	Concentration (mg/l)
Macro nutrients	Sucrose	$C_{12}H_{22}O_{11}$	200.0
	Peptone (Primatone)		222.0
	Magnesium Sulfate	$MgSO_47H_2O$	62.0
	Potassium Phosphate	K_2HPO_4	44.0
	Ammonium Chloride	NH_4Cl	57.4
Micro nutrients	Boric Acid	H_3BO_3	10.0
	Cupric Sulfate	$CuSO_45H_2O$	0.8
	Potassium Iodide	KI	1.9
	Manganous Sulfate	$MnSO_4H_2O$	7.8
	Sodium Molybdate	$Na_2MoO_42H_2O$	4.0
	Zinc Sulfate	$ZnSO_47H_2O$	7.8
	Calcium Chloride	$CaCl_22H_2O$	1.9
	Ferric Chloride	$FeCl_34H_2O$	0.2

This powdered waste is mixed with water in three 265 gallon plastic supply tanks every nine days. Wastewater from the tanks runs though a 5/8 inch hose into an eight port manifold. The manifold is constructed from one-inch diameter PVC pipe. It is then drawn into a peristaltic pump which delivers the influent through 5 mm tubing to each of the eight CW cells at a rate of 30 milliliters per minute.

Inflow Rates

An accurate record of inflow rates was necessary to complete the cell water balance. Inflow rates were set at 30 ml/min resulting in a five-day hydraulic residence time in the CW. Influent rates were checked volumetrically with timed flow into a graduated cylinder. Maintaining this rate was problematic, however. The pump flow rates, contrary to the manufacturer's literature, were slightly affected by head on the supply side. Continual mechanical degradation of the delivery line caused occasional line breaks. There was also an inherent variability in the pump's settings. As such, volumetric checks were made at least four times per week and the flow was recalibrated to 30.0 ml/min +/- 0.5 ml/min. Each time the flow rate was corrected, the pre and post adjustment rates were recorded. Flow rates at intermediate times were linearly interpolated from these measurements.

Outflow Rates

Outflow measurements completed the water balance that formed the basis for ET computations. Several problems precluded the use of 'off-the-shelf' flow meters. First, the majority of the commercially available meters required pressures or flow rates greater than those present in these bench-scale wetland cells. Secondly, those commercial meters that would operate within the desired range (0 to 50 ml/min) were designed for use with clean water only. The particulate mater in the effluent stream would quickly foul such meters. Initially, a tipping bucket rain gauge was used to measure effluent rates. Biofilm development quickly fouled the tipping mechanism and made readings inaccurate.

A custom-made low-flow outflow meter, which was not subject to biofilm fouling, was designed (see Figure 3.4). The mechanism consisted of the existing outflow box, an electric solenoid-valve, two sensor electrodes and an electronic control. The outflow box is a smaller polypropylene box mounted to the rear of each CW cell. A hose barb is tapped through the outflow box and into the wetland cell (One inch above the cell base.). A one-inch outside diameter hose is connected to the barb and terminates at a height of 17 inches above the outflow box base. Another hose barb is tapped through the rear of the outflow box and connected to the drain solenoid. The height of effluent in the outflow box is controlled by two parallel electrodes. The upper sensor electrode (US) and the lower sensor electrode (LS) define the top and bottom, respectively, of the flush volume. The electrodes, 30 inch stainless-steel rods, are tapped through the sensor mount and wired to the electronic control. The electrodes (or sensor rods) are threaded through the polypropylene sensor mount to permit adjustments in the flush volume. Plastic discs are affixed to the top of each sensor to act as turning knobs and prevent errant shorts between the electrodes above the reservoir. An automotive fuel tank valve was used as an electric solenoid-valve. This drain solenoid is water resistant, largely unaffected by biofilm development and operates on a 12V DC power supply. It is connected, via 5/8" plastic tubing, to the hose barb at the rear of the outflow box. The power for the solenoid originates from the electronic control. The electronic control casing is mounted on the exterior of the outflow box and houses the logic circuitry for the periodic flush events. A data port on the electronic control connects the device with an 8 port datalogger. Figure 3.5 shows the outflow metering system and data collection equipment as built.

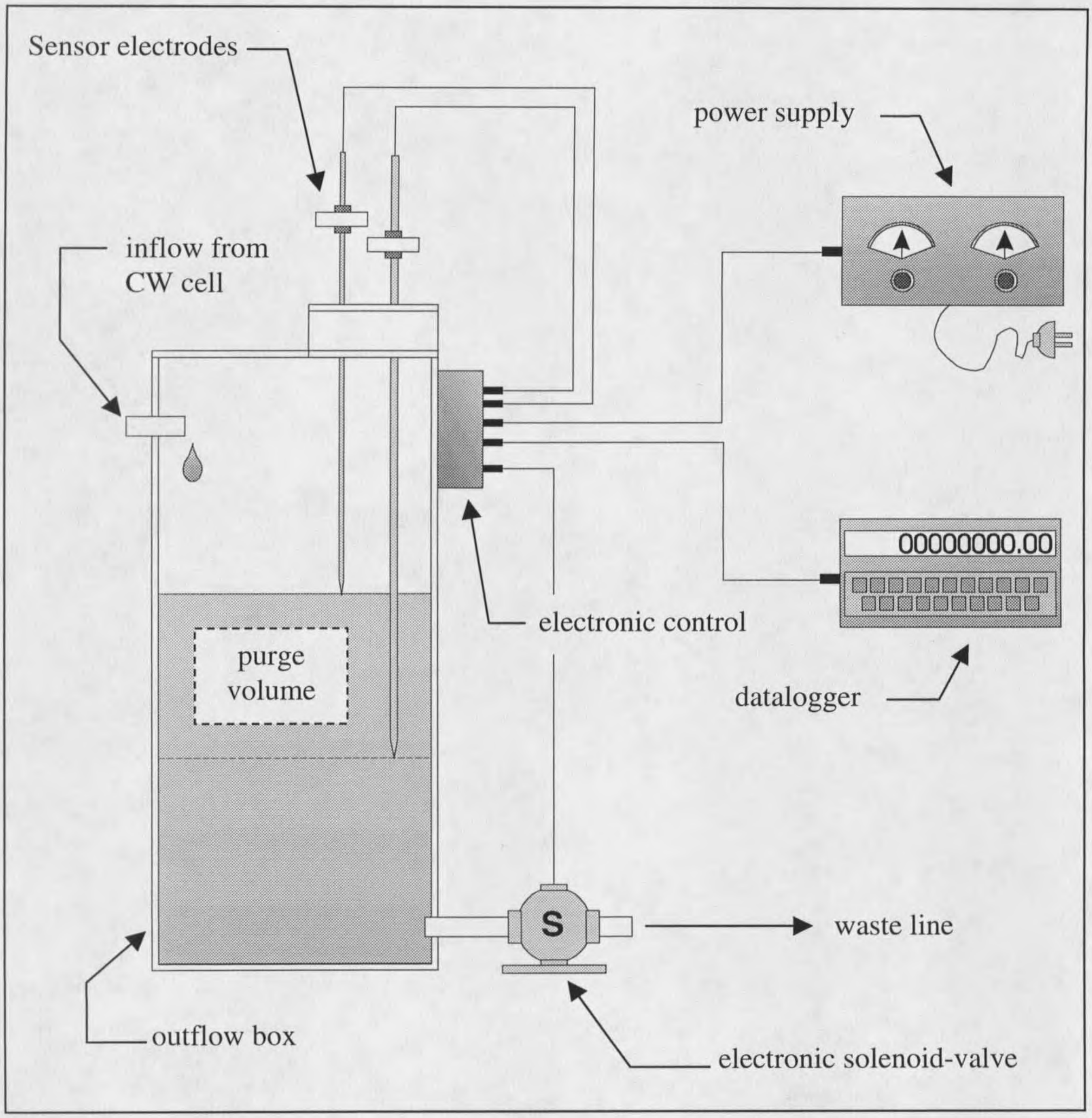

Figure 3.4. Schematic of constructed wetland cell outflow metering system.

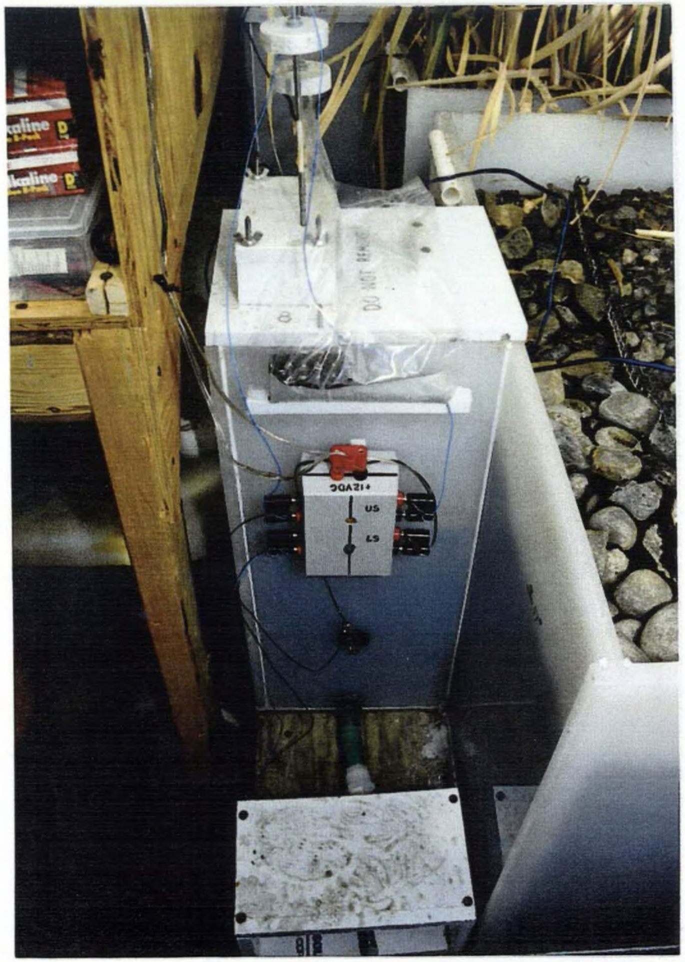

Figure 3.5. Photograph of the cell outflow metering system as built.

Figure 3.6. Photograph of the data collection equipment & peristaltic pump.

Operation of the outflow meter involves the periodic flush of a known volume at recorded time intervals to measure the time-averaged outflow during the interval. Water enters the outflow box at a height of 17 inches above the cell bottom and drips into the reservoir (see Figure 3.4). The lower limit of this reservoir is defined by the LS. As water fills the outflow box, the drain solenoid remains closed. When the effluent level reaches the US, the solenoid will open and the box will begin to drain. Once the water level drops below the LS, the flush event is terminated and the cycle restarts. This process is monitored by the electronic datalogger and flush events are recorded. The outflow is approximated as:

$$Q_o = \Delta V / \Delta t \tag{3.1}$$

where Q_o is the outflow in ml/min; ΔV is the flush volume of the outflow box in ml; Δt is the time between flush events in minutes.

Net Solar Radiation

Measurements of solar radiation were made using a net radiometer. Calibration was verified annually by the manufacturer, although little wandering was observed. The instrument was mounted in the approximate center of the greenhouse at a height of 10 feet. This was sufficiently high to ensure that the plant canopies did not shade the device and affect the readings. The radiometer reported to a datalogger (shared with the relative humidity probe), and readings were logged every thirty minutes.

Air Temperature

Air temperature was measured with a thermocouple. The thermocouple (TC) was suspended at a height of 8 feet in the approximate center of the greenhouse. The tip of the thermocouple was insulated and connected to the datalogger at the rear of the greenhouse. Measurements were logged every 30 minutes. The relative humidity probe (installed at the southern end of the greenhouse) also measured air temperature. A comparison of the values from the two locations indicated no significant gradient across the greenhouse. So, the TC mounted in the center of the room was used to represent the air temperature for the entire system.

Soil Temperature

Soil temperature was measured with insulated thermocouples. A separate TC was installed in each wetland cell at the front-left quadrant sampling port. The thermocouples were connected to an electronic datalogger and temperatures were logged every 30 minutes.

Relative Humidity

The actual vapor pressure, e_a, is required to calculate vapor pressure deficit, an important indicator of ET (see equation 2.9 & 2.10). Relative humidity and air temperature were measured with a temperature/RH probe. The actual vapor pressure was calculated as:

$$e_a = (\mathrm{RH}/100)e_s \tag{3.2}$$

where RH is the relative humidity in percent; e_a is actual vapor pressure in mbar; e_s is saturation vapor pressure in mbar calculated using (Shuttleworth 1993):

$$e_s = 611\mathrm{e}^{[17.27\,\mathrm{T}\,/\,(237.3\,+\,\mathrm{T})]} \tag{3.3}$$

where T is the mean air temperature in °C.

Plant Status

An indication of plant status is essential to the quantification of a crop coefficient. Green leaf area was used as a measure of plant status. Conventional methods, such as light attenuation meters, do not account for dead leaf matter in the canopy. Therefore, the parameter green leaf area index (LAIg) is introduced. Green leaf area index is defined as the fraction of the total leaf area index (LAI) that is green, alive and actively growing. Mathematically, LAIg is the product of leaf area index and the fraction of green leaf area as observed from above.

$$LAI_G = LAI^{*}\ \mathrm{GLF} \tag{3.4}$$

where LAI_G is the dimensionless green leaf area index; LAI is the dimensionless leaf area index; and GLF is the green leaf fraction or ratio of green leaf area to total leaf area.

Leaf Area

Leaf area was measured with a commercially available light attenuation meter. The instrument measures direct and diffuse radiation at five different angles. One light measurement was taken above each canopy at a height of 8 feet and five measurements were recorded at the center of the plant's base. Measurements from above and below the plant canopy correlate to the interception rate. In this experiment, the light attenuation meter was pre-programmed with the canopy volumes (entered as lengths along the lens angles). Internal algorithms converted recorded radiation readings into foliage density (*FD*) measurements. Foliage density and leaf area index are related as follows:

$$LAI = FD * Z_c \tag{3.5}$$

where FD is the foliage density in inches^{-1}; and Z_c is the average canopy height in inches. These foliage density values are based solely on light interception due to canopy surface area and therefore do not differentiate between dead and live plant matter. LAI data was collected approximately every 6 weeks during the growing season. All three sets of measurements were made at approximately the same time of day under visually similar lighting conditions.

Green Leaf Fractions

Green leaf partitioning measurements were made on the same days as LAI readings. A color analysis method was used to differentiate between live and dead plant matter in the canopies. Cattail cell numbers 1 and 6, and bulrush cell numbers 5 and 7, were photographed with a 35mm camera (see Figures 3.7 and 3.8). The color photographs were consistently taken from directly overhead at a height of eight feet above the floor. Temporary wooden scaffolding was built to ensure stability while taking the photographs and to provide a consistent height and focal length. The focal length and aperture settings on the camera were maintained throughout all three sets as well.

Once developed (as 4 x 6 matte prints), images were digitized using a color scanner, formatted as 256 color TIFF files. These files were then analyzed with image analysis software on a personal computer. The software partitioned, by color, living plant matter, dead plant matter and other. The green leaf fractions (GLF) of the total projected area as seen from above were based on this partitioning.

Figure 3.7. An example of photographs used to calculate the green leaf fraction (GLF) measurements for cattails (April 1998).

Figure 3.8. An example of the photographs used to calculate green leaf fraction (GLF) measurements for cattails (August 1998).

4.0 RESULTS & DISCUSSION

Environmental factors and outflow rates were recorded automatically. Air and soil temperature, radiation and relative humidity readings were taken automatically every 30 minutes. Outflow flush events were event-driven and, as such, were not recorded at any regular interval. All these readings were written by the datalogger to storage modules located in the greenhouse and downloaded to a personal computer every 2 to 4 weeks. Inflow readings were manually recorded each time the peristaltic pump was re-calibrated. Visual Basic programs were written to sort and summarize these data into hourly and daily averages.

Temperature

Air and soil temperatures were measured every 30 minutes and converted into hourly means. Typical seasonal hourly trends were calculated by averaging hourly means for 2 two-week periods. Figures 4.1 and 4.2 document these hourly trends for a typical winter period (3/12/98 through 3/26/98) and for a typical summer period (7/29/98 through 8/12/98), respectively.

The winter period was characterized by a marked difference between air and soil temperature means. The air temperature during this period remained below the set temperature (8 °C) through the hours of darkness. This difference approached 2 °C (see Figure 4.1) and was likely due to instrument location. The air thermocouple, placed in the approximate center of the greenhouse experienced lower temperatures than the PGC thermostat located on the north wall nearest the entrance to the greenhouse. Physical inspection verified that during winter months, higher temperatures existed at this wall which bordered the well-heated PGC hallway. Despite this, the temperature gradient between the air thermocouple and the relative humidity probe (located at the south end of the greenhouse) was small suggesting that the air thermocouple was representative of the overall greenhouse environment. During the day, air temperatures rose rapidly in response to solar warming of the air in the greenhouse. In sharp contrast to air temperature trends, the soil temperature decreased as much as 2 °C during the daylight hours. While some of this decrease may be a delayed response to the nighttime sensible heat loss, this significant temperature decrease can be better explained by latent energy loss due to the higher daytime evapotranspiration rates. Vaporization, the mechanism for evapotranspiration, requires energy. In the absence of any other input or heat loss, 1 cm of ET in a wetland cell would result in a 1.25 °C change in the constructed wetland cell's soil temperature. The effect of ET on soil temperature is supported by the contrast between the three treatments. The lower soil temperatures observed in the planted cell correlate with higher ET rates and consequently higher latent energy loss.

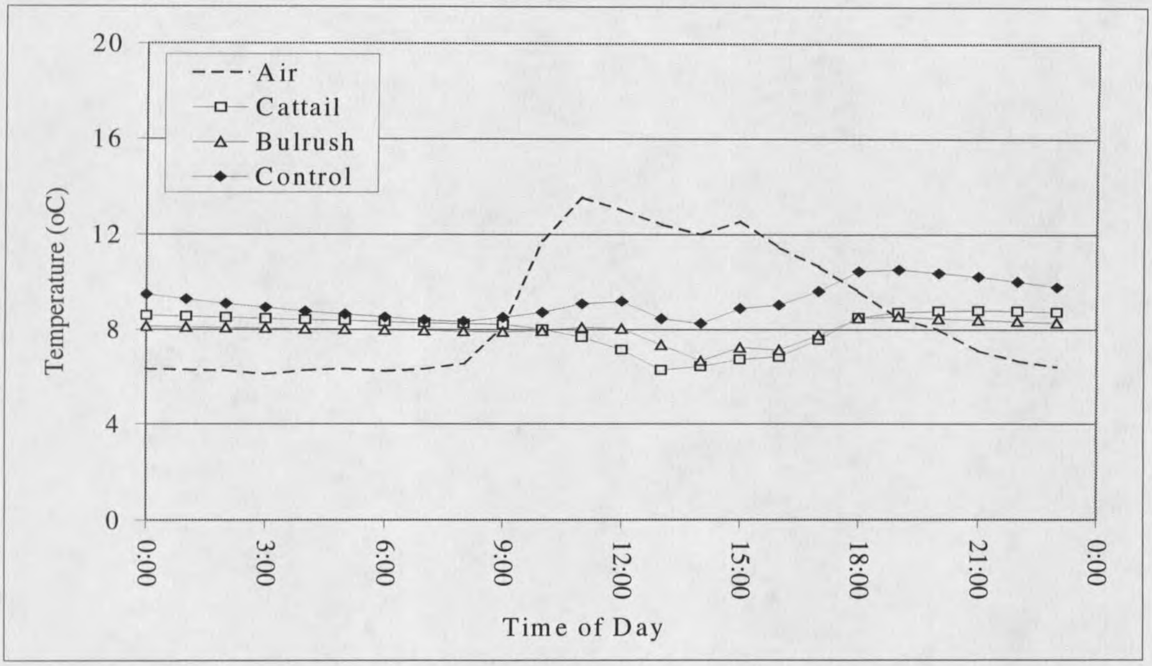

Figure 4.1. Hourly air and soil temperature trends for a typical two-week winter period.

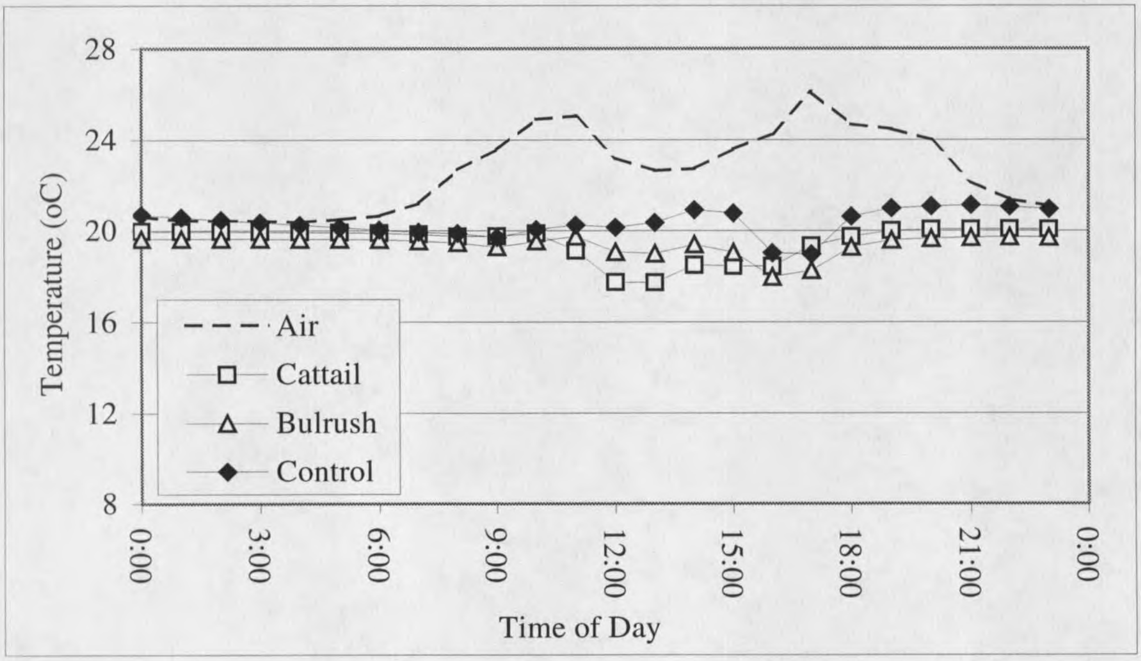

Figure 4.2. Hourly air and soil temperature trends for a typical two-week summer period.

The summer period was characterized by similar differences between the air and soil temperatures. During the night hours, air and soil temperatures approached the set temperature of 20 °C with air temperature readings remaining slightly higher than those seen in the cells. The input of solar radiation during the day resulted in a separation approaching 5 °C (see Figure 4.2). Solar energy caused an increase in sensible heat while soil temperature decreased. Again, the planted cells experienced a sharper temperature decrease demonstrating the effect ET has on hourly soil temperature changes.

Temperature changes between treatment types were also apparent. Control cells were consistently warmer than the planted cells. The lack of plants affected soil temperatures in two ways. First, exposed directly to sunlight, the saturated gravel bed warmed more rapidly than those cells shaded by plant canopies. Secondly, the ET_C rates seen in the control were lower than either of the two planted treatments. Lower ET_C rates translated into lower latent energy loss. Temperature differences were also seen between the two planted treatments, cattail and bulrush. Though not as pronounced, the same processes caused differences in daytime and nighttime temperature trends. During the night hours, the temperatures in cattail-planted cells were regularly higher than the bulrush treatment. The higher foliage density seen in the cattail cells may have provided some degree of insulation against vertical soil heat flux. This may also be a consequence of position in the greenhouse. Conversely, cattail soil temperatures often dropped below bulrush soil temperatures during the day. This again was likely a result of higher ET rates and consequently higher latent energy losses in the cattail treatment.

Two-week air and soil temperature averages were computed for each treatment over the season starting 3/10/98 and ending 8/24/98. The general seasonal trend was characterized by a gradual increase in temperatures. In early March, temperatures averaged 8 °C and increased to averages of 20 °C in the period beginning 8/11/98. Figure 4.3 illustrates the seasonal trends for two-week mean temperatures for all three treatments and the air thermocouple.

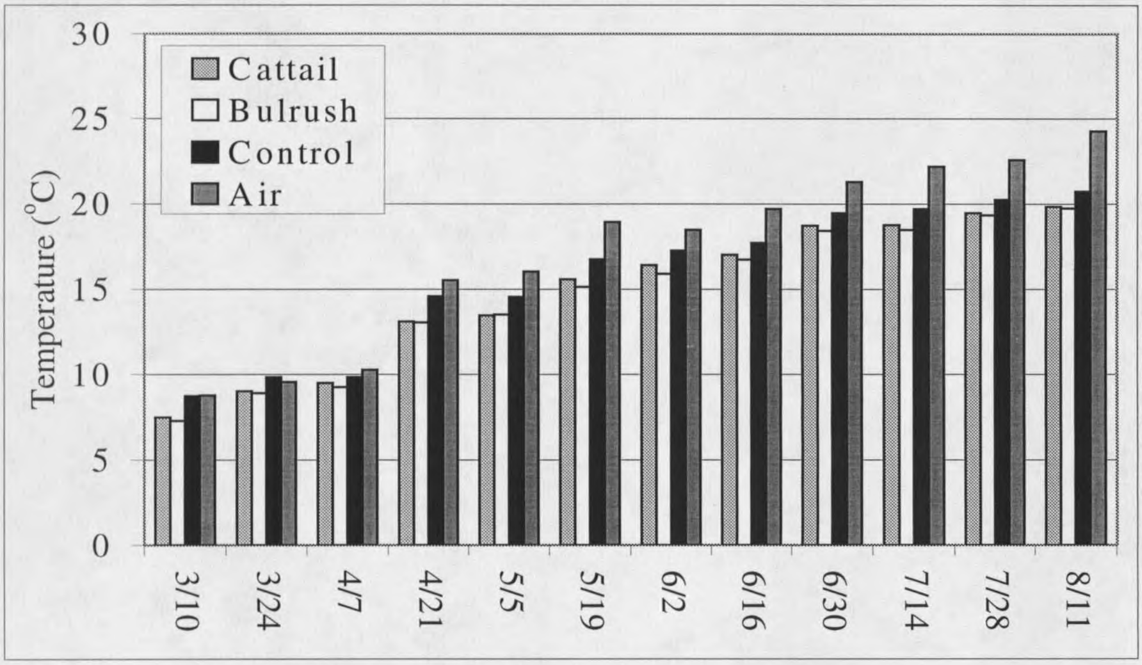

Figure 4.3. Two-week air and soil temperature means.

Differences in the average soil temperature were seen between the two planted treatment types. Cattail soil temperatures were greater than the bulrush soil temperatures in all but one of the 12 two-week periods reported. Given the trends shown in Figures 4.1 and 4.2, the effect of ET on the two-week temperature means was less important than those of foliage density and position in the greenhouse. Indeed, position may play the largest role as the two cattail cells were closer to the southern end of the greenhouse and thus received more solar radiation on average. However, the separation between the two species was always less than one degree Celsius suggesting the plant species effect on two-week average soil temperatures, and therefore two-week average ET rates, was small.

Control cells experienced a higher average temperature than did either of the two planted treatments. Three possible causes exist; position in the greenhouse; lower latent heat loss, and lack of shading in the unplanted control. The control cell, located at the southern end of the greenhouse may have, on average, received more solar energy that the planted cells. Furthermore, the effect of advective energy loss due to the overhead blowers (located at the north end) would have been minimized. Lower evapotranspiration rates in the control cell resulted in lower latent energy loss and consequently higher soil temperatures. Finally, much of the incident solar radiation that would be intercepted by the plants in cells 1, 5, 6, and 7 directly strikes (and warms) the dark green gravel surface of the unplanted control.

The relationship between air and soil temperatures varied over the season. In March, mean air temperatures were often less than the soil temperatures. During the warmer months, air temperatures exceeded the soil temperatures of all wetland cells. While the higher air temperature seen in the warmer months may be explained by latent energy losses in the wetland cells, as Figure 4.2 illustrates, this separation between air and soil temperatures persists through the night. It is therefore more likely that the PGC environment controls are the cause. During the winter months, the environmental controls opened the outside air vent to lower the greenhouse temperature. This vent is centered approximately 9 feet above the floor. This influx of cold air blew across the air thermocouple having a greater effect on it than the well-insulated wetland cells. As the season progressed, the environmental controls maintained a set temperature by turning on floor-level evaporative coolers. The heavier cool air would settle, affecting the wetland cells more than the elevated air thermocouple.

Relative Humidity

Relative humidity, coupled with air temperature, was measured to calculate vapor pressure deficit (the difference between saturation vapor pressure and actual vapor pressure). Dalton's Law, and consequently Penman's equation, are functions of vapor pressure deficit (VPD). No seasonal trend was apparent in the two-week relative humidity averages. The most significant change occurred from 4/7/98 to 4/21/98. A 14% drop in relative humidity and a 5 °C increase in average temperature resulted in a 5.1 mbar increase in VPD contributing to an increase in the ET rates during the same interval (see Figure 4.4). The use of evaporative coolers late in the season probably contributed to the higher relative humidity readings seen then.

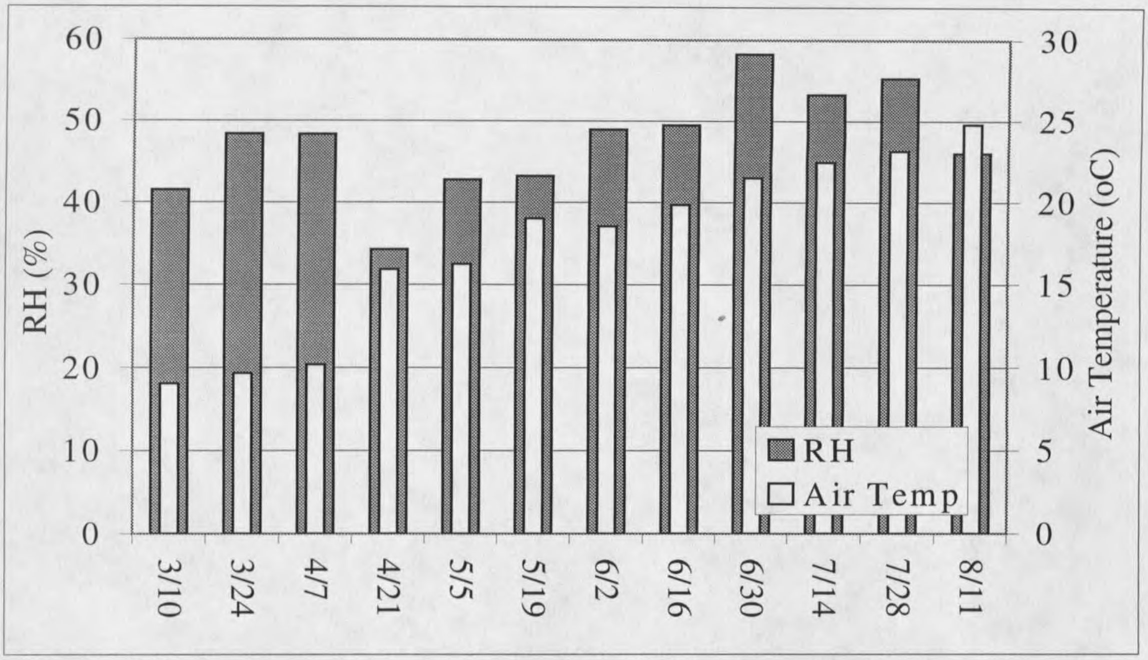

Figure 4.4. Two-week relative humidity and air temperature means.

Net Solar Radiation

Net solar radiation heavily weights the results of Penman's equation for potential evapotranspiration. Net solar radiation was measured every 30 minutes in the greenhouse and converted to daily and two-week means. Two-week averages beginning 3/10/98 are reported in Figure 4.5. No seasonal trend in R_n was apparent. Values ranged from 2.8 MJ/m^2 to 8.4 MJ/m^2 during the season with peaks observed during the weeks of 4/21/98 and 7/14/98. The relatively low values of R_n caused some concern, so these readings were compared to the measurements taken at a nearby USGS weather station.

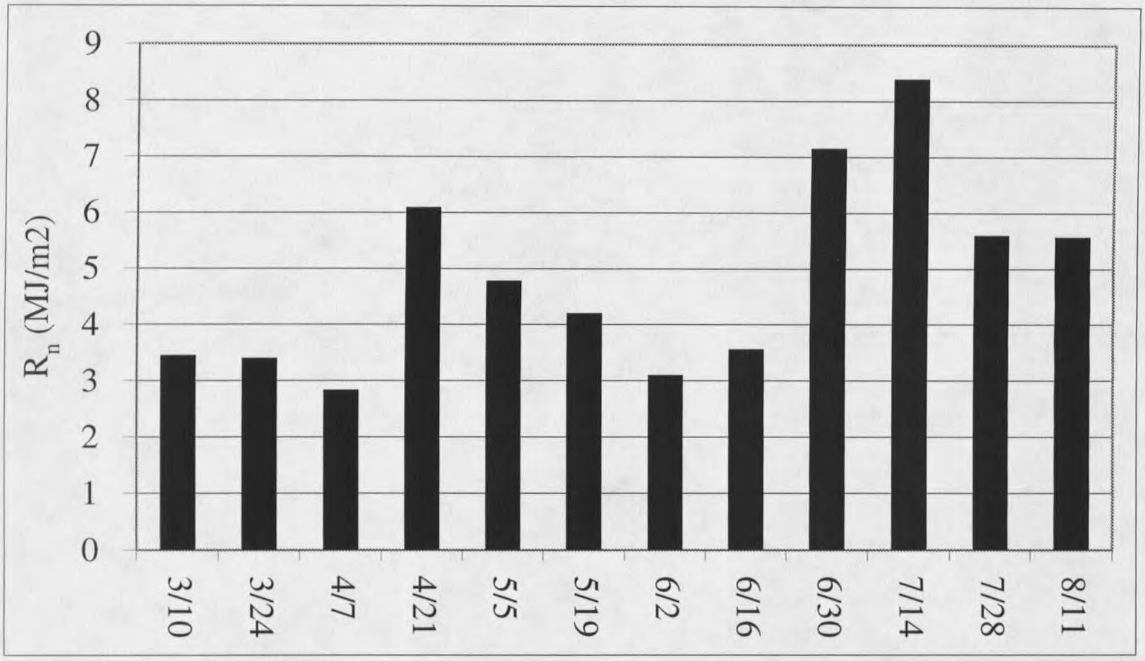

Figure 4.5. Two-week cumulative daily net solar radiation means.

The reliability of the radiometer was checked against solar radiation readings from the Bozeman AgriMet weather station. A linear regression of the two data sets yielded an R^2 of 0.68 and a slope of 0.24. The relatively low R^2 value is likely due to differences in cloud cover between the sites, which are four miles apart. This interception rate (1 - 0.24 = 0.76) was higher than the published value (0.63) for the overhead shade, but may be explained by the condition (dirty) of the overhead shade and the presence of a side shade. Nevertheless, the low values of R_n were of concern. Solar radiation dominates evapotranspiration processes both as available energy and sunlight's affect on plant physiology. Actual evaporation was calculated as the difference between inflow and outflow. Relative error on both inflow and outflow measurements was approximately 0.5 ml/m (0.6 mm/day). The season average of R_n, 5.07 MJ/m^2, was the equivalent of 2.06

mm/day of ET. Thus, ET_c calculations based on the lower R_n values observed in the greenhouse were only an order of magnitude higher than relative error.

Plant Status

Canopy height, foliage density and green leaf fractions were recorded to indicate plant status. Plants had reached maturity the year before and though dead or dormant, developed bulrush and cattail canopies were in place at the beginning of the season. In the first observation of plant status (3/10/98), no actively growing green leaf matter was observed in any cell. The first LAI measurements were taken coincident with the first evidence of new growth. An assumption of no growth was made from 3/10/98 until the first plant status measurements made on 4/29/98. Subsequent measurements were made on 6/10/98 and 8/31/98. All other daily values were interpolated from the measured points. These measurements are reported as a green leaf fraction, leaf area index and green leaf area index. Leaf area index or LAI is the product of the canopy height and foliage density. Green leaf fraction or GLF is the ratio of live plant matter to total plant matter. The green leaf area index or LAIg is the product of the GLF and the leaf area index. LAI, GLF and LAIg are reported as two-week averages in Figures 4.6, 4.7 and 4.8.

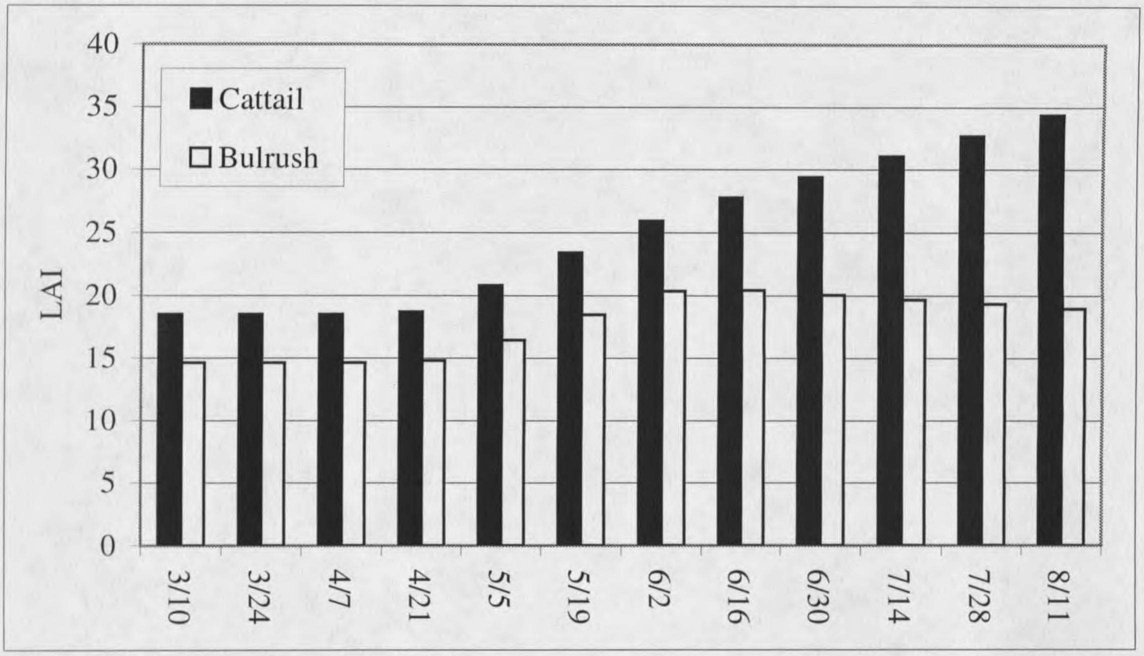

Figure 4.6. Two-week leaf area index means.

LAI increased beginning in April and continued through 6/10/98 for both plant species. While the cattail LAI continued to increase at nearly the same rate throughout the season, the bulrush LAI slightly decreased. The increasing cattail LAI, compared to bulrush values, was likely due to differences in the physical structure of these two plant species. The small, tubular stalks of the bulrush are relatively fragile and prone to collapse upon senescence. Conversely, the cattail stalks are sturdier and support themselves by growing in discreet groups of 6 to 12 leaves. Thus, the cattail stalks were less likely to fall to the bed surface upon senescence. Consequently, the cattail LAI, a measure of leaf area (dead and alive) continued to increase, whereas bulrush LAI decreased as dead matter readily fell to the ground as litter.

Green leaf fractions increased rapidly in the first 14 weeks of the season. Cattail and Bulrush cells reached a maximum GLF of 92% and 77%, respectively. GLF for both species decreased slightly after 6/10/98 to values of 71% and 62%. As an indicator of plant status, these measurements suggest both species reached a peak in growth activity during the first two weeks of June 1998.

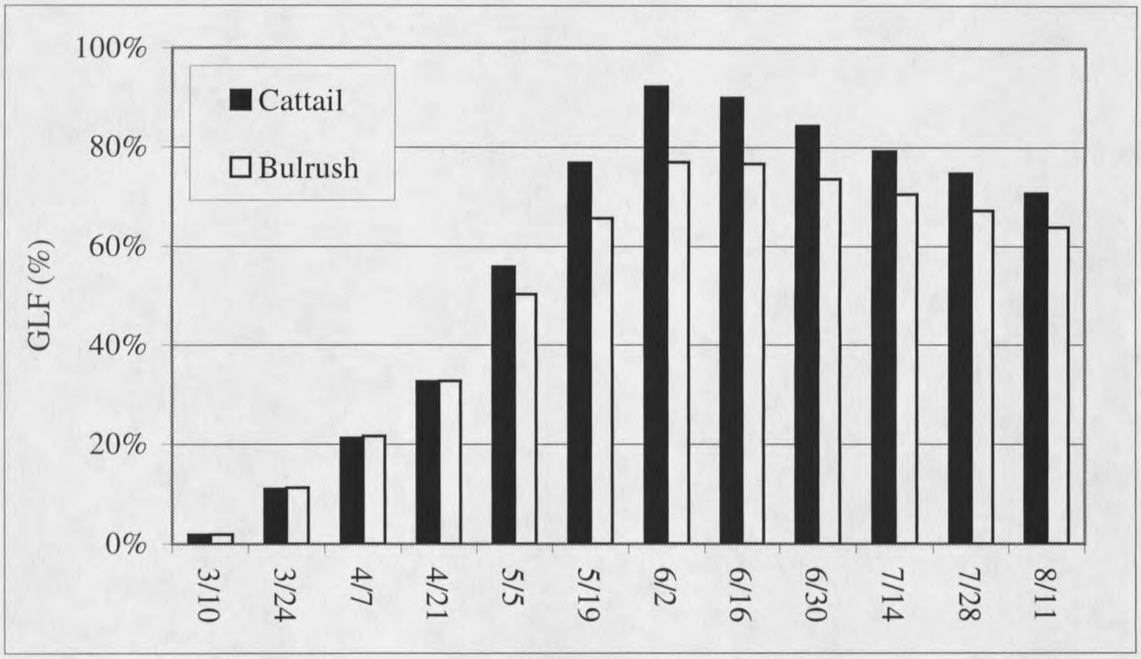

Figure 4.7. Two-week green leaf fraction means.

Taken in conjunction, GLF and LAI measurements yield green leaf area measurements or LAI_g. As an indicator of live plant matter and crop growth it is a good estimate of overall plant status. Figure 4.8 illustrates live plant matter development over the growing season. Cattail LAI_g levels off once maturity is reached while bulrush began a slow process of dying off.

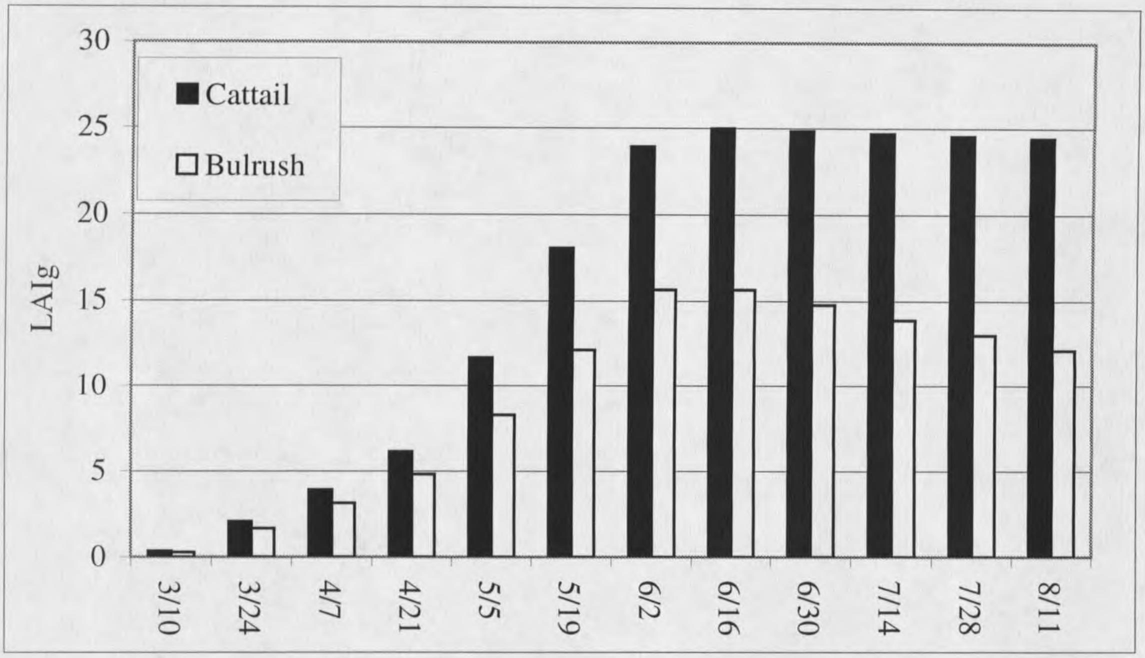

Figure 4.8. Two-week green leaf area index means.

Inflow Rates

Actual evapotranspiration was calculated as the difference between inflow and outflow. The target inflow rate was 30 milliliters per minute. Each time the pump was calibrated, the observed and corrected flow rates were recorded. Inflow rates were interpolated from these observed points to form the basis of average daily inflow rates.

A great deal of variability was observed in the inflow rate. The peristaltic pump settings demonstrated a tendency to wander approximately +/-1.0 ml/min each day. In addition, the inflow rates had a slight dependence on the elevation head in the supply tanks (contrary to the manufacturer's claim that the pump model was head-independent). This variability required frequent re-calibration of the pump to 30 ml/min. To maintain the inflow rate near the design rate, rates were manually calibrated with a stopwatch and graduated cylinder. This was performed 4 times a week, on average. This variability was the largest contributor to the variability in ET_C which necessitated the examination of ET_C on a two-week, instead of a daily, basis.

Outflow Rates

Flush events were the basis for calculating outflow rates. A flush event represents a filling of the volume between the upper and lower sensor rod in the outflow box. This occurred approximately 4 to 12 times per day depending upon inflow rates and the environmental conditions controlling ET. Average hourly outflow rates were calculated for 2 two-week periods; a typical summer period and typical winter period. These rates represent the results of a polynomial regression analysis of outflow rates over each period and are presented for comparision purposes only. Figure 4.9 shows this average hourly outflow rate comparison.

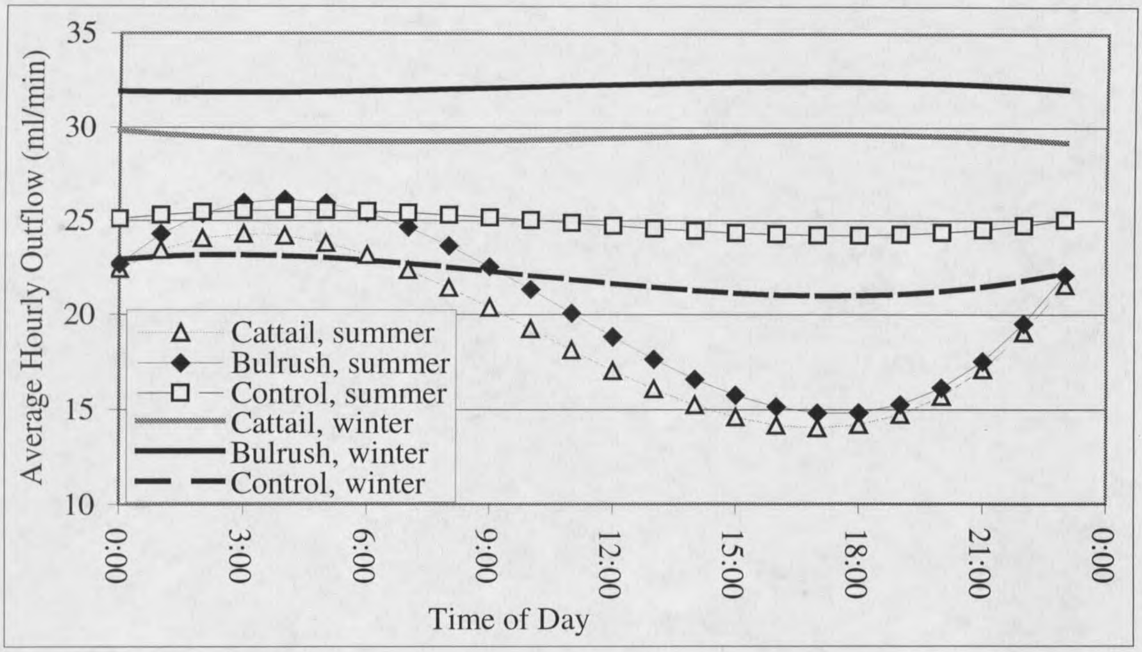

Figure 4.9. Average hourly outflow rates.

Seasonal differences in hourly outflow trends were readily apparent. During the winter period, little hourly variation was observed in the outflow rates in any of the three treatment types. Significant treatment effects persisted through the summer period, however. While little diurnal fluctuation occurred in the unplanted control, cattail and bulrush cells experienced a dramatically reduced outflow rate during the daylight hours. This reduction peaked during the hours of 15:00 to 19:00 when ET rates were greatest. This indicates that plants greatly affect diurnal variations in ET_C. Indeed, these treatment effects suggest that Penman's method may be invalid over periods shorter that 24 hours for this system. To accurately predict ET using this energy based method would necessitate the measurement of Penman's equation inputs at each canopy. Uniform greenhouse approximations of radiation, humidity and air temperature are valid for periods greater than one day only.

Actual Evapotranspiration

Actual ET, or ET_c, rates were calculated as the difference between the inflow and outflow rates. A large degree of variability was seen in daily ET values that could not be accounted for by changes in environmental conditions. This variability was likely due to inaccuracies in inflow measurements as described previously. The resulting inaccuracy prohibited the analysis of the actual ET on a daily basis. Two-week truncated averages (excluding 1 and 100 percentile values) were calculated for the period starting 3/10/98 and ending 8/24/98 and are presented in Figure 4.10.

No data was collected during the two-week period beginning 6/30/98. During the first week of July, the peristaltic pump head assembly failed. Unavailability of replacement parts kept the project offline for most of this period. For consistency in presentation, this entire period has been deleted.

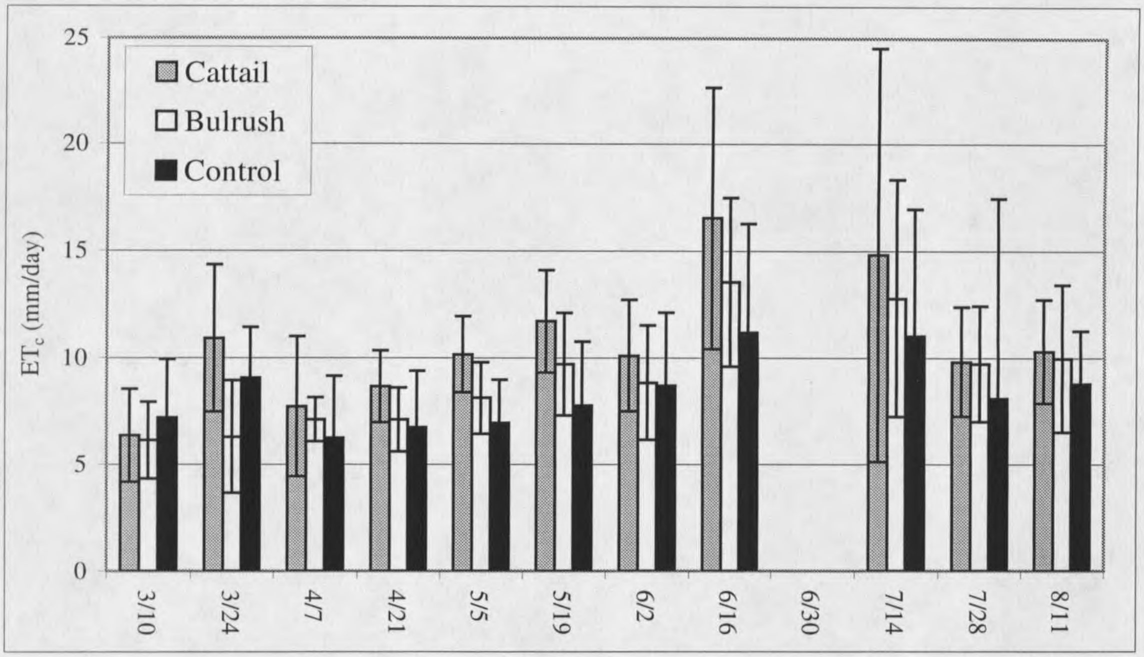

Figure 4.10. Two-week actual ET means in equivalent depth of water (Error bars represent +/- 1 standard deviation in daily ET$_c$ calculations.).

Seasonal trends in ET$_C$ were apparent. At the outset (3/10/98 to 3/23/98), ET$_c$ averaged approximately 6.6 mm/day (5.3 ml/min). Rates increased to an average of 13.8 mm/day (11.1 ml/min) during the period of 6/16/98 to 6/29/98 and then slowly decreased again. Exceptions to this trend did exist, however. Spikes in the ET$_C$ were observed in the period starting 3/24/98 where the average was 8.8 mm/day (7.1 ml/min). No change in environmental conditions can easily account for this increase. The drastic differences in treatments infer a mechanical error, though no evidence of one was found. During the period starting 6/2/98, a decrease in ET$_C$ was observed. Unlike the ET$_C$ values seen in 3/24/98, this break in the season trend may be explained. This two-week period was characterized by a low net solar radiation. In fact, this value was approximately 62% of the seasonal average and contributed to the low ET$_C$ recorded during this period.

Plant/Control Evapotranspiration Ratios

Plant/control evapotranspiration rates illustrate the plant effects on evapotranspiration. These were calculated as the ratio of cattail and bulrush ET_C to the control ET_C for each two-week period. Table 4.1 lists these ratios.

Table 4.1. Average plant/control ET ratios

Treatment		Date†											
		3/10	3/24	4/7	4/21	5/5	5/19	6/2	6/16	6/30	7/14	7/28	8/11
Cattail	ET_c/ET_X	0.88	1.20	1.24	1.29	1.46	1.51	1.16	1.48	††	1.35	1.21	1.17
Bulrush	ET_b/ET_X	0.85	0.70	1.14	1.06	1.17	1.25	1.02	1.21	††	1.16	1.20	1.14

† date represents start of two-week period
†† no data collected.

With the exception of periods 1 and 2, the presence of plants tended to increase the water demands above and beyond that of the saturated gravel bed. The values calculated for period 2 (beginning 3/24/98) are difficult to explain given the difference in the two planted cells. However, the low $ET_{PLANT}/ET_{CONTROL}$ ratio in the initial week may still be a plant effect. As Figure 4.8 illustrates, plant activity in the initial weeks of the season was non-existent. However, a developed, albeit dead, plant was in place in cells 1, 5, 6 and 7 (see Figure 4.6). The presence of dead canopies that were not transpiring may have worked to reduce ET_C rates by shading the underlying gravel bed and thereby reducing available energy for evaporation. Thus, $ET_{PLANT}/ET_{CONTROL}$ ratios would remain less than 1.0.

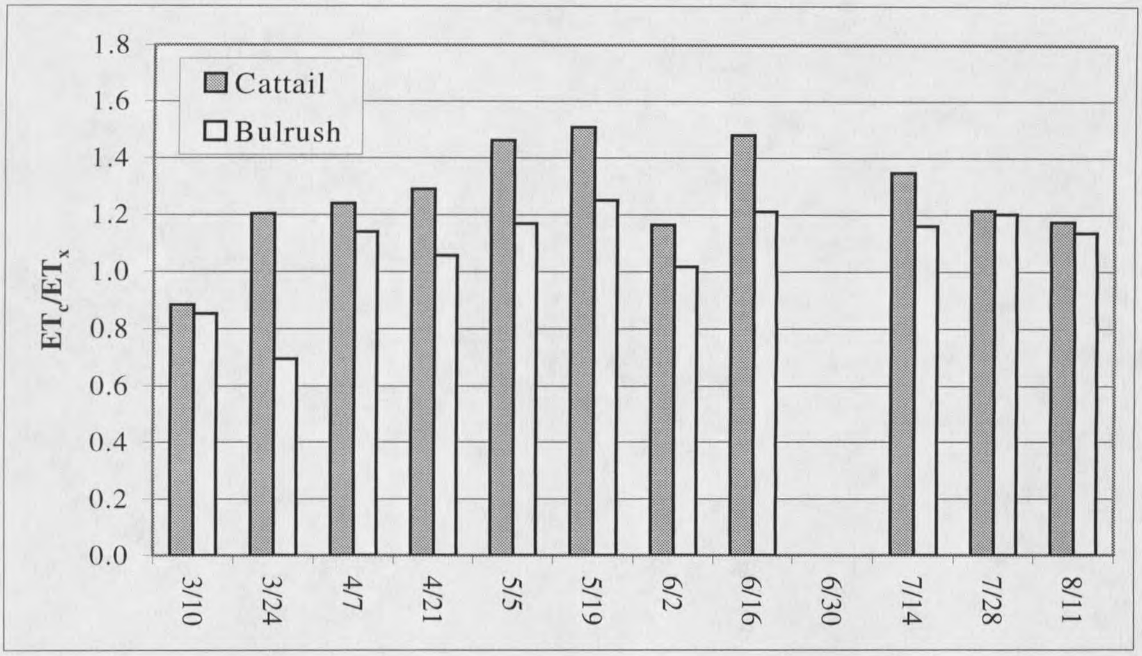

Figure 4.11. Two-week plant/control ET ratios.

Cattail $ET_{PLANT}/ET_{CONTROL}$ ratios were consistently higher than those observed in the bulrush cells. The season averages for $ET_{PLANT}/ET_{CONTROL}$ were 1.27 and 1.08 for cattail and bulrush, respectively. Both values were well within the range reported in a literature review of similar studies. These values are analogous to the Penman's crop coefficient, which is developed in the next section. It is important to note however, that these ratios represent an empirical relationship between a saturated gravel bed (i.e. potential ET) and a vegetated surface (i.e. crop ET). They are not true crop coefficients calibrated to Penman's equation.

Calibration of Penman's Equation

Penman's equation is a combination of energy balance principles and Dalton's Law. As such, its empiricism is based on the sensible heat flux approximation and the mass transfer coefficient in Dalton's Law. The portion of Penman's equation often subject to empirical tuning is referred to as the wind function.

Penman's equation was calibrated to match evaporation observed in the control cell by manipulating the intercept of the wind function. This was based on the assumption that no prevailing wind existed in the greenhouse, thereby reducing *f*(u) to the intercept, a_W. Theoretically, a_W represents that portion of the sensible heat transfer that occurs under zero wind-speed conditions. The following seasonal averages were observed:

Table 4.2. Seasonal means of the dimensionless wind function (*f*(u)).

	Cattail	Bulrush	Control	All Treatments
Mean	2.62	2.25	1.96	2.33
Median	2.38	2.20	1.88	2.23
Standard Deviation	1.41	1.09	1.29	1.01
Minimum	0.07	-0.14	-0.34	0.25
Maximum	8.85	5.56	5.67	7.20

The mean value of *f*(u) was approximately an order of magnitude higher than those reported by Penman (1948, 1963) and others. However, it is important to note that a_W values reported in these studies were a product of a linear regression analysis based on observed wind speeds under field conditions. While the assumption can be made that a linear equation best fits Penman's experimental data, the intercepts in these models were not calculated at a zero wind-speed condition. This may explain the differences in the magnitude of a_W when comparing field studies with this environmentally controlled greenhouse experiment.

Investigation of the Wind Function Distribution

The discrepancy between published values of a_W and experimental data warranted an investigation of the wind function's effect on the magnitude of ET_O calculations. Ideally, *f*(u) is independent of environmental factors other than wind. Based on a zero-wind assumption, *f*(u) reduced to a_W (a constant). A small variability in the experimentally-determined wind function could have been attributed to experimental or mechanical error. However, the true distribution of a_W covered an extensive range. Clearly it was not a constant.

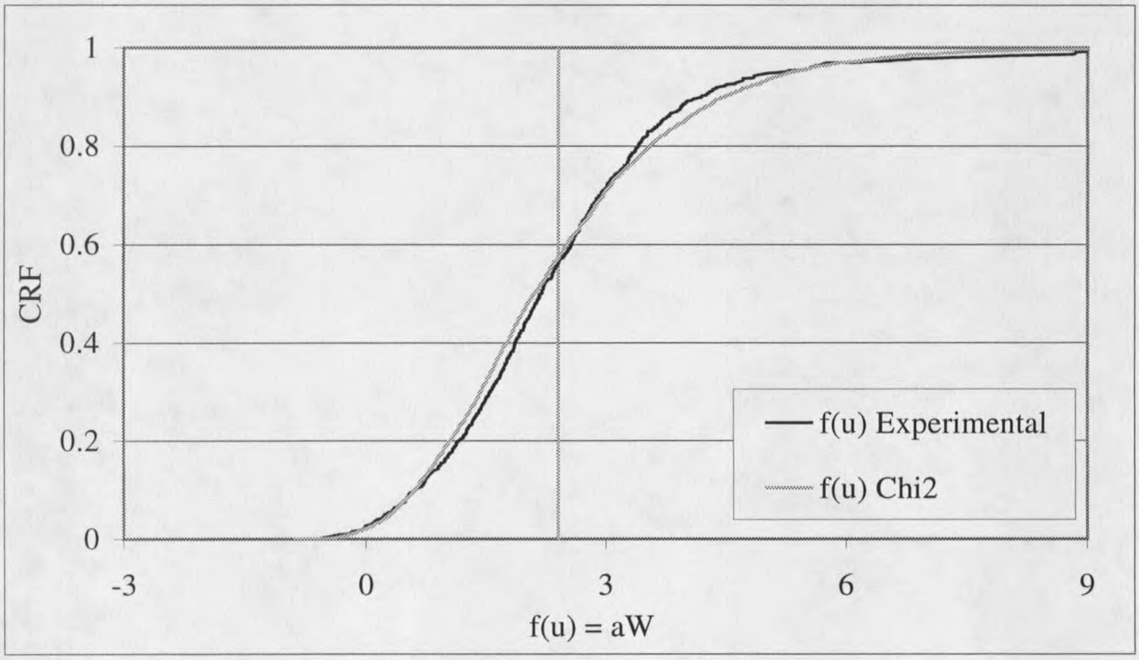

Figure 4.12. Simulated and experimental wind factor distributions.

A Monte Carlo simulation of ET_o was performed using 5000 randomly generated wind function values. The a_W values were based on a chi^2 distribution using the mean and standard deviation observed in the experimental data. The observed distributions are presented in Figure 4.12. The observed *f*(u) was heavily skewed in the positive direction. The maximum value calculated was 5.4 standard deviations above the mean; the minimum fell 1.8 standard deviations below the mean (see Table 4.2).

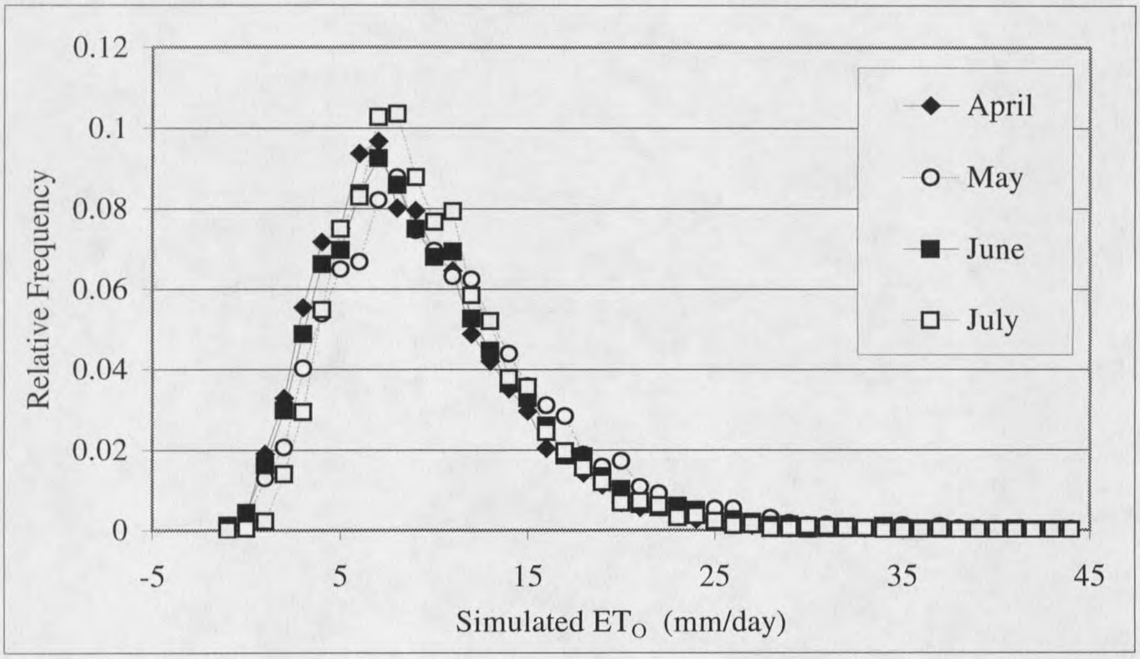

Figure 4.13. Simulated Penman ET$_O$ values based on a Chi^2 distribution of *f*(u).

The chi^2 distributed a$_W$ simulated data set was input into Penman's function to generate 4 sets of simulated ET$_o$ data. The ET$_o$ values were based on the means of radiation, temperature and relative humidity obersevered during April, May, June and July of 1998 as well as the randomly generated *f*(u). The relative frequency distribution of simulated ET$_o$ is presented in Figure 4.13. This clearly indicates not only the variability of *f*(u), but its effect on the magnitude of ET$_o$ calculations. The 5th and 95th percentiles represent a spread of approximately 15 mm/day of ET$_o$. Because of the wind function's effect on ET_o the use of an averaged wind function value may not be justified for use outside this experiment.

Seasonal Variation in the Wind Function

Seasonal variation in the wind factor was observed. Figure 4.14 shows the average values of the wind function for 12 two-week periods.

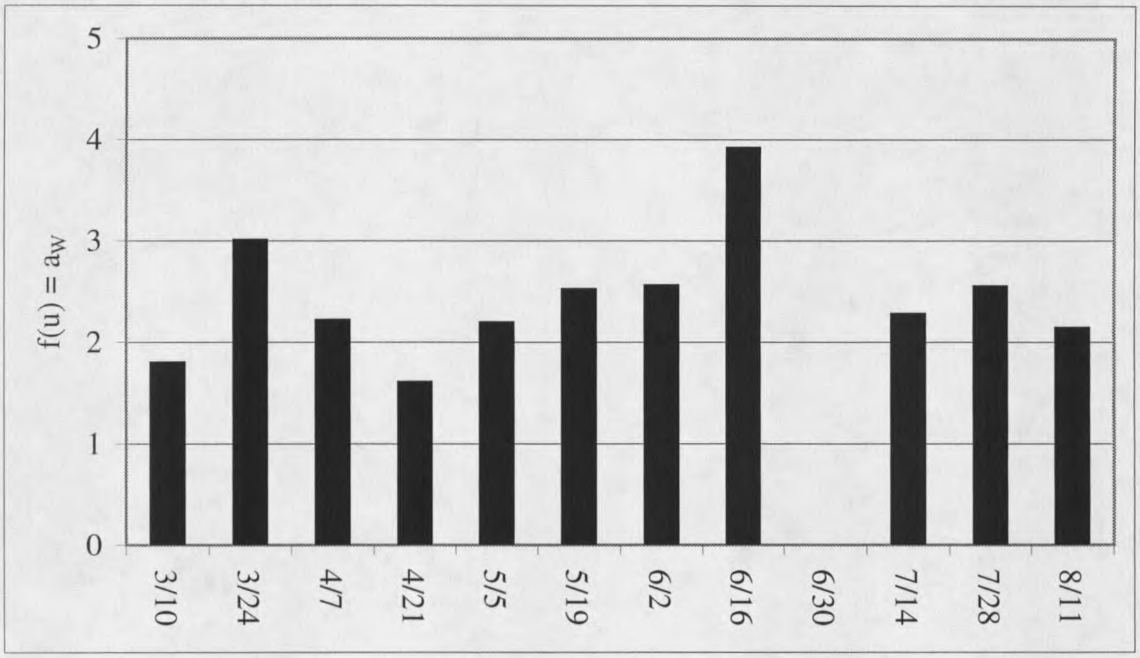

Figure 4.14. Two-week wind factor variations.

The distribution, magnitude and seasonal variation in *f*(u) calculations further suggest that the zero wind assumption was not valid. Wind micro-currents induced by environmental controls in the greenhouse undoubtedly affected ET_C rates and the calculation of a wind function intercept. While it is not possible to gauge the magnitude of such micro-currents, it may be possible to suggest that these elevated wind factors are more than merely a function of an uncalibrated uni-directional wind speed. Using the mean *f*(u), Penman's values for a_W and b_W and back-calculating a wind speed yields 14.7 meter per second. This is obviously higher than the currents produced by the environmental controls in the greenhouse. The differences may be due to an "oasis effect" or "edge effect". Penman's equation, specifically the wind function, was tuned for the evapotranspiration experienced by an extensive crop in response to a uni-directional wind measured at 2 meters above the ground. The constructed wetland cells used in this project are essentially isolated stands exposed to swirling, multi-direction wind micro-currents. Functionally, this means that the plant was exposed to wind on four lateral fronts as well as the top of the canopy, greatly increasing the effect of advective energy.

Wind Response

While the use of daily ET predictions were made inappropriate due to the variability in inflow rates, a higher degree of confidence may be placed in two-week averages. The ET_C values in Figure 4.10 indicate a strong relationship among the three treatment types (cattail, bulrush and control). While some of the variability in inflow, and therefore ET_C, was due to elevation head in the supply tanks, the movement of inflow rates from the design flow was different in each CW cell. If inflow was the cause of poor fit to Penman's equation, variability should have been observed among the treatments as well as across time periods.

This suggests that the inability to fit observed data to Penman's equation is not due, in large part, to the inaccuracies in inflow. The wind function, in fact, may be the likely source of error. The assumption that no significant wind occurred in the greenhouse was incorrect. This assumption was made during the previous season when summer temperatures in the greenhouse were not controlled. During 1998, however, temperatures in the greenhouse were raised in discreet steps to facilitate the kinetic modeling of CW treatment performance. As a result, environmental controls were constantly active. Air movement within the greenhouse was increased due to an average difference between greenhouse and outside temperature in excess of 5 °C. The agreement between treatment types in wind function calculations suggests they were all subject to a similar undetermined environmental condition (i.e. advection).

Potential Evapotranspiration

Potential evapotranspiration or ET_O was calculated using the temperature, net solar radiation and relative humidity readings taken in the greenhouse. Figure 4.15 documents these ET_O values in equivalent flow rate.

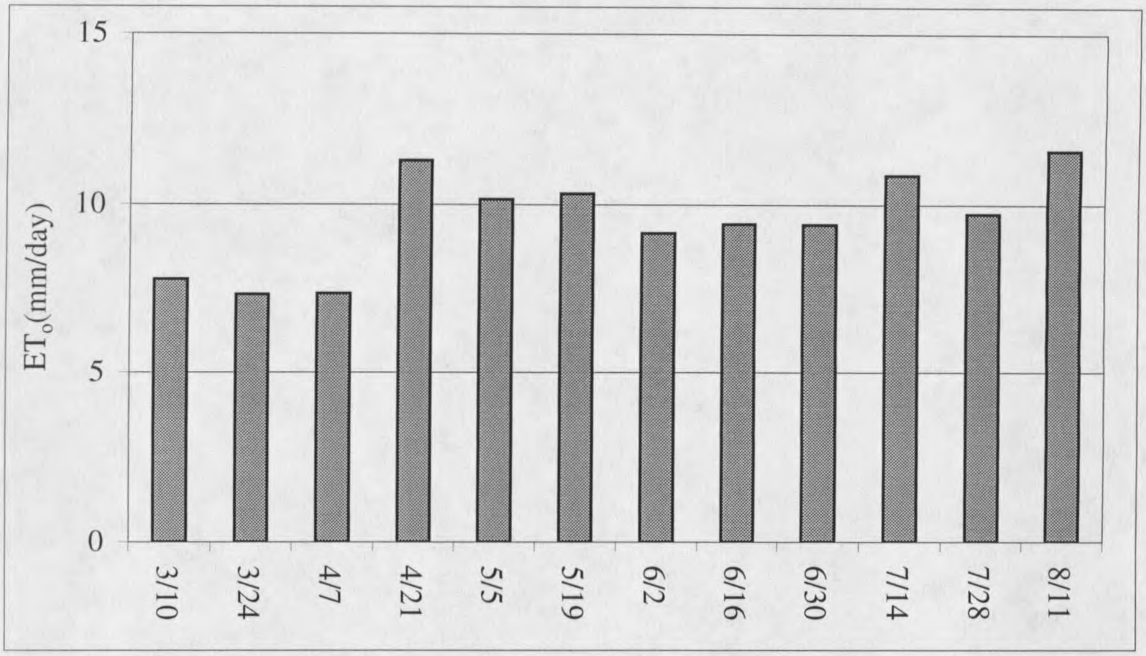

Figure 4.15. Two-week potential ET means in equivalent depth of water.

Potential ET was calculated on a daily basis and averaged over a two-week period. The second term of Penman's equation was calibrated using the mean wind function value (*f*(u) = 2.33) described in the previous section. Taken as a seasonal average, the Penman's equation produced results within 2.5% of the actual ET. On a bi-weekly basis, however, Penman's equation yielded poor results. In particular, the ET_O calculation for the period beginning 6/16/98 was 36.8% less than the measured actual crop ET. This was the extreme case, however.

Crop Coefficients

ET_C/ET_O ratios measured at any plant stage are referred to as basal crop coefficients. The basal crop coefficients, K_b, listed in Table 4.3 were specifically calibrated to the Penman equation variant outlined in this text.

Table 4.3. Penman's basal crop coefficients, K_b

Treatment		Date†											
		3/10	3/24	4/7	4/21	5/5	5/19	6/2	6/16	6/30	7/14	7/28	8/11
Cattail	K_b	0.88	1.62	1.13	0.83	1.09	1.23	1.20	1.90	††	1.47	1.09	0.96
	SD‡	0.30	0.76	0.70	0.18	0.26	0.21	0.34	0.79	-	1.08	0.29	0.31
Bulrush	K_b	0.86	0.93	1.04	0.68	0.87	1.02	1.05	1.55	††	1.28	1.08	0.93
	SD‡	0.29	0.45	0.35	0.17	0.28	0.33	0.34	0.78	-	0.63	0.29	0.37

‡ standard deviation of daily K_b calculations during two-week period.
† date represents start of two-week period
†† no data collected.

Penman's equation predicts potential evapotranspiration, which by definition, does not account for plant growth stage. Ideally, K_b values should near 1.0 at the beginning of the season (in a saturated bed), change sharply as the crop develops and level off as the plant reaches maturity. The crop coefficient, K_c, is not a function of plant stage, but is defined as K_b at that point in the curve when the plant has reached maturity. K_c can be greater or less than 1.0 depending upon the plant species.

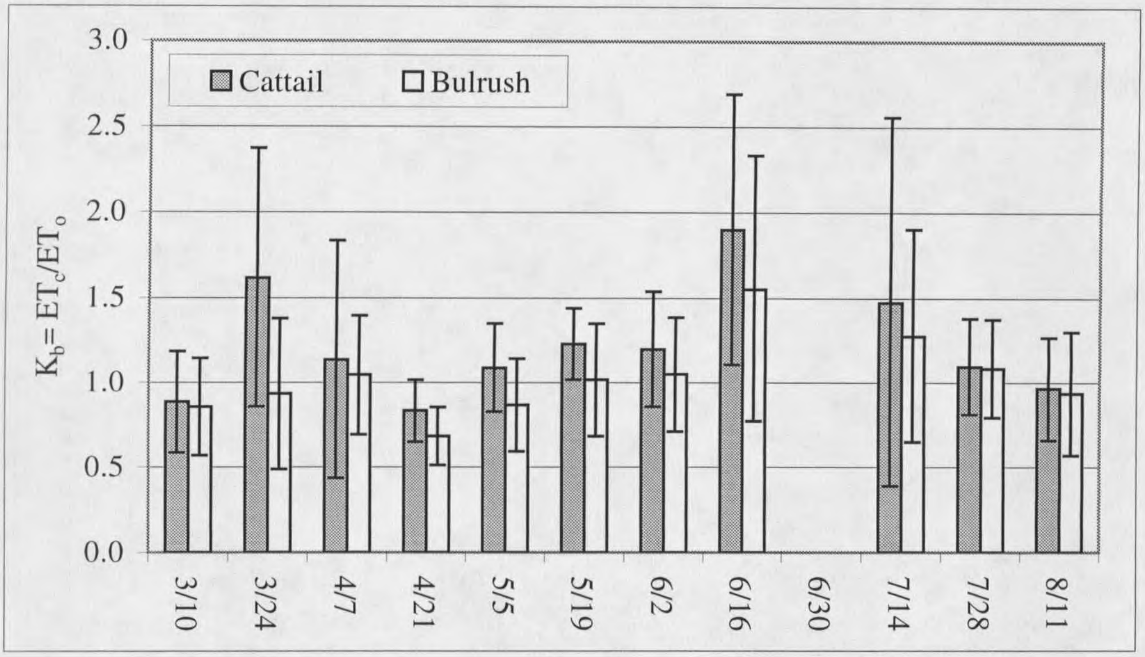

Figure 4.16. Calculated Penman's crop coefficient. (Error bars represent +/- 1 standard deviation in daily K_b calculations.)

While the results of this experiment agreed with similar studies in suggesting a crop coefficient in excess of 1.0, the seasonal progression of K_b was erratic. That part of the season where plants had reached maturity (6/2/98 to 8/11/98) was identified using plant status measurements. During this time, K_b varied from 1.90 to 0.96 for cattail and 1.55 to 0.93 for bulrush. This made the approximation of K_c difficult. Overall, an examination of the basal crop coefficient trend in Figure 4.16 revealed a gradual increase from values slightly less than 1.0 to a peak of less than 2.0 observed in the period beginning 6/16/98. These values coincided with the largest values of green leaf area index (LAI_g) suggesting maturity in both hydrophytes. Peak crop coefficients, K_c, of 1.90 and 1.55 for cattail and bulrush, respectively, are indicated.

Application of Penman's Crop Coefficient

While the accuracy of fitting potential evapotranspiration calculations to measured ET_C was poor, the effect of wetland hydrophytes on evapotranspiration was clear. The use of a crop coefficient greater than 1.0 for both hard-stem bulrush and broad-leaf cattail was warranted. However, the use of the peak K_C values was not justified as they were observed only briefly. Taken in context with the K_b values seen throughout the season, plant status dependent ET_C/ET_O ratios of smaller magnitude may be more appropriate.

A suitable method for the construction of a basal crop coefficient curve is outlined in Dorenboss and Pruitt (1993). An important consideration in the application of this method is the issue of water availability. While the technique presented by Dorenboss and Pruitt (1993) is for an irrigated crop, which may be water stressed at points throughout the season, the wetland cells in this experiment were saturated throughout the year. Thus, no account of soil moisture was necessary. However, naturally occurring wetland plants may experience periods of limited water availability and under these circumstances, adjustments in the crop coefficients may be necessary. Dorenboss and Pruitt (1993) partition the crop coefficient curve into four discrete sub-seasons that are defined by certain plant indicators. In this experiment, green leaf fractions and LAIg were used in lieu of the indicators Dorenboss and Pruitt (1993) suggest (ground cover and other more qualitative plant status measurements). The initial stage is defined as that point early in the season when ground cover is less than 10%. Dead or dormant bulrush and cattail plants were in place at the start of the season making ground cover a meaningless parameter. An analogy was made to green leaf fractions as an indicator of this stage. A GLF of approximately 20% was used. This coincided with the start of rapid development of both species in mid-April 1998. The crop development stage is defined as starting at the end of the initial stage and continuing until full effective ground cover is reached. LAIg values peaked during the periods of 6/2/98 and 6/16/98 for bulrush and cattail, respectively. The boundary between mid-season and late season stages is indicated by a discoloration in the crop. Discoloration of the wetland plants, a decreased LAIg and lower ET_C rates were used to identify this point. It is important to note that some approximation was made to continue this curve through the end of the season. While the collection of data ceased in August of 1998, it seemed reasonable that ET_C rates and plant status measurements would return to those values recorded in March of 1998. Therefore the slope of the late season stage was chosen such that crop coefficients values at the end of the season were equal to those at the start of the season. The crop coefficient curves presented in Figures 4.17 and 4.18 may prove useful to the practitioner. It is strongly urged that the conditions under which this Penman-calibrated K_c was derived be well understood before applying it to other situations.

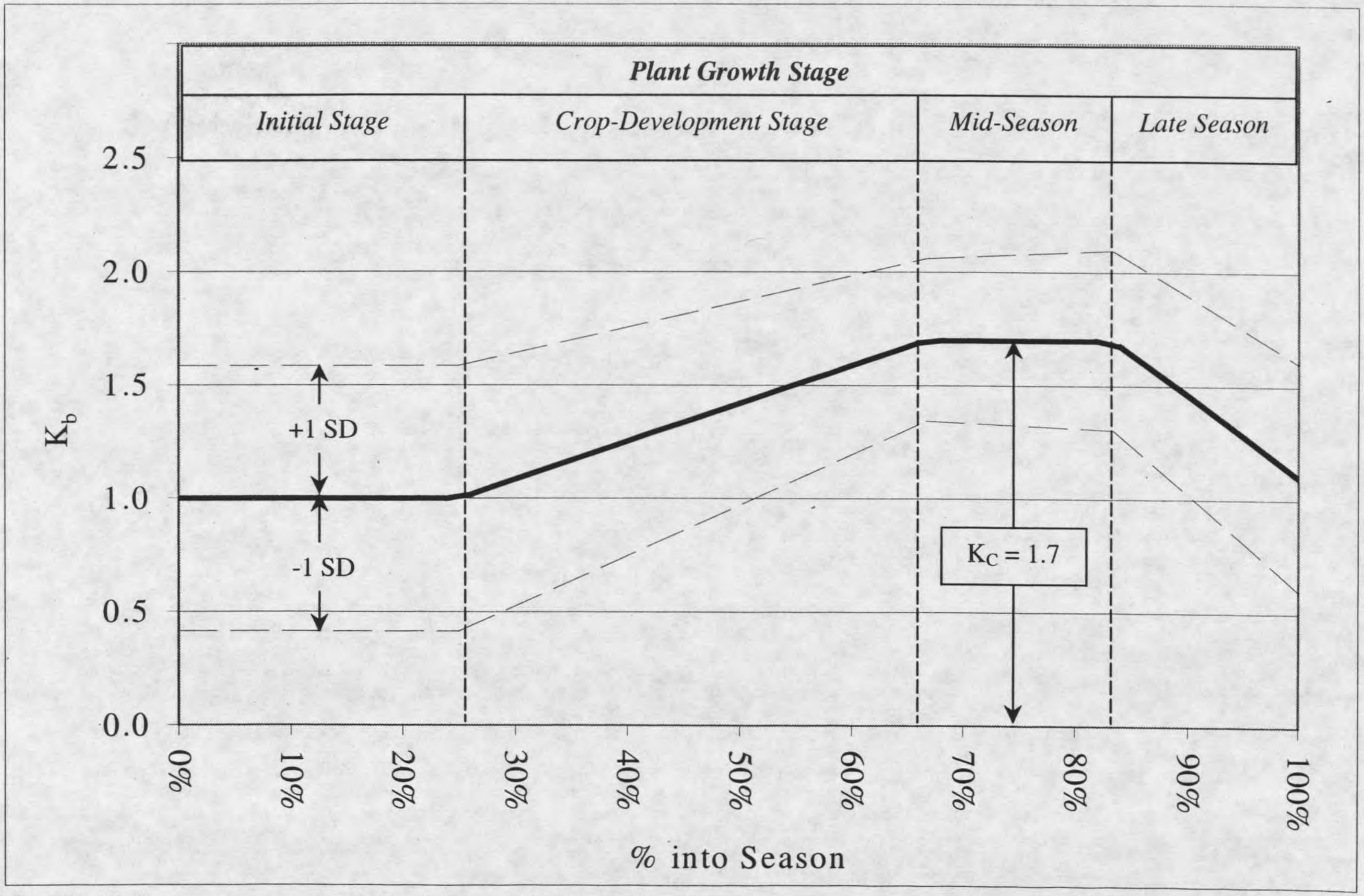

Figure 4.17. Penman's crop coefficient for broad-leaf cattail.

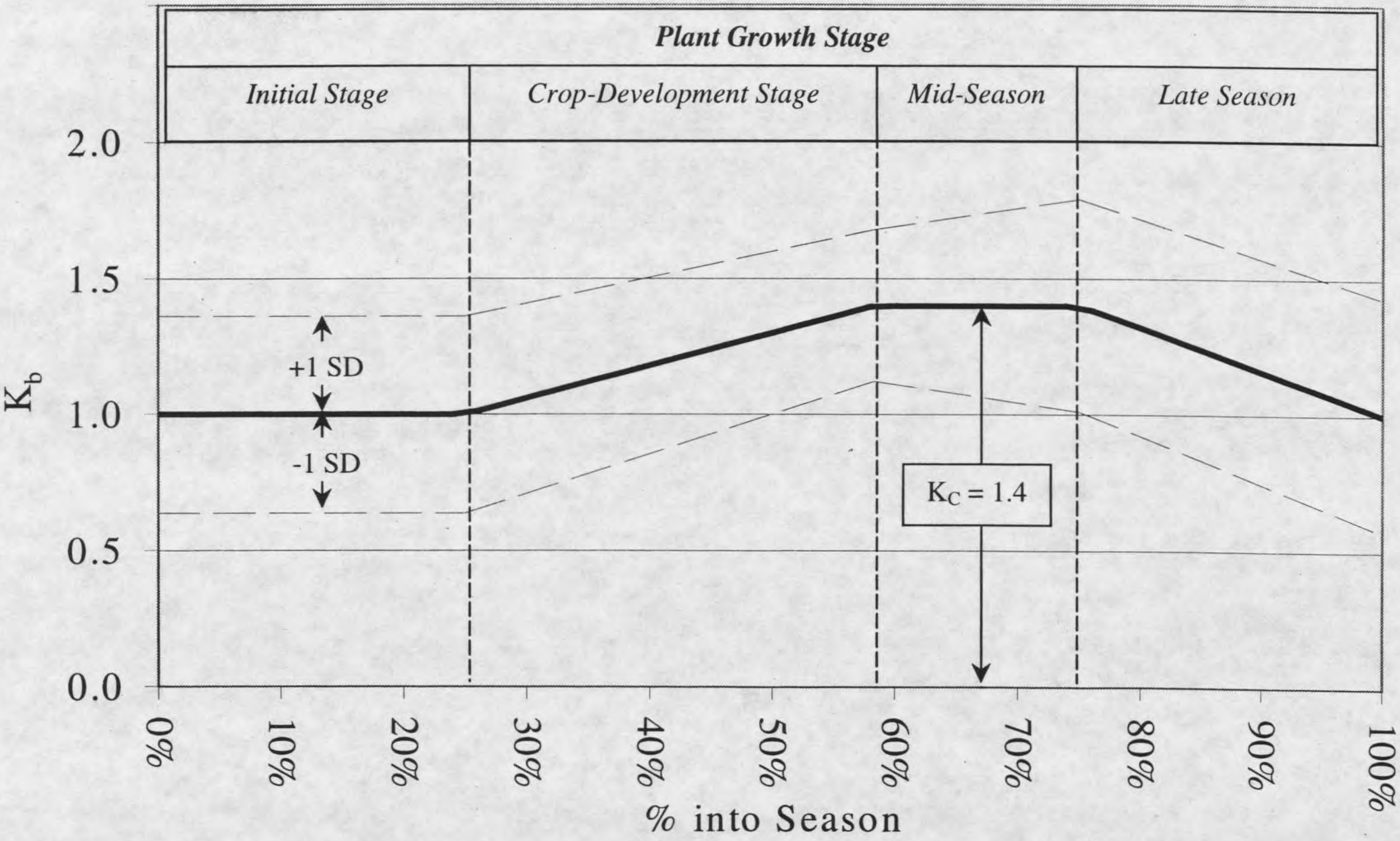

Figure 4.18. Penman's crop coefficient for hard-stem bulrush.

5.0 SUMMARY

Results of this study demonstrated a clear relationship between environmental factors and evapotranspiration. Diurnal observations of soil temperature documented the differences between ET_C in a saturated gravel bed and those cells planted with cattail and bulrush. During the daylight hours, sharper temperature decreases were observed in the planted cells indicating a higher rate of latent heat flux. During darkness, slightly higher temperatures were maintained in the planted cells possibly demonstrating a decreased sensible heat loss due the insulating effects of plant canopies. The effect of latent heat flux was seen in two-week averages of soil temperature, as well. Temperature in the unplanted control cell was consistently higher than the values recorded in the cattail and bulrush treatments. The effect of net solar radiation on the system was less obvious, although decreases in cumulative daily net solar radiation during the first week of June 1998 corresponded to a sharp drop in actual ET. Despite ET's theoretical dependence on vapor pressure deficit, no clear relationship between ET_C and relative humidity measurements could be inferred.

Measurements of plant status proved useful in identifying the maturity of the wetland plants. Foliage density and green leaf fraction were explicitly measured and used to calculate green leaf area indices. Green leaf area index, a ratio of live plant matter surface area over the projected area of the canopy, was then used in conjunction with ET_C/ET_O ratios to define K_C for both species.

Calibration of Penman's equation (ET_O) to control ET_C was performed by adjusting the empirical wind function. Daily ET_O calculations poorly matched ET_C due largely to the errors produced by variability in influent rates and an unquantified advective loss. Pump inaccuracies prohibited the examination of ET_C on a daily basis. Furthermore, the assumption that the wind function reduced to a constant, a_W, in the absence of a prevailing wind was inaccurate. In fact, wind micro-currents, created by the environmental controls in the Plant Growth Center, produced an advective loss similar to the prevailing wind term in Penman's original equation. Despite these problems, examining ET means on a two-week basis proved insightful. The seasonal trend of evapotranspiration progressed as expected. During the winter months (e.g. March, April), plant effects were negligible and ET_C rates in all the treatment types were low. As the season continued, ET_C rates increased and plant effects became clear. Both species (cattail and bulrush) exhibited higher ET_C rates than the unplanted control and cattail cells consistently recorded higher losses than the bulrush cells. After peak losses were observed in June, ET_C rates slowly decreased until the termination of the project in late August.

The ratios of control ET_C to plant ET_C exceeded 1.0 throughout much of the growing season. This supported the use of a crop coefficient greater than 1.0. A crop coefficient curve was constructed for both plant species (cattail and bulrush) based on the peak observed Kc values and plants growth status measurements. The development of these curves was based on the method presented by Dorenbos and Pruitt (1977) and may prove useful to the practitioner. It is strongly urged that the conditions under which this Penman-calibrated K_c was derived be well understood before applying it to other situations.

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APPENDICES

APPENDIX A

VISUAL BASIC DATA SORTING PROGRAMS

```
'Wetland Add-In v4.0
'  written 4/20/98 by B. W. Towler
'  updated 10/2/98

'This routine handles all CAL sorting
routines
Sub Calibration()
  'Opening Dialog box.  Asks if you want to
continue
  MsgA = "Do you want to run the
calibration" & Chr(13)
  MsgB = "data sorting routines?" & Chr(13)
& Chr(13) + "Press OK to begin." + Chr(13)
  MsgC = MsgA & MsgB
  Style = vbOKCancel + vbInformation +
vbDefaultButton2
  Title = "Calibration data sorting program"
  Help = "DEMO.HLP"
  Ctxt = 1000
  Response = MsgBox(MsgC, Style, Title,
Help, Ctxt)
  If Response = vbOK Then
    Application.ScreenUpdating = False
    Call InflowRecord
    Call InflowMeans
    Application.ScreenUpdating = True
  End If
  End
End Sub

Sub InflowMeans()
  'Declarations
  Dim RowEl, i, j, k, iMax, jMax, BackCount,
cell As Integer
  Dim RecordDate(500), RecordFlow(6,
500), RecordDateMin, RecordDateMax As
Single
  Dim MeanFlow(6, 200), MeanIndex(200)
As Single
  Dim MeanDate(200) As Integer
  'Suspend screen updating
  Application.ScreenUpdating = False
  'Set variables
  RowEl = 4
  i = 0
  'Read Loop from calibration sheet
  Do Until
Worksheets("Record").Cells(RowEl + 1, 1) =
""
    'Index of row on calibration sheet
    RowEl = RowEl + 1
    'Index of variables
    i = i + 1
    'Determines maximum value for i
    If i > iMax Then
      iMax = i
    End If
    'Determines staring, ending dates for
report
    If RecordDate(i) < RecordDateMin
Then
      RecordDateMin = Int(RecordDate(i))
    End If
    If RecordDate(i) > RecordDateMax
Then
      RecordDateMax = Int(RecordDate(i))
+ 1
    End If
    'Records date
    RecordDate(i) =
Worksheets("Record").Cells(RowEl, 1)
    'Records both observed flow and
calibrated flow
    For cell = 1 To 6
      RecordFlow(cell, i) =
Worksheets("Record").Cells(RowEl, (cell +
1))
    Next cell
  Loop
  j = 0
  jMax = 0
  'Calc means loop
  For i = 1 To iMax
    If RecordDate(i) - Int(RecordDate(i)) <
0.0001 Then
      j = j + 1
      MeanDate(j) = RecordDate(i)
      MeanIndex(j) = i
      BackCount = MeanIndex(j) -
MeanIndex(j - 1)
      For cell = 1 To 6
        For k = 1 To BackCount
          MeanFlow(cell, j) =
MeanFlow(cell, j) + RecordFlow(cell, i - k +
1) * (RecordDate(i - k + 1) - RecordDate(i -
k))
        Next k
        MeanFlow(cell, j) =
MeanFlow(cell, j) / (MeanDate(j) -
MeanDate(j - 1))
      Next cell
      If j > jMax Then jMax = j
    End If
  Next i
  'Write Loop
  RowEl = 5
  For j = 1 To jMax
```

```
      Worksheets("Means").Cells(RowEl,
1).Value = MeanDate(j)
      For cell = 1 To 6
         Worksheets("Means").Cells(RowEl,
1 + cell).Value = MeanFlow(cell, j)
      Next cell
      RowEl = RowEl + 1
   Next j
   ’Labels Sheet
   With Worksheets("Means")
      .Range("A1") = "Mean Daily Inflow"
      .Range("B2") = "Means calculated
using Reimann Sums from Record sheet."
      .Range("A4") = "Date"
      .Range("b4") = "Cell 1"
      .Range("c4") = "Cell 3"
      .Range("d4") = "Cell 5"
      .Range("e4") = "Cell 6"
      .Range("f4") = "Cell 7"
      .Range("g4") = "Cell 8"
   End With
   Application.ScreenUpdating = True
End Sub

Sub InflowRecord()
   ’Declarations
   Dim ObsFlow(6, 100), FlowDate(100),
CalFlow(6, 100) As Single
   Dim RowEl, i As Integer
   Dim FlowDateMin, FlowDateMax As
Integer
   Dim MeanDate As Integer
   Dim MeanDate_ll, MeanDate_ul As Single
   Dim MeanFlow(6), MeanFlow_ll(6),
MeanFlow_ul(6) As Single
   ’Suspend screen updating
   Application.ScreenUpdating = False
   ’Set variables
   FlowDateMin = 366
   FlowDateMax = 0
   iMax = 0
   ’Read Loop from calibration sheet
   RowEl = 5
   i = 0
   Do Until
Worksheets("Calibration").Cells(RowEl, 1) =
""
      ’Index of row on calibration sheet
      RowEl = RowEl + 1
      ’Index of variables
      i = i + 1
      ’Determines maximum value for i
      If i > iMax Then
         iMax = i
      End If
      FlowDate(i) =
Worksheets("Calibration").Cells(RowEl, 3)
      ’Determines staring, ending dates for
report
      If FlowDate(i) < FlowDateMin Then
         FlowDateMin = Int(FlowDate(i))
      End If
      If FlowDate(i) > FlowDateMax Then
         FlowDateMax = Int(FlowDate(i)) + 1
      End If
      ’Records both observed flow and
calibrated flow
      For cell = 1 To 6
         ObsFlow(cell, i) =
Worksheets("Calibration").Cells(RowEl, (cell
* 2 + 2))
         CalFlow(cell, i) =
Worksheets("Calibration").Cells(RowEl, (cell
* 2 + 3))
      Next cell
   Loop
   ’Write Loop
   RowEl = 5
   i = 0
   ’writes interpolated values for each day in
record (midnight -start of day)
   For i = 1 To iMax
      If Int(FlowDate(i)) < Int(FlowDate(i + 1))
Then
         DayCount = Int(FlowDate(i + 1)) -
Int(FlowDate(i))
         For n = 1 To DayCount
            MeanDate = Int(FlowDate(i)) + n
            MeanDate_ll = FlowDate(i)
            MeanDate_ul = FlowDate(i + 1)
            For cell = 1 To 6
               MeanFlow_ll(cell) =
CalFlow(cell, i)
               MeanFlow_ul(cell) =
ObsFlow(cell, i + 1)
               MeanFlow(cell) =
((MeanFlow_ul(cell) - MeanFlow_ll(cell)) /
(MeanDate_ul - MeanDate_ll)) * (MeanDate
- MeanDate_ll) + MeanFlow_ll(cell)
            Next cell
            ’Write output to Record Sheet

Worksheets("Record").Cells(RowEl,
1).Value = MeanDate
            For cell = 1 To 6

Worksheets("Record").Cells(RowEl, 1 +
cell).Value = MeanFlow(cell)
```

```
        Next cell
        RowEl = RowEl + 1
      Next n
    End If
  Next i
  'writes original observations/calibrations
onto record sheet
  For i = 1 To iMax - 1
    Worksheets("Record").Cells(RowEl,
1).Value = FlowDate(i)
    For cell = 1 To 6
      Worksheets("Record").Cells(RowEl,
1 + cell).Value = ObsFlow(cell, i)
    Next cell
    RowEl = RowEl + 1
    Worksheets("Record").Cells(RowEl,
1).Value = FlowDate(i) + 0.01
    For cell = 1 To 6
      Worksheets("Record").Cells(RowEl,
1 + cell).Value = CalFlow(cell, i)
    Next cell
    RowEl = RowEl + 1
  Next i
  'Sorts record into decending order
  Range("A5:G1000").Select
  Selection.Sort Key1:=Range("A5"),
Order1:=xlAscending, Header:=xlNo, _
    OrderCustom:=1, MatchCase:=False,
Orientation:=xlTopToBottom
  'Labels Sheet
  With Worksheets("Record")
    .Range("A1") = "Record of Inflow"
    .Range("B2") = "Whole date values
interpolated from calibration data."
    .Range("A4") = "Date"
    .Range("b4") = "Cell 1"
    .Range("c4") = "Cell 3"
    .Range("d4") = "Cell 5"
    .Range("e4") = "Cell 6"
    .Range("f4") = "Cell 7"
    .Range("g4") = "Cell 8"
  End With
  Application.ScreenUpdating = True
End Sub


'Wetland Add-In v4.0
'  written 4/20/98 by B. W. Towler
'  updated 10/2/98
'This code reads the settings and installs the
Wetland Data
'menu bar which will call the TF, RH, CAL
routines.
```

```
'Declare settings variables as Public
Public cell1VolumeVar As Single
Public cell3VolumeVar As Single
Public cell5VolumeVar As Single
Public cell6VolumeVar As Single
Public cell7VolumeVar As Single
Public cell8VolumeVar As Single
Public volume(8) As Single
Public posCalVar As Single
Public negCalVar As Single
Public Neg0Flag As Boolean
Public AutoRRFlag As Boolean
Public AutoTFFlag As Boolean

'This routine conditionally loads menu &
reads settings
'Placed in the XLSTART directory, it will
automatically load
Sub Auto_Open()
  'Declare decision variables for Wetland
menu
  Dim WetlandBarVar As Boolean
  Dim WetlandAddInVar As Boolean
  Dim addinVar As AddIn
  'Set inital conditions (assumptions) for
Wetland menu
  WetlandBarVar = False
  WetlandAddInVar = False
  'Read settings for cell volumes &
calibration
  Call ReadSettingsFile
  If Neg0Flag = True Then
    SettingsForm.Neg0Box.Value = -1
  Else
    SettingsForm.Neg0Box.Value = 0
  End If
  If AutoRRFlag = True Then
    SettingsForm.AutoRRBox.Value = -1
  Else
    SettingsForm.AutoRRBox.Value = 0
  End If
  If AutoTFFlag = True Then
    SettingsForm.AutoTFBox.Value = -1
  Else
    SettingsForm.AutoTFBox.Value = 0
  End If
  'Check if menu is loaded
  For Each Bar In
CommandBars("worksheet menu
bar").Controls
    If Bar.Caption = "&Wetlands" Then
WetlandBarVar = True
  Next Bar
  'Check if Add-In is loaded
```

```
   For Each addinVar In Application.AddIns
      If UCase(addinVar.Name) =
UCase("Wetlands v40.xla") Then
         On Error Resume Next   ’Ignores
error if Wetland not in Add-In dialog Box
            If AddIns("Wetlands Add-In
v4.0").Installed = True Then
               WetlandAddInVar = True
            End If
      End If
   Next
   ’If menu is loaded but not addin, delete
menu
   If WetlandBarVar = True And
WetlandAddInVar = False Then
      Call deleteWetlandMenu
   End If
   ’If addin is loaded but not menu, load
menu
   If WetlandBarVar = False And
WetlandAddInVar = True Then
      Call installWetlandMenu
   End If
End Sub

Sub installWetlandMenu()
   On Error Resume Next

   Dim newpopup As Object
   Dim CB As CommandBar
   Dim CBControl As CommandBarControl
   Dim CBControlType As String
   Dim rowl, Position As Integer

   ’Determines Position of "&Data" popup
   rowl = 1
   For Each CBControl In
Application.CommandBars("worksheet
menu bar").Controls
      CBControlType =
TypeName(CBControl)
      If CBControlType =
"CommandBarPopup" Then
         If CBControl.Caption = "&Data" Then
Position = CBControl.Index
      End If
      rowl = rowl + 1
   Next CBControl

   Set newpopup =
Application.CommandBars("Worksheet
Menu Bar") _
      .Controls.Add(msoControlPopup, , ,
Position + 1, False)
```

```
   With newpopup
      .Caption = "&Wetlands"
      With .Controls
         ’Temp and Flow Suite (runs all TF
programs)
         With .Add(msoControlButton, 186)
            .Caption = "Temp and Flow suite"
            .OnAction = "Sort_TF"
         End With
         ’Individual Temp and Flow macros
         With .Add(msoControlPopup)
            .Caption = "TF Macros"
            With .Controls
               With .Add(msoControlButton)
                  .Caption = "1. Sort Temp and
Flow Data"
                  .OnAction =
"TempFlowDataSort"
               End With
               With .Add(msoControlButton)
                  .Caption = "2. Partition Flow
Data"
                  .OnAction = "FlowPartition"
               End With
               With .Add(msoControlButton)
                  .Caption = "3. Organize
Hourly Flow Data"
                  .OnAction = "FlowHourly"
               End With
               With .Add(msoControlButton)
                  .Caption = "4. Summarize
T&emperature Data"
                  .OnAction =
"TempSummary2 "
               End With
               With .Add(msoControlButton)
                  .Caption = "5. Summarize
&Flow Data by Cell"
                  .OnAction =
"FlowSummary2"
               End With
               With .Add(msoControlButton)
                  .Caption = "6. Summarize
&Flow Data by Day"
                  .OnAction =
"FlowSummary3"
               End With
            End With
         End With
         ’Radiation and RH Suite (runs all
RH programs)
         With .Add(msoControlButton, 186)
            .Caption = "Rn and RH suite"
```

```
         .OnAction = "Sort_RH"
         .BeginGroup = True
      End With
      'Individual Radiation and RH macros
      With .Add(msoControlPopup)
         .Caption = "RH Macros"
         With .Controls
            With .Add(msoControlButton)
               .Caption = "1. Sort RnRh
Data"
               .OnAction = "RnRhDataSort"
            End With
            With .Add(msoControlButton)
               .Caption = "2. Calibrate Rn
values"
               .OnAction = "RnCalc"
            End With
            With .Add(msoControlButton)
               .Caption = "3. Summarize
R&aditation"
               .OnAction = "RnSummary2"
            End With
            With .Add(msoControlButton)
               .Caption = "4. Summarize
Relative &Humidity"
               .OnAction = "RhSummary2"
            End With
         End With
      End With
      'Calibration suite
      With .Add(msoControlButton, 186)
         .Caption = "Calibration suite"
         .OnAction = "Calibration"
         .BeginGroup = True
      End With
      'Inflow macros
      With .Add(msoControlPopup)
         .Caption = "CAL Macros"
         With .Controls
            With .Add(msoControlButton)
               .Caption = "1. Inflow
&Record"
               .OnAction = "InflowRecord"
            End With
            With .Add(msoControlButton)
               .Caption = "2. Inflow
&Means"
               .OnAction = "InflowMeans"
            End With
         End With
      End With
      'Show Settings dialog box
      With .Add(msoControlButton, 220)
         .Caption = "&Settings..."
```

```
            .OnAction = "showSettingsForm"
            .BeginGroup = True
         End With
         'Wetlands Add-In help
         With .Add(msoControlButton, 984)
            .Caption = "Wetlands Add-In
&Help"
            .OnAction = "showHelpForm"
         End With
         'Wetlands About dialog box
         With .Add(msoControlButton, 2949)
            .Caption = "&About Wetlands Add-
In"
            .OnAction = "showAboutForm"
         End With
      End With
   End With
End Sub

'This routine displays the about dialog box
Sub showAboutForm()
   AboutForm.Show
End Sub

'This routine displays the Help dialog box
Sub showHelpForm()
   HelpForm.Show
End Sub

'This routine deletes the custom menu bar
(inactive)
Sub deleteWetlandMenu()
   For Each Bar In
CommandBars("worksheet menu
bar").Controls
      If Bar.Caption = "&Wetlands" Then
Bar.Delete
   Next Bar
End Sub

'This routine calls the settings dialog box
Sub showSettingsForm()
   Call ReadSettingsFile
   SettingsForm.Cell1VolumeBox =
cell1VolumeVar
   SettingsForm.Cell3VolumeBox =
cell3VolumeVar
   SettingsForm.Cell5VolumeBox =
cell5VolumeVar
   SettingsForm.Cell6VolumeBox =
cell6VolumeVar
   SettingsForm.Cell7VolumeBox =
cell7VolumeVar
```

```
   SettingsForm.Cell8VolumeBox =
cell8VolumeVar
   SettingsForm.posCalBox = posCalVar
   SettingsForm.negCalBox = negCalVar
   If Neg0Flag = True Then
      SettingsForm.Neg0Box.Value = True
   Else
      SettingsForm.Neg0Box.Value = False
   End If
   If AutoRRFlag = True Then
      SettingsForm.AutoRRBox.Value = True
   Else
      SettingsForm.AutoRRBox.Value =
False
   End If
   If AutoTFFlag = True Then
      SettingsForm.AutoTFBox.Value = True
   Else
      SettingsForm.AutoTFBox.Value =
False
   End If
   SettingsForm.Show
End Sub


'Wetland Add-In v4.0
'  written 4/20/98 by B. W. Towler
'  updated 10/2/98

Function xCell(cell As Integer)
   Select Case cell
      Case 1
         xCell = 98.5
      Case 3
         xCell = 30
      Case 5
         xCell = 30
      Case 6
         xCell = 30
      Case 7
         xCell = 30
      Case 8
         xCell = 133.5
   End Select
End Function

Function yCell(cell As Integer)
   Select Case cell
      Case 1
         yCell = 163.5
      Case 3
         yCell = 210
      Case 5
         yCell = 15.5
      Case 6
         yCell = 49.5
      Case 7
         yCell = 102
      Case 8
         yCell = 163.5
   End Select
End Function


'Wetland Add-In v4.0
'  written 4/20/98 by B. W. Towler
'  updated 10/2/98

Public numRadi As Integer

'This routine handles all RH sorting & calls
other subs in module
Sub Sort_RH()
   'Opening Dialog box.  Asks if you want to
continue
   MsgA = "This program will sort the
radiation and" & Chr(13)
   MsgB = "humidity data into half hour
readings." & Chr(13) & Chr(13)
   MsgC = "Do you wish to continue?"
   MsgD = MsgA & MsgB & MsgC
   Style = vbOKCancel + vbInformation +
vbDefaultButton2
   Title = "Rn & Rh data sorting program"
   Help = "DEMO.HLP"
   Ctxt = 1000
   Response = MsgBox(MsgD, Style, Title,
Help, Ctxt)
   If Response = vbOK Then
      Application.ScreenUpdating = False
      'Read settings for cell volumes &
calibration
      Call ReadSettingsFile
      Call RnRhDataSort
      Call RnCalc
      If AutoRRFlag = True Then
         Call RnSummary2
         Call RhSummary2
      End If
      Call RnRhSheetOrganize
      Application.ScreenUpdating = True
   End If
End Sub

'This routine sorts data into radiation (RADI)
& humidity (RH) sheets
Sub RnRhDataSort()
   'Renames Active Sheet rhDATA
```

```
   ActiveSheet.Name = "rhDATA"
   ’Creates Sheets for RADI and RH
   Sheets.Add
   ActiveSheet.Name = "Rn Hourly"
   Sheets.Add
   ActiveSheet.Name = "Rh Hourly"
   ’Selects raw data to manipulate
   Sheets("rhDATA").Select
   ’Determines how many lines of data
   rwCheck = 1
   numRadi = 0
   numRH = 0
   Do While
Application.Sum(Worksheets("rhDATA").Ra
nge(Cells(rwCheck, 1), Cells(rwCheck + 10,
1))) > 0
      If
Worksheets("rhDATA").Cells(rwCheck, 1)
<> 0 Then
         rwCheck = rwCheck + 1
         If Cells(rwCheck, 1) = 102 Then
            numRadi = numRadi + 1
         End If
         If Cells(rwCheck, 1) = 203 Then
            numRH = numRH + 1
         End If
      End If
   Loop
   rwMax = rwCheck - 1
      ’Sorts data into RADI & RH sheets
      For rwIndex = 1 To rwMax
         If
Worksheets("rhDATA").Cells(rwIndex, 1) =
102 Then
            Call SheetCopy("Rn Hourly",
"rhDATA", rwIndex)
         End If
         If
Worksheets("rhDATA").Cells(rwIndex, 1) =
203 Then
            Call SheetCopy("Rh Hourly",
"rhDATA", rwIndex)
         End If
      Next rwIndex
      ’Cleans data of empty rows and sets up
headings
      Call CleanSheet("Rn Hourly")
      Call Labels_RnHourly
      Call CleanSheet("Rh Hourly")
      Call Labels_RhHourly
End Sub

’This routine corrects the raw readings with
a calibration factor and converts to kJ of Rn
```

```
Sub RnCalc()
   Dim RowIndex As Integer
   Dim DeltaTime As Single
   Sheets("Rn Hourly").Select
   For RowIndex = 2 To numRadi
      If Cells(RowIndex, 2).Value >= 0 Then
         Cells(RowIndex, 5).Value =
Cells(RowIndex, 2).Value * posCalVar
      Else
         Cells(RowIndex, 5).Value =
Cells(RowIndex, 2).Value * negCalVar
      End If
      If RowIndex > 2 Then
         DeltaTime = Worksheets("Rn
Hourly").Cells(RowIndex, 4).Value -
Worksheets("Rn Hourly").Cells(RowIndex -
1, 4).Value
         If DeltaTime = -2330 Or DeltaTime =
70 Then
            DeltaTime = 30
         End If
      Else
         DeltaTime = 30
      End If
      Worksheets("Rn
Hourly").Cells(RowIndex, 6).Value =
DeltaTime
      Worksheets("Rn
Hourly").Cells(RowIndex, 7).Value =
(Worksheets("Rn Hourly").Cells(RowIndex,
5).Value * (DeltaTime * 60)) / 1000
      If Neg0Flag = True Then
         If Worksheets("Rn
Hourly").Cells(RowIndex, 7).Value > 0 Then
            Worksheets("Rn
Hourly").Cells(RowIndex, 8).Value =
Worksheets("Rn Hourly").Cells(RowIndex,
7).Value
         Else
            Worksheets("Rn
Hourly").Cells(RowIndex, 8).Value = 0
         End If
      End If
   Next RowIndex
End Sub

Sub RnSummary()
   ’Opening Dialog box.  Asks if you want to
continue
   MsgA = "This program will create a daily"
& Chr(13)
   MsgB = "summary sheet for radiation
data." & Chr(13) & Chr(13)
   MsgC = "Do you wish to continue?"
```

```
   MsgD = MsgA & MsgB & MsgC
   Style = vbOKCancel + vbInformation +
vbDefaultButton2
   Title = "Rn summary program"
   Help = "DEMO.HLP"
   Ctxt = 1000
   Response = MsgBox(MsgD, Style, Title,
Help, Ctxt)
   If Response = vbOK Then
      Call RnSummary2
   End If
End Sub

Sub RnSummary2()
      Application.ScreenUpdating = False
      ’Declarations
      Dim RnDate As Integer
      Dim RnDateOld As Integer
      Dim RnDay As Double
      Dim RnDay0 As Double
      Dim n As Integer
      Dim RowIndex As Integer
      Dim OutRow As Integer
      ’Initial conditions
      RnDateOld = 0
      ’Create Summary sheet
      Sheets.Add
      ActiveSheet.Name = "Rn Daily"
      RnDate = Worksheets("Rn
Hourly").Cells(2, 3).Value
      RnDateOld = RnDate
      RowIndex = 2
      n = 0
      RnDay = 0
      RnDay0 = 0
      OutRow = 2
      Worksheets("Rn Daily").Cells(2, 1) =
102
      Do Until Worksheets("Rn
Hourly").Cells(RowIndex, 1) = ""
         RnDate = Worksheets("Rn
Hourly").Cells(RowIndex, 3).Value
         If RnDate = RnDateOld Then
            RnDay = RnDay +
((Worksheets("Rn Hourly").Cells(RowIndex,
7).Value))
            RnDay0 = RnDay0 +
((Worksheets("Rn Hourly").Cells(RowIndex,
8).Value))
            n = n + 1
         Else
            Worksheets("Rn
Daily").Cells(OutRow, 2).Value = RnDateOld
            Worksheets("Rn
Daily").Cells(OutRow, 3) = n
            Worksheets("Rn
Daily").Cells(OutRow, 4).Value = RnDay
            Worksheets("Rn
Daily").Cells(OutRow, 5).Value =
Worksheets("Rn Daily").Cells(OutRow,
4).Value * (0.239006249473467 * 1000) * (1
/ (100 * 100))
            Worksheets("Rn
Daily").Cells(OutRow, 6).Value = RnDay0
            Worksheets("Rn
Daily").Cells(OutRow, 7).Value =
Worksheets("Rn Daily").Cells(OutRow,
6).Value * (0.239006249473467 * 1000) * (1
/ (100 * 100))
            n = 0
            RnDay = 0
            RnDay0 = 0
            OutRow = OutRow + 1
            RowIndex = RowIndex - 1
            RnDateOld = RnDate
         End If
         RowIndex = RowIndex + 1
      Loop
      Worksheets("Rn Daily").Cells(OutRow,
2).Value = RnDateOld
      Worksheets("Rn Daily").Cells(OutRow,
3) = n
      Worksheets("Rn Daily").Cells(OutRow,
4).Value = RnDay
      Worksheets("Rn Daily").Cells(OutRow,
5).Value = Worksheets("Rn
Daily").Cells(OutRow, 4).Value *
(0.239006249473467 * 1000) * (1 / (100 *
100))
      Worksheets("Rn Daily").Cells(OutRow,
6).Value = RnDay0
      Worksheets("Rn Daily").Cells(OutRow,
7).Value = Worksheets("Rn
Daily").Cells(OutRow, 6).Value *
(0.239006249473467 * 1000) * (1 / (100 *
100))
      Call Labels_RnDaily
      Application.ScreenUpdating = True
End Sub
Sub RhSummary()
   ’Opening Dialog box.  Asks if you want to
continue
   MsgA = "This program will create a daily"
& Chr(13)
   MsgB = "summary sheet for humidty
data." & Chr(13) & Chr(13)
   MsgC = "Do you wish to continue?"
```

```
  MsgD = MsgA & MsgB & MsgC
  Style = vbOKCancel + vbInformation +
vbDefaultButton2
  Title = "Rh summary program"
  Help = "DEMO.HLP"
  Ctxt = 1000
  Response = MsgBox(MsgD, Style, Title,
Help, Ctxt)
  If Response = vbOK Then
    Call RhSummary2
  End If
End Sub

Sub RhSummary2()
    Application.ScreenUpdating = False
    'Declarations
    Dim RHDate As Integer
    Dim RHDateOld As Integer
    Dim RhDay As Double
    Dim TDay As Double
    Dim n As Integer
    Dim RowIndex As Integer
    Dim OutRow As Integer
    'Initial conditions
    RHDateOld = 0
    'Create Summary sheet
    Sheets.Add
    ActiveSheet.Name = "Rh Daily"
    RHDate = Worksheets("Rh
Hourly").Cells(2, 4).Value
    RHDateOld = RHDate
    RowIndex = 2
    n = 0
    RhDay = 0
    OutRow = 2
    Worksheets("Rh Daily").Cells(2, 1) =
203
    Do Until Worksheets("Rh
Hourly").Cells(RowIndex, 1) = ""
      RHDate = Worksheets("Rh
Hourly").Cells(RowIndex, 4).Value
      If RHDate = RHDateOld Then
        TDay = TDay + ((Worksheets("Rh
Hourly").Cells(RowIndex, 2).Value))
        RhDay = RhDay +
((Worksheets("Rh Hourly").Cells(RowIndex,
3).Value))
        n = n + 1
      Else
        Worksheets("Rh
Daily").Cells(OutRow, 2) = RHDateOld
        Worksheets("Rh
Daily").Cells(OutRow, 3) = TDay / n
        Worksheets("Rh
Daily").Cells(OutRow, 4) = RhDay / n
        Worksheets("Rh
Daily").Cells(OutRow, 5) = n
        n = 0
        RhDay = 0
        TDay = 0
        OutRow = OutRow + 1
        RowIndex = RowIndex - 1
        RHDateOld = RHDate
      End If
      RowIndex = RowIndex + 1
    Loop
    Worksheets("Rh Daily").Cells(OutRow,
2) = RHDateOld
    Worksheets("Rh Daily").Cells(OutRow,
3) = TDay / n
    Worksheets("Rh Daily").Cells(OutRow,
4) = RhDay / n
    Worksheets("Rh Daily").Cells(OutRow,
5) = n
    Call Labels_RhDaily
    Application.ScreenUpdating = True
End Sub

'Range copying subroutine
Sub SheetCopy(ToSheetString,
FromSheetString, row_num)

Worksheets(FromSheetString).Range(Cells(
row_num, 1), Cells(row_num, 15)).Copy
  Sheets(ToSheetString).Select
  ActiveSheet.Paste
Destination:=Worksheets(ToSheetString).Ra
nge(Cells(row_num, 1), Cells(row_num, 15))
  Sheets(FromSheetString).Select
End Sub

'Cleaning subroutine
Sub CleanSheet(SheetString2)
  Sheets(SheetString2).Select
  rwClean = 1
  Do While
Application.Sum(Worksheets(SheetString2).
Range(Cells(rwClean, 1), Cells(rwClean +
100, 1))) > 0
    If
Worksheets(SheetString2).Cells(rwClean, 1)
= 0 Then
      Rows(rwClean).Select
      Selection.Delete Shift:=xlUp
    Else: rwClean = rwClean + 1
    End If
  Loop
```

```
End Sub

'Labelling Radimeter sheet subroutine
Sub Labels_RnHourly()
  Sheets("Rn Hourly").Select
  Range("A1:E1").Select
  With Selection
    .HorizontalAlignment = xlCenter
    .VerticalAlignment = xlBottom
    .WrapText = False
    .Orientation = xlHorizontal
  End With
  Columns("A:A").Select
  With Selection.Interior
    .ColorIndex = 15
    .Pattern = xlSolid
  End With
  Rows("1:1").Select
  With Selection.Interior
    .ColorIndex = 15
    .Pattern = xlSolid
  End With
  With Worksheets("Rn Hourly")
    .Range("A1") = "ID"
    .Range("B1") = "Raw"
    .Range("c1") = "Day"
    .Range("d1") = "Time"
    .Range("e1") = "Rn(W/m2)"
    .Range("f1") = "DTime(min)"
    .Range("g1") = "Rn(kJ/m2)"
    .Range("h1") = "Rn*(kJ/m2)"
  End With
End Sub
'Labelling Radimeter sheet subroutine
Sub Labels_RnDaily()
  Sheets("Rn Daily").Select
  Range("A1:F1").Select
  With Selection
    .HorizontalAlignment = xlCenter
    .VerticalAlignment = xlBottom
    .WrapText = False
    .Orientation = xlHorizontal
  End With
  Columns("A:A").Select
  With Selection.Interior
    .ColorIndex = 15
    .Pattern = xlSolid
  End With
  Rows("1:1").Select
  With Selection.Interior
    .ColorIndex = 15
    .Pattern = xlSolid
  End With
  With Worksheets("Rn Daily")
    .Range("A1") = "ID"
    .Range("B1") = "Day"
    .Range("c1") = "Readings"
    .Range("d1") = "Rn(kJ/m2)"
    .Range("e1") = "Rn(cal/cm2)"
    .Range("f1") = "Rn*(kJ/m2)"
    .Range("g1") = "Rn*(cal/cm2)"
  End With
  Columns("D:G").Select
  Selection.NumberFormat = "0.00"
  Range("A1").Select
End Sub

'Labelling RH sheet subroutine
Sub Labels_RhHourly()
  Sheets("Rh Hourly").Select
  Range("A1:D1").Select
  With Selection
    .HorizontalAlignment = xlCenter
    .VerticalAlignment = xlBottom
    .WrapText = False
    .Orientation = xlHorizontal
  End With
  Columns("A:A").Select
  With Selection.Interior
    .ColorIndex = 15
    .Pattern = xlSolid
  End With
  Rows("1:1").Select
  With Selection.Interior
    .ColorIndex = 15
    .Pattern = xlSolid
  End With
  With Worksheets("Rh Hourly")
    .Range("A1") = "ID"
    .Range("B1") = "AirTemp(C)"
    .Range("C1") = "RH(%)"
    .Range("D1") = "Day"
    .Range("E1") = "Time"
  End With
  Columns("B:C").Select
  Selection.NumberFormat = "0.00"
  Range("A1").Select
End Sub
'Labelling Relative Humdity sheet subroutine
Sub Labels_RhDaily()
  Sheets("Rh Daily").Select
  Range("A1:E1").Select
  With Selection
    .HorizontalAlignment = xlCenter
    .VerticalAlignment = xlBottom
    .WrapText = False
    .Orientation = xlHorizontal
  End With
```

```
    Columns("A:A").Select
    With Selection.Interior
        .ColorIndex = 15
        .Pattern = xlSolid
    End With
    Rows("1:1").Select
    With Selection.Interior
        .ColorIndex = 15
        .Pattern = xlSolid
    End With
    With Worksheets("Rh Daily")
        .Range("A1") = "ID"
        .Range("B1") = "Day"
        .Range("c1") = "Temp (oC)"
        .Range("d1") = "RH%"
        .Range("e1") = "Readings"
    End With
End Sub

Sub RnRhSheetOrganize()
    On Error Resume Next
    Sheets("Rh Daily").Move
Before:=Sheets(1)
    Sheets("Rn Daily").Move
Before:=Sheets(2)
    Sheets("Rh Hourly").Move
Before:=Sheets(3)
    Sheets("Rn Hourly").Move
Before:=Sheets(4)
    Sheets("rhDATA").Visible = False
End Sub


'Wetland Add-In v4.0
'   written 4/20/98 by B. W. Towler
'   updated 10/2/98
'This code handles test files used in settings

'This routine reads in settings file
Sub ReadSettingsFile()
    Open "C:\Windows\wetlands.txt" For Input
As #1
    Input #1, cell1VolumeVar,
cell3VolumeVar, cell5VolumeVar _
        , cell6VolumeVar, cell7VolumeVar,
cell8VolumeVar _
        , posCalVar, negCalVar, Neg0Flag,
AutoRRFlag, AutoTFFlag
    Close 1
End Sub

'This routine writes to settings file
Sub WriteSettingsFile()
    ' Create a new text fSeile called Test.txt.
    Open "C:\Windows\wetlands.txt" For
Output As #1
    Write #1, cell1VolumeVar,
cell3VolumeVar, cell5VolumeVar _
        , cell6VolumeVar, cell7VolumeVar,
cell8VolumeVar _
        , posCalVar, negCalVar, Neg0Flag,
AutoRRFlag, AutoTFFlag
    Close #1
End Sub


'Wetland Add-In v4.0
'   written 4/20/98 by B. W. Towler
'   updated 10/2/98
'This code was developed to sort the
tempertaure and flow
'data downloaded from a CSI datalogger in
MSU's CW project.

'This routine handles all TF sorting & calls
other subs in module
Sub Sort_TF()
    'Opening Dialog box.  Asks if you want to
continue
    MsgA = "Do you want to run the
temperature &" & Chr(13)
    MsgB = "flow data sorting routines?" &
Chr(13) & Chr(13) + "Press OK to begin." +
Chr(13)
    MsgC = MsgA & MsgB
    Style = vbOKCancel + vbInformation +
vbDefaultButton2
    Title = "Temp&Flow data sorting program"
    Help = "DEMO.HLP"
    Ctxt = 1000
    Response = MsgBox(MsgC, Style, Title,
Help, Ctxt)
    If Response = vbOK Then
        Application.ScreenUpdating = False
        Call DataImport
        Call TempFlowDataSort
        Call FlowPartition
        Call FlowHourly
        If AutoTFFlag = True Then
            Call TempSummary2
            Call FlowSummary2
            Call FlowSummary3
        End If
        Call TempFlowSheetOrganize
        Application.ScreenUpdating = True
    End If
    End
End Sub
```

```
'This routine separates temp and flow data
into 2 sheets, TEMP and FLOW
Sub TempFlowDataSort()
   'Renames Active Sheet tfDATA
   ActiveSheet.Name = "tfDATA"
   'Creates Sheets for FLOW, TEMP and
TRASH
   Sheets.Add
   ActiveSheet.Name = "Flow Raw"
   Sheets.Add
   ActiveSheet.Name = "Temp Hourly"
   'Selects raw data to manipulate
   Sheets("tfDATA").Select
   'Determines how many lines of data
   rwCheck = 1
   numFlow = 0
   numTemp = 0
   Do While
Application.Sum(Worksheets("tfDATA").Ran
ge(Cells(rwCheck, 1), Cells(rwCheck + 10,
1))) > 0
      If
Worksheets("tfDATA").Cells(rwCheck, 1) <>
0 Then
         rwCheck = rwCheck + 1
         If Cells(rwCheck, 1) = 100 Then
            numFlow = numFlow + 1
         End If
         If Cells(rwCheck, 1) = 109 Then
            numTemp = numTemp + 1
         End If
      End If
   Loop
   rwMax = rwCheck - 1
      'Sorts data into FLOW, TEMP sheets
      For rwIndex = 1 To rwMax
         If
Worksheets("tfDATA").Cells(rwIndex, 1) =
109 Then
            Call SheetCopy("Temp Hourly",
"tfDATA", rwIndex)
         End If
         If
Worksheets("tfDATA").Cells(rwIndex, 1) =
100 Then
            Call SheetCopy("Flow Raw",
"tfDATA", rwIndex)
         End If
      Next rwIndex
      'Cleans data of empty rows and sets up
headings
      Call CleanSheet("Temp Hourly")
      Call Labels_TempHourly
      Call CleanSheet("Flow Raw")
      Call Labels_FlowRaw
End Sub
Sub TempSummary()
   'Opening Dialog box.  Asks if you want to
continue
   MsgA = "This program will create a daily"
& Chr(13)
   MsgB = "summary sheet for temperature
data." & Chr(13) & Chr(13)
   MsgC = "Do you wish to continue?"
   MsgD = MsgA & MsgB & MsgC
   Style = vbOKCancel + vbInformation +
vbDefaultButton2
   Title = "Temperature summary program"
   Help = "DEMO.HLP"
   Ctxt = 1000
   Response = MsgBox(MsgD, Style, Title,
Help, Ctxt)
   If Response = vbOK Then
      Call TempSummary2
   End If
End Sub
Sub TempSummary2()
      Application.ScreenUpdating = False
      'Declarations
      Dim TempDate As Integer
      Dim TempDateOld As Integer
      Dim TempDay(50) As Double
      Dim Count As Integer
      Dim ColIndex As Integer
      Dim n As Integer
      Dim RowIndex As Integer
      Dim OutRow As Integer
      'Initial conditions
      TempDateOld = 0
      'Create Summary sheet
      Sheets.Add
      ActiveSheet.Name = "Temp Daily"
      TempDate = Worksheets("Temp
Hourly").Cells(2, 24).Value
      TempDateOld = TempDate
      RowIndex = 2
      n = 0
      OutRow = 2
      Worksheets("Temp Daily").Cells(2, 1) =
109
      Do Until Worksheets("Temp
Hourly").Cells(RowIndex, 1) = ""
         TempDate = Worksheets("Temp
Hourly").Cells(RowIndex, 24).Value
         If TempDate = TempDateOld Then
            For Count = 1 To 22
```

```
               TempDay(Count) =
TempDay(Count) + ((Worksheets("Temp
Hourly").Cells(RowIndex, Count + 1).Value))
            Next Count
            n = n + 1
         Else
            Worksheets("Temp
Daily").Cells(OutRow, 2).Value =
TempDateOld
            Worksheets("Temp
Daily").Cells(OutRow, 3) = n
            For Count = 1 To 22
               Worksheets("Temp
Daily").Cells(OutRow, Count + 3).Value =
TempDay(Count) / n
            Next Count
            n = 0
            For Count = 1 To 22
               TempDay(Count) = 0
            Next Count
            OutRow = OutRow + 1
            RowIndex = RowIndex - 1
            TempDateOld = TempDate
         End If
         RowIndex = RowIndex + 1
      Loop
      Worksheets("Temp
Daily").Cells(OutRow, 2) = TempDateOld
      Worksheets("Temp
Daily").Cells(OutRow, 3) = n
      For Count = 1 To 22
         If n >= 1 Then
            Worksheets("Temp
Daily").Cells(OutRow, Count + 3).Value =
TempDay(Count) / n
         End If
      Next Count
      Call Labels_TempDaily
      Application.ScreenUpdating = True
End Sub
Sub FlowSummary()
   ’Opening Dialog box.  Asks if you want to
continue
   MsgA = "This program will create a daily"
& Chr(13)
   MsgB = "summary sheet for flow data." &
Chr(13) & Chr(13)
   MsgC = "Do you wish to continue?"
   MsgD = MsgA & MsgB & MsgC
   Style = vbOKCancel + vbInformation +
vbDefaultButton2
   Title = "Flow Rate summary program"
   Help = "DEMO.HLP"
   Ctxt = 1000
```

```
   Response = MsgBox(MsgD, Style, Title,
Help, Ctxt)
   If Response = vbOK Then
      Call FlowSummary2
   End If
End Sub
Sub FlowSummary2()
      Application.ScreenUpdating = False
      ’Declarations
      Dim FlowDate, FlowDateOld, Count,
ColIndex, n _
         , RowIndex, OutRow, FlowCell As
Integer
      Dim FlowDay As Double
      Dim FlowVol As Single
      ’Initial conditions
      FlowDateOld = 0
      ’Create Summary sheet
      Sheets.Add
      ActiveSheet.Name = "Flow Daily 1"
      FlowDate = Worksheets("Flow
Hourly").Cells(3, 2).Value
      FlowDateOld = FlowDate
      RowIndex = 3
      n = 0
      OutRow = 2
      Worksheets("Flow Daily 1").Cells(2, 1)
= 100
      Do Until Worksheets("Flow
Hourly").Cells(RowIndex, 1) = ""
            FlowDate = Worksheets("Flow
Hourly").Cells(RowIndex, 2).Value
         If FlowDate = FlowDateOld Then
            FlowDay = FlowDay +
((Worksheets("Flow
Hourly").Cells(RowIndex, 6).Value))
            FlowDay2 = FlowDay2 +
((Worksheets("Flow
Hourly").Cells(RowIndex, 6).Value)) ^ 2
            FlowCell = Worksheets("Flow
Hourly").Cells(RowIndex, 1).Value
            FlowVol = Worksheets("Flow
Hourly").Cells(RowIndex, 7).Value
            n = n + 1
         Else
            Worksheets("Flow Daily
1").Cells(OutRow, 2).Value = FlowDateOld
            Worksheets("Flow Daily
1").Cells(OutRow, 3).Value = FlowCell
            Worksheets("Flow Daily
1").Cells(OutRow, 4).Value = FlowVol
            Worksheets("Flow Daily
1").Cells(OutRow, 5).Value = FlowDay / n
’           On Error Resume Next
```

```
            If n > 1 Then
               Worksheets("Flow Daily
1").Cells(OutRow, 6).Value = ((FlowDay2 -
(FlowDay ^ 2) / n) / (n - 1)) ^ (1 / 2)
            End If
            Worksheets("Flow Daily
1").Cells(OutRow, 7).Value = n
            n = 0
            FlowDay = 0
            FlowDay2 = 0
            OutRow = OutRow + 1
            RowIndex = RowIndex - 1
            FlowDateOld = FlowDate
         End If
         RowIndex = RowIndex + 1
      Loop
      Worksheets("Flow Daily
1").Cells(OutRow, 2).Value = FlowDateOld
      Worksheets("Flow Daily
1").Cells(OutRow, 3).Value = FlowCell
      Worksheets("Flow Daily
1").Cells(OutRow, 4).Value = FlowVol
      Worksheets("Flow Daily
1").Cells(OutRow, 5).Value = FlowDay / n
      Worksheets("Flow Daily
1").Cells(OutRow, 6).Value = ((FlowDay2 -
(FlowDay ^ 2) / n) / (n - 1)) ^ (1 / 2)
      Worksheets("Flow Daily
1").Cells(OutRow, 7).Value = n
      Call Labels_FlowDaily1
      Application.ScreenUpdating = True
End Sub

Sub FlowSummary3()
   Application.ScreenUpdating = False
   'Declarations
   Dim RowIndex, FlowDate, cell As Integer
   Dim FlowDaily(366, 8) As Single

   'Initial conditions

   'Sort Flow Daily 1
   Sheets("Flow Daily 1").Select
   Range("A1:N1000").Select
   Selection.Sort Key1:=Range("B2"),
Order1:=xlAscending, Key2:=Range("C2") _
   , Order2:=xlAscending, Header:=xlYes,
OrderCustom:=1, MatchCase:= _
   False, Orientation:=xlTopToBottom

   'Create Flow Daily 2 sheet
   Sheets.Add
   ActiveSheet.Name = "Flow Daily 2"

   RowIndex = 2
   FlowDateStart = Worksheets("Flow Daily
1").Cells(2, 2).Value
   FlowDateEnd = 0

   'Read Loop
   Do Until Worksheets("Flow Daily
1").Cells(RowIndex, 2) = ""
      FlowDate = Worksheets("Flow Daily
1").Cells(RowIndex, 2).Value
      If FlowDate > FlowDateEnd Then
FlowDateEnd = FlowDate
      cell = Worksheets("Flow Daily
1").Cells(RowIndex, 3).Value
      FlowDaily(FlowDate, cell) =
Worksheets("Flow Daily 1").Cells(RowIndex,
5).Value
      RowIndex = RowIndex + 1
   Loop

   RowIndex = 1

   'Write Loop
   For FlowDate = FlowDateStart To
FlowDateEnd
      RowIndex = RowIndex + 1
      Worksheets("Flow Daily
2").Cells(RowIndex, 1).Value = FlowDate
      For cell = 1 To 8
         Worksheets("Flow Daily
2").Cells(RowIndex, 1 + cell).Value =
FlowDaily(FlowDate, cell)
      Next cell
   Next FlowDate

   Call Labels_FlowDaily2
   Application.ScreenUpdating = True
End Sub


'Range copying subroutine
Sub SheetCopy(ToSheetString,
FromSheetString, row_num)

Worksheets(FromSheetString).Range(Cells(
row_num, 1), Cells(row_num, 30)).Copy
   Sheets(ToSheetString).Select
   ActiveSheet.Paste
Destination:=Worksheets(ToSheetString).Ra
nge(Cells(row_num, 1), Cells(row_num, 30))
   Sheets(FromSheetString).Select
End Sub

'Cleaning subroutine
```

```
Sub CleanSheet(SheetString2)
   Sheets(SheetString2).Select
   rwClean = 1
   Do While
Application.Sum(Worksheets(SheetString2).
Range(Cells(rwClean, 1), Cells(rwClean +
100, 1))) > 0
      If
Worksheets(SheetString2).Cells(rwClean, 1)
= 0 Then
         Rows(rwClean).Select
         Selection.Delete Shift:=xlUp
      Else: rwClean = rwClean + 1
      End If
   Loop
End Sub

’Labelling Temp subroutine
Sub Labels_TempHourly()
   Rows("1:1").Select
   Selection.Insert Shift:=xlDown
   Sheets("Temp Hourly").Select
   Range("A1:L1").Select
   With Selection
      .HorizontalAlignment = xlCenter
      .VerticalAlignment = xlBottom
      .WrapText = False
      .Orientation = xlHorizontal
   End With
   Columns("A:A").Select
   With Selection.Interior
      .ColorIndex = 15
      .Pattern = xlSolid
   End With
   Rows("1:1").Select
   With Selection.Interior
      .ColorIndex = 15
      .Pattern = xlSolid
   End With
   With Worksheets("Temp Hourly")
      .Range("A1") = "ID"
      .Range("B1") = "Cell 1"
      .Range("c1") = "Cell 2"
      .Range("d1") = "Cell 3"
      .Range("e1") = "Cell 4"
      .Range("f1") = "Cell 5"
      .Range("g1") = "Cell 6"
      .Range("h1") = "Cell 7"
      .Range("i1") = "Cell 8"
      .Range("j1") = "Air TC"
      .Range("k1") = "n/a"
      .Range("l1") = "Col. 1"
      .Range("m1") = "Col. 2"
      .Range("n1") = "Col. 3"
      .Range("o1") = "Col. 4"
      .Range("p1") = "Col. 5"
      .Range("q1") = "Col. 6"
      .Range("r1") = "Col. 7"
      .Range("s1") = "Col. 8"
      .Range("t1") = "Col. 9"
      .Range("u1") = "Col. 10"
      .Range("v1") = "Col. 11"
      .Range("w1") = "Col. 12"
      .Range("x1") = "Day"
      .Range("y1") = "hrs:min"
   End With
   Range("A1").Select
End Sub

’Labelling Flow subroutine
Sub Labels_FlowRaw()
   Rows("1:1").Select
   Selection.Insert Shift:=xlDown
   Sheets("Flow Raw").Select
   Range("A1:D1").Select
   With Selection
      .HorizontalAlignment = xlCenter
      .VerticalAlignment = xlBottom
      .WrapText = False
      .Orientation = xlHorizontal
   End With
   Columns("A:A").Select
   With Selection.Interior
      .ColorIndex = 15
      .Pattern = xlSolid
   End With
   Rows("1:1").Select
   With Selection.Interior
      .ColorIndex = 15
      .Pattern = xlSolid
   End With
   With Worksheets("Flow Raw")
      .Range("A1") = "ID"
      .Range("B1") = "Day"
      .Range("C1") = "hrs:min"
      .Range("D1") = "sec."
      .Range("E1") = "Cells Draining"
   End With
   Range("A1").Select
End Sub

’This routine partitions flow data from FLOW
sheet into
’cell-seperated data on sheet FLOW 2
Sub FlowPartition()
   ’Selects raw data to manipulate
   Sheets("Flow Raw").Select
   ’Reads Volumes from settings file
```

```
   Call ReadSettingsFile
   ’Converts volumes to inches
   volume(3) = cell1VolumeVar * (2.54 ^ 3)
   volume(4) = cell3VolumeVar * (2.54 ^ 3)
   volume(5) = cell5VolumeVar * (2.54 ^ 3)
   volume(6) = cell6VolumeVar * (2.54 ^ 3)
   volume(7) = cell7VolumeVar * (2.54 ^ 3)
   volume(8) = cell8VolumeVar * (2.54 ^ 3)
   ’Determines how many lines of data
   rowCheck = 2
   Do While
Application.Sum(Worksheets("Flow
Raw").Range(Cells(rowCheck, 1),
Cells(rowCheck + 10, 1))) > 0
      If Worksheets("Flow
Raw").Cells(rowCheck, 1) <> 0 Then
         rowCheck = rowCheck + 1
      End If
   Loop
   rowMax = rowCheck - 1
   ’Reads matrix into flowData variable
   ReDim flowData(rowMax, 10)
   For rowCount = 1 To rowMax
      For colCount = 1 To 10
         flowData(rowCount, colCount) =
Cells(rowCount + 1, colCount)
      Next colCount
   Next rowCount
   ’Orders data by cell number and writes to
FLOW2 sheet
   rowAdvance = 2
   Sheets.Add
   ActiveSheet.Name = "Flow Part"
   For CellIndex = 3 To 8
      For rowCount = 1 To rowMax
         For colCount = 5 To 10
            If flowData(rowCount, colCount) =
CellIndex Then
               Cells(rowAdvance, 1) =
CellIndex
               Cells(rowAdvance, 2) =
flowData(rowCount, 2)
               hrsminAbbrev =
flowData(rowCount, 3) / 100
               hrsVar =
Application.RoundDown(hrsminAbbrev, 0)
               minVar = ((flowData(rowCount,
3) / 100) - hrsVar) * 100
               secVar = flowData(rowCount, 4)
               timeVar = hrsVar + (minVar /
60) + (secVar / 3600)
               Cells(rowAdvance, 3) = timeVar
               daytimeVar =
flowData(rowCount, 2) + (timeVar / 24)
```

```
               Cells(rowAdvance, 4) =
daytimeVar
               rowAdvance = rowAdvance + 1
            End If
         Next colCount
      Next rowCount
   Next CellIndex
   ’Re-determines how many lines of data in
FLOW2 sheet
   rowCheck = 2
   Do While
Application.Sum(Worksheets("Flow
Part").Range(Cells(rowCheck, 1),
Cells(rowCheck + 10, 1))) > 0
      If Worksheets("Flow
Part").Cells(rowCheck, 1) <> 0 Then
         rowCheck = rowCheck + 1
      End If
   Loop
   rowMax = rowCheck - 1
   ’Calculates minutes elapsed and volume
   For rowAdvance = 2 To rowMax
      ’calculates elapsed time between flush
events
      If Cells(rowAdvance, 1) =
Cells(rowAdvance - 1, 1) Then
         currentStep = (Cells(rowAdvance, 4)
- Cells(rowAdvance - 1, 4)) * (24 * 60)
         If currentStep < 1 Then
            increment = increment +
currentStep
         Else
            Cells(rowAdvance, 5) =
(Cells(rowAdvance, 4) - Cells(rowAdvance -
1, 4)) * (24 * 60) + increment
            increment = 0
         End If
      End If
      ’computes volume of cell based on port
number
      If Cells(rowAdvance, 1).Value > 0 Then
         CellIndex = Cells(rowAdvance,
1).Value
      End If
      If Cells(rowAdvance, 5) > 0 Then
         Cells(rowAdvance, 6).Value =
volume(CellIndex) / Cells(rowAdvance, 5)
         Cells(rowAdvance, 7).Value =
volume(CellIndex)
      Else
         Cells(rowAdvance, 6) = ""
         Cells(rowAdvance, 7) = ""
      End If
   Next rowAdvance
```

```
   Call Labels_FlowPart
 End Sub

'Labelling FlowPart subroutine
Sub Labels_FlowPart()
   With Worksheets("Flow Part")
      .Range("A1") = "Port #"
      .Range("B1") = "Day"
      .Range("c1") = "Time(h)"
      .Range("d1") = "Day.Time"
      .Range("e1") = "D Time(m)"
      .Range("f1") = "Flow(ml/m)"
      .Range("g1") = "Vol.(cm)"
   End With
   Columns("A:A").Select
   With Selection.Interior
      .ColorIndex = 15
      .Pattern = xlSolid
   End With
   Rows("1:1").Select
   With Selection.Interior
      .ColorIndex = 15
      .Pattern = xlSolid
   End With
   Columns("C:D").NumberFormat = "0.00"
   Columns("F:f").NumberFormat = "0.00"
   Columns("g:g").NumberFormat = "0"
   Range("A1").Select
End Sub

'This routine organizes Flow Part into Flow
Hourly by removing blank
'lines, labelling ports as cells.
Sub FlowHourly()
   'Creates Flow Hourly sheet
   Sheets.Add
   ActiveSheet.Name = "Flow Hourly"
   Sheets("Flow Part").Select
   Cells.Select
   Selection.Copy
   Sheets("Flow Hourly").Select
   Cells.Select
   ActiveSheet.Paste
   rwClean = 3
   If ActiveSheet.Cells(2, 1) = 3 Then
      ActiveSheet.Cells(2, 1) = 1
   End If
   If ActiveSheet.Cells(2, 1) = 4 Then
         ActiveSheet.Cells(2, 1) = 3
   End If
   Do While ActiveSheet.Cells(rwClean, 1)
<> ""
      If ActiveSheet.Cells(rwClean, 1) = 3
Then
         ActiveSheet.Cells(rwClean, 1) = 1
      End If
      If ActiveSheet.Cells(rwClean, 1) = 4
Then
         ActiveSheet.Cells(rwClean, 1) = 3
      End If
      If ActiveSheet.Cells(rwClean, 5) = ""
Then
         Rows(rwClean).Select
         Selection.Delete Shift:=xlUp
      Else: rwClean = rwClean + 1
      End If
   Loop
   Call Labels_FlowHourly
End Sub

'Labelling FlowHourly subroutine
Sub Labels_FlowHourly()
   With Worksheets("Flow Hourly")
      .Range("A1") = "Cell"
   End With
   Range("A1").Select
End Sub
'Labelling Temp Daily sheet subroutine
Sub Labels_TempDaily()
   Sheets("Temp Daily").Select
   Range("A1:Z1").Select
   With Selection
      .HorizontalAlignment = xlCenter
      .VerticalAlignment = xlBottom
      .WrapText = False
      .Orientation = xlHorizontal
   End With
   Columns("A:A").Select
   With Selection.Interior
      .ColorIndex = 15
      .Pattern = xlSolid
   End With
   Rows("1:1").Select
   With Selection.Interior
      .ColorIndex = 15
      .Pattern = xlSolid
   End With
   With Worksheets("Temp Daily")
      .Range("A1") = "ID"
      .Range("B1") = "Day"
      .Range("c1") = "Readings"
      .Range("d1") = "Cell 1"
      .Range("e1") = "Cell 2"
      .Range("f1") = "Cell 3"
      .Range("g1") = "Cell 4"
      .Range("h1") = "Cell 5"
      .Range("i1") = "Cell 6"
      .Range("j1") = "Cell 7"
```

```
        .Range("k1") = "Cell 8"
        .Range("l1") = "Air TC"
        .Range("m1") = "n/a"
        .Range("n1") = "Col. 1"
        .Range("o1") = "Col. 2"
        .Range("p1") = "Col. 3"
        .Range("q1") = "Col. 4"
        .Range("r1") = "Col. 5"
        .Range("s1") = "Col. 6"
        .Range("t1") = "Col. 7"
        .Range("u1") = "Col. 8"
        .Range("v1") = "Col. 9"
        .Range("w1") = "Col. 10"
        .Range("x1") = "Col. 11"
        .Range("y1") = "Col. 12"
    End With
    Columns("D:Y").Select
    Selection.NumberFormat = "0.00"
    Range("A1").Select
End Sub
'Labelling Flow Daily 1 sheet subroutine
Sub Labels_FlowDaily1()
    Sheets("Flow Daily 1").Select
    Range("A1:F1").Select
    With Selection
        .HorizontalAlignment = xlCenter
        .VerticalAlignment = xlBottom
        .WrapText = False
        .Orientation = xlHorizontal
    End With
    Columns("A:A").Select
    With Selection.Interior
        .ColorIndex = 15
        .Pattern = xlSolid
    End With
    Rows("1:1").Select
    With Selection.Interior
        .ColorIndex = 15
        .Pattern = xlSolid
    End With
    With Worksheets("Flow Daily 1")
        .Range("A1") = "ID"
        .Range("B1") = "Day"
        .Range("c1") = "Cell"
        .Range("d1") = "Vol.(cm3)"
        .Range("e1") = "Flow(ml/m)"
        .Range("f1") = "SD Flow"
        .Range("g1") = "# Flush"
    End With
    Columns("d").Select
    Selection.NumberFormat = "0"
    Selection.ColumnWidth = 10
    Columns("e:f").Select
    Selection.NumberFormat = "0.00"
    Selection.ColumnWidth = 10
    Range("A1").Select
End Sub
'Labelling Flow Daily 2 sheet subroutine
Sub Labels_FlowDaily2()
    Sheets("Flow Daily 2").Select
    Range("A1:I1").Select
    With Selection
        .HorizontalAlignment = xlCenter
        .VerticalAlignment = xlBottom
        .WrapText = False
        .Orientation = xlHorizontal
    End With
    Rows("1:1").Select
    With Selection.Interior
        .ColorIndex = 15
        .Pattern = xlSolid
    End With

    Columns("C:C").Select
    Selection.Delete Shift:=xlToLeft
    Columns("D:D").Select
    Selection.Delete Shift:=xlToLeft

    With Worksheets("Flow Daily 2")
        .Range("A1") = "Date"
        .Range("B1") = "Cell 1"
        .Range("c1") = "Cell 3"
        .Range("d1") = "Cell 5"
        .Range("e1") = "Cell 6"
        .Range("f1") = "Cell 7"
        .Range("g1") = "Cell 8"
    End With
    Columns("a").Select
    Selection.NumberFormat = "0"
    Selection.ColumnWidth = 10
    Columns("b:g").Select
    Selection.NumberFormat = "0.0"
    Selection.ColumnWidth = 10
    Range("A1").Select
End Sub
Sub DataImport()
    If ActiveSheet.Cells(1, 2) = "" Then
        Columns("A:A").Select
        Selection.TextToColumns
Destination:=Range("A1"),
DataType:=xlDelimited, _
            TextQualifier:=xlDoubleQuote,
ConsecutiveDelimiter:=False, Tab:=False, _
            Semicolon:=False, Comma:=True,
Space:=False, Other:=False, FieldInfo _
            :=Array(Array(1, 1), Array(2, 1),
Array(3, 1), Array(4, 1), Array(5, 1))
        Range("A1").Select
```

```
   End If
End Sub

Sub TempFlowSheetOrganize()
   On Error Resume Next
   Sheets("Temp Daily").Move
Before:=Sheets(1)
   Sheets("Flow Daily 1").Move
Before:=Sheets(2)
   Sheets("Flow Daily 2").Move
Before:=Sheets(3)
   Sheets("Temp Hourly").Move
Before:=Sheets(4)
   Sheets("Flow Hourly").Move
Before:=Sheets(5)
   Sheets("Flow Part").Visible = False
   Sheets("Flow Raw").Visible = False
   Sheets("tfDATA").Visible = False
End Sub
```

APPENDIX B

ADDITIONAL DATA & MEASUREMENTS

Cell Dimensions

	(in.)	*(m)*	*(cm)*
w	30	0.762	76.2
h	17	0.4318	43.18
l	60	1.524	152.4

	(in.2)	*(m2)*	*(cm2)*
SA_{top}	1800	1.161	11613
SA_{total}	6660	4.297	42968

	(in3.)	*(m3)*	*(cm2)*
V	30600	0.501	501444.2

Where:

w = width
h = height
l = length
SA = surface area
v =
volume

Soil Heat Flux Calculations

Cell information:

V	0.501	*(m^3)*
SA	1.161	*(m^2)*
α	0.40	

Weighted Cs calculation:

	(MJ/m^3C)	*(m^3)*	*(MJ/C)*
	C_s	**V**	**C_sV**
gravel	2.211	0.301	0.665
water	4.186	0.201	0.840
media		$\Sigma =$	1.505

Soil Heat Flux per ΔT:

C_s	3.00	*(MJ/m^3C)*
G/°C	1.50	*(MJ/C)*
G/°C/m	3.48	*(MJ/mC)*
G/°C/mm	3.48E-06	*(MJ/mmC)*

Where:

V = volume
SA = horizontal surface area
a = porosity
Cs = specific heat
G = soil heat flux

Notes:

Porosity measured at start of project.
Cs value taken from PCA manual for typical aggregates.

Tabulated ET_c Values (in equivalent flow rate)

ETc
2 week averages
truncated (1%-99% of values)
by treatment

Period	Date	*ml/m* Cattail	*ml/m* Bulrush	*ml/m* Control	*ml/m* AVG.
1	3/10	5.1	4.9	5.8	5.3
2	3/24	8.8	5.1	7.3	7.1
3	4/7	6.2	5.7	5.0	5.7
4	4/21	7.0	5.7	5.4	6.0
5	5/5	8.2	6.6	5.6	6.8
6	5/19	9.4	7.8	6.3	7.8
7	6/2	8.1	7.1	7.0	7.4
8	6/16	13.3	10.9	9.0	11.1
9	6/30				
10	7/14	12.0	10.3	8.9	10.4
11	7/28	7.9	7.8	6.5	7.4
12	8/11	8.3	8.0	7.1	7.8
13	8/25	6.7	8.1	2.4	5.7
	MIN	5.1	4.9	2.4	
	MAX	13.3	10.9	9.0	
	AVG	8.4	7.3	6.4	

ETc
2 week SD
truncated (1%-99% of values)
by treatment

Period	Date	mm/d Cattail	mm/d Bulrush	mm/d Control	mm/d AVG.
1	3/10	2.7	2.2	3.4	2.8
2	3/24	4.3	3.3	2.9	3.5
3	4/7	4.1	1.3	3.6	3.0
4	4/21	2.1	1.9	3.3	2.4
5	5/5	2.2	2.1	2.5	2.3
6	5/19	3.0	3.0	3.7	3.2
7	6/2	3.2	3.3	4.3	3.6
8	6/16	7.6	4.9	6.3	6.3
9	6/30				
10	7/14	12.0	6.9	7.4	8.8
11	7/28	3.2	3.4	11.6	6.0
12	8/11	3.0	4.3	3.1	3.5
13	8/25	3.8	5.0	1.9	3.6
	MIN	2.1	1.3	1.9	
	MAX	12.0	6.9	11.6	
	AVG	4.3	3.5	4.5	

Tabulated ET_c Values (in equivalent depth of water)

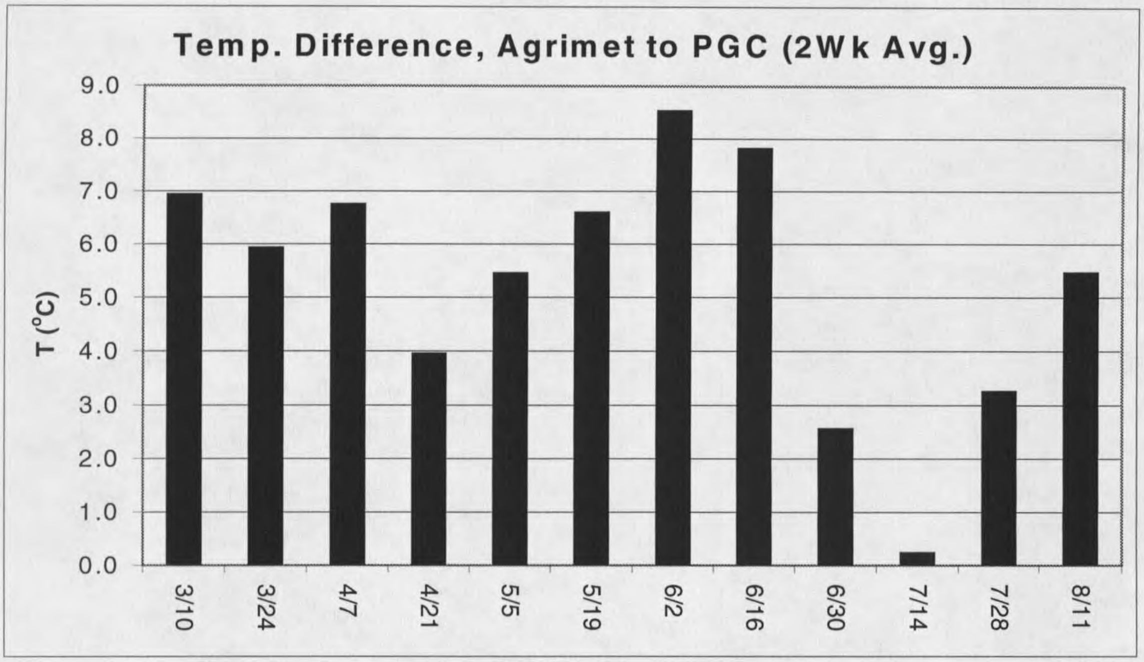
ETc
2 week averages
truncated (1%-99% of values)
by treatment

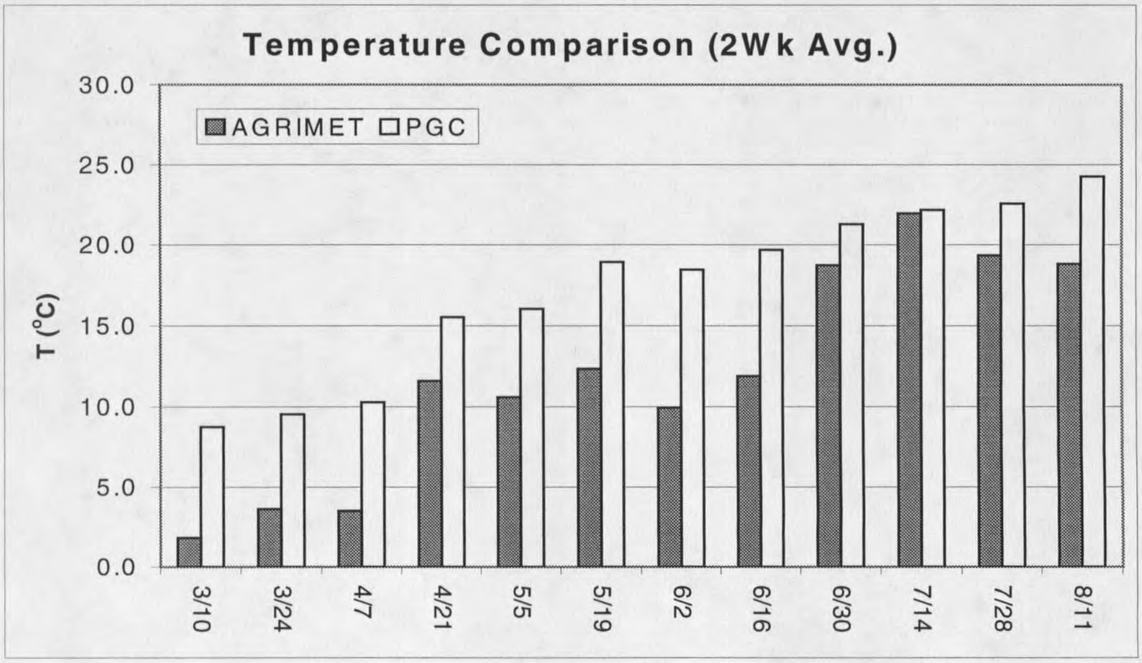
Period	**Date**	mm/d **Cattail**	mm/d **Bulrush**	mm/d **Control**	mm/d **AVG.**
1	3/10	6.4	6.1	7.2	6.6
2	3/24	10.9	6.3	9.1	8.8
3	4/7	7.7	7.1	6.2	7.0
4	4/21	8.7	7.1	6.7	7.5
5	5/5	10.2	8.1	7.0	8.4
6	5/19	11.7	9.7	7.8	9.7
7	6/2	10.1	8.8	8.7	9.2
8	6/16	16.5	13.5	11.2	13.8
9	6/30				
10	7/14	14.8	12.8	11.0	12.9
11	7/28	9.8	9.7	8.1	9.2
12	8/11	10.3	10.0	8.8	9.7
13	8/25	8.3	10.0	3.0	7.1
	MIN	6.4	6.1	3.0	
	MAX	16.5	13.5	11.2	
	AVG	10.5	9.1	7.9	

ETc
2 week SD
truncated (1%-99% of values)
by treatment

Period	**Date**	*ml/m* **Cattail**	*ml/m* **Bulrush**	*ml/m* **Control**	*ml/m* **AVG.**
1	3/10	2.2	1.8	2.7	2.2
2	3/24	3.4	2.7	2.4	2.8
3	4/7	3.3	1.0	2.9	2.4
4	4/21	1.7	1.5	2.7	2.0
5	5/5	1.8	1.7	2.0	1.8
6	5/19	2.4	2.4	3.0	2.6
7	6/2	2.6	2.7	3.4	2.9
8	6/16	6.1	3.9	5.1	5.0
9	6/30				
10	7/14	9.7	5.5	5.9	7.1
11	7/28	2.6	2.7	9.4	4.9
12	8/11	2.4	3.5	2.5	2.8
13	8/25	3.0	4.0	1.5	2.9
	MIN	1.7	1.0	1.5	
	MAX	9.7	5.5	9.4	
	AVG	3.4	2.8	3.6	

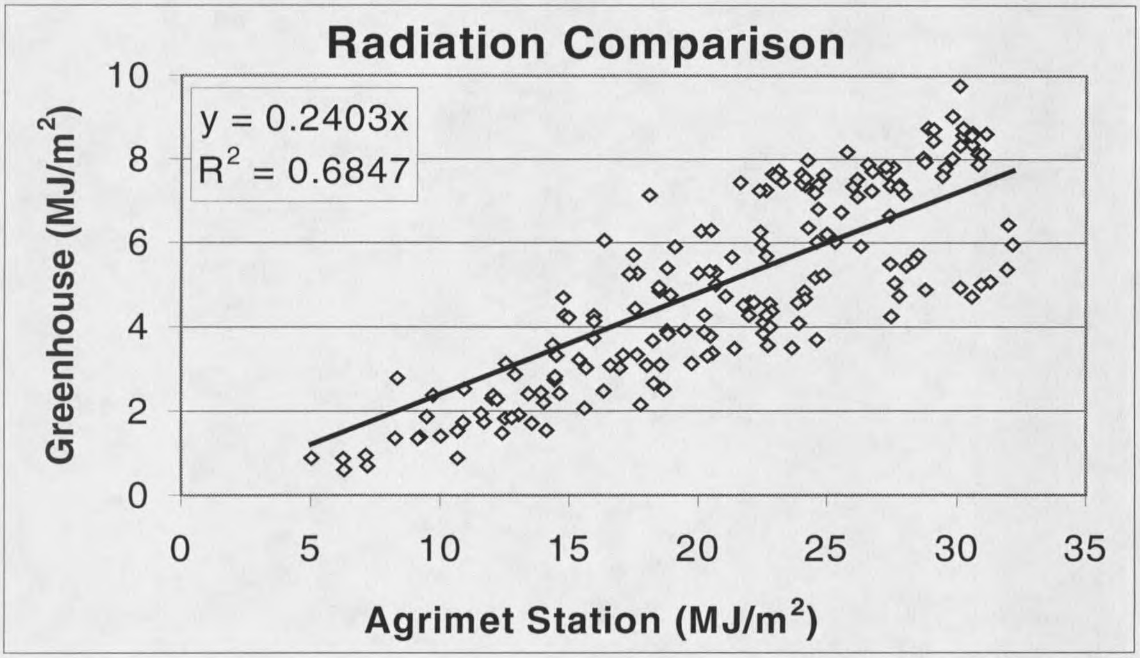
Mean Temperature Differences between Agrimet Station (local Bozeman conditions) and PGC

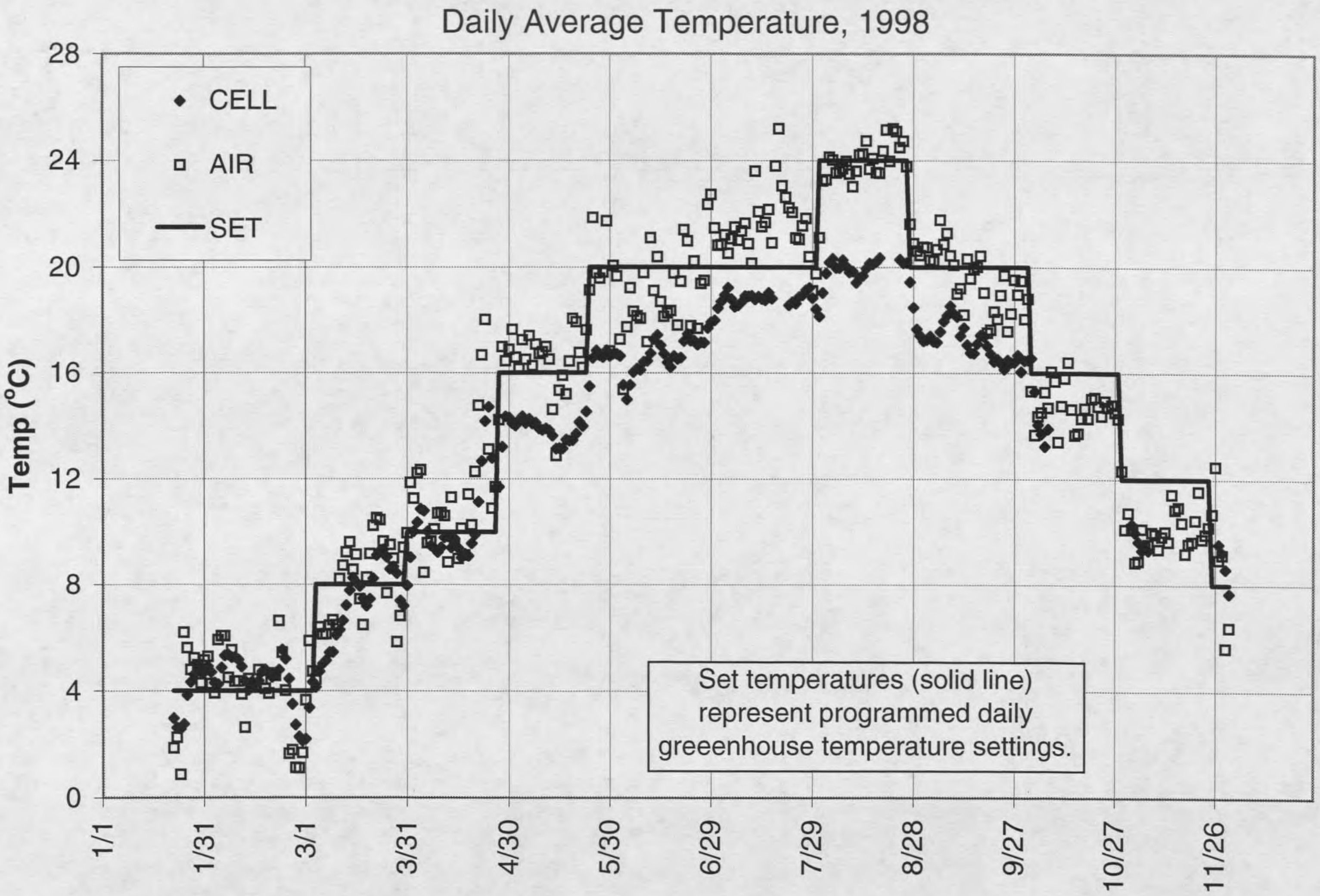




Radiation Comparison

The following is a comparison of net solar radiation record in the PGC and at the local Agrimet station. A linear regression verifies the interception rate of 76% for the shades in the greenhouse.

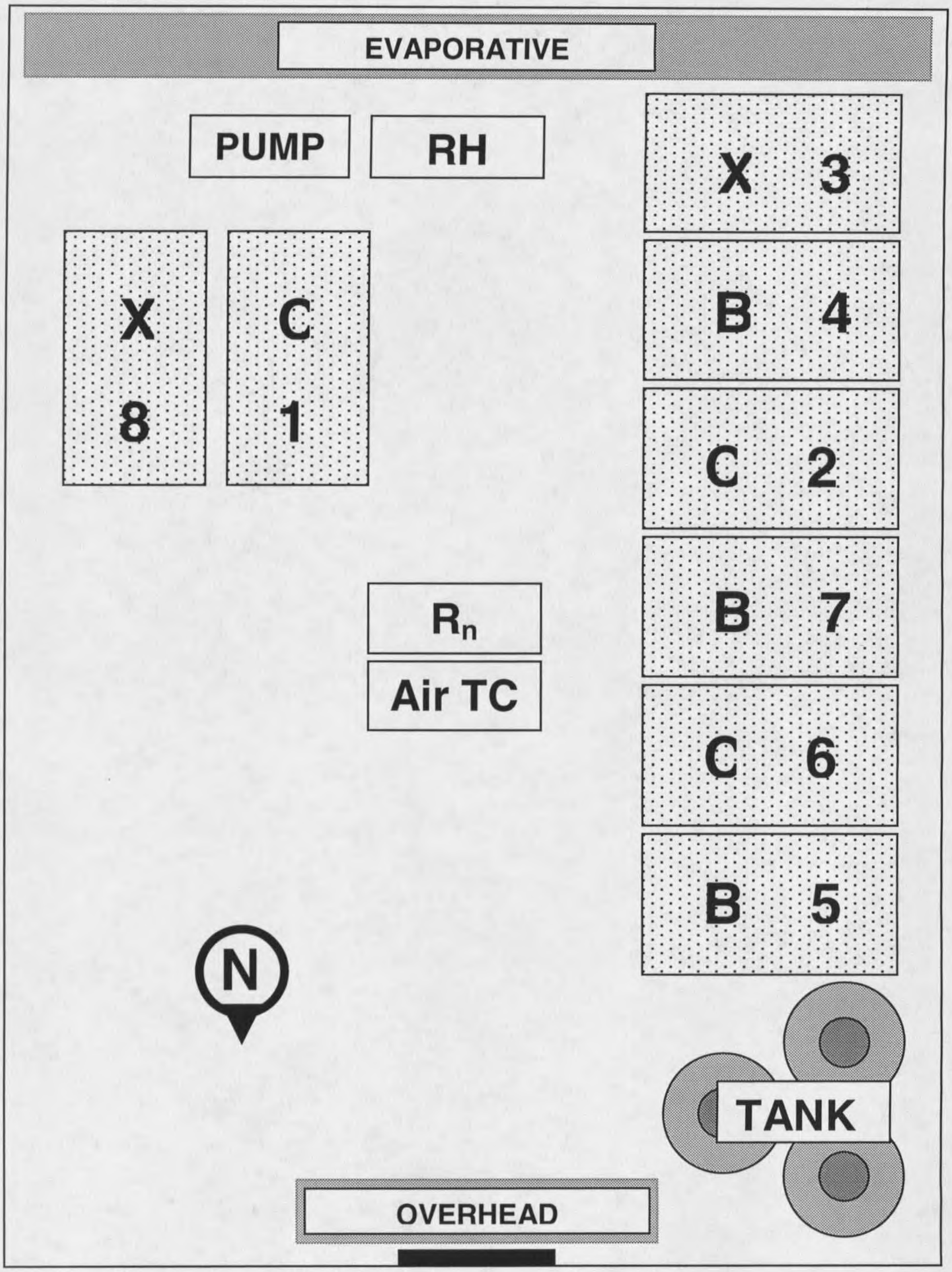




Set temperatures (solid line) represent programmed daily greeenhouse temperature settings.

APPENDIX C

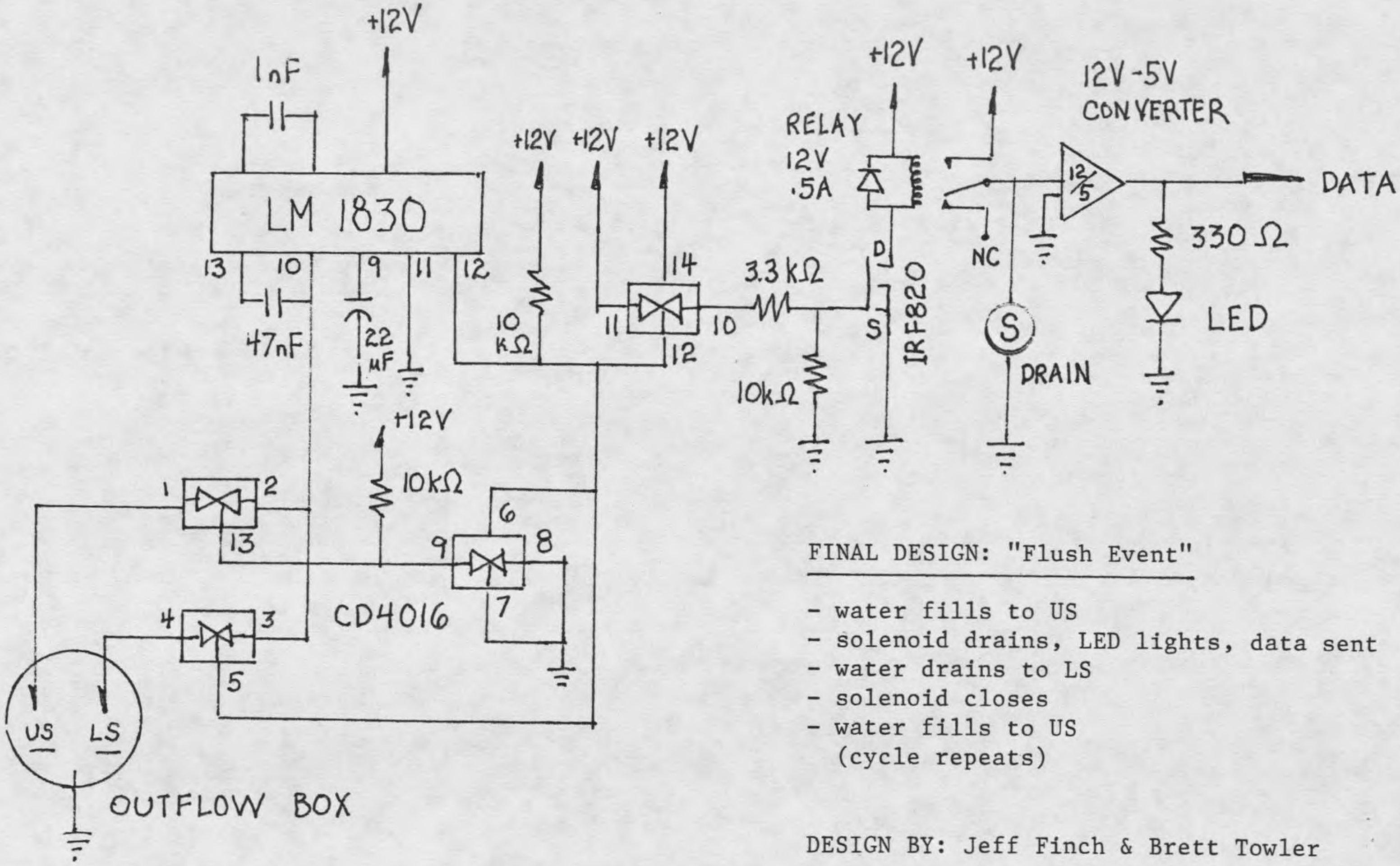
EQUIPMENT SPECIFICATIONS & LAYOUT



C : Cattail CW Cell
B : Bulrush CW Cell
X: : Control CW Cell

Rn : Net Radiometer
Air TC : Air Temp. Thermocouple
RH : Relative Humidity Probe

PGC GREENHOUSE PLAN (Not to Scale)



FINAL DESIGN: "Flush Event"

- water fills to US
- solenoid drains, LED lights, data sent
- water drains to LS
- solenoid closes
- water fills to US
  (cycle repeats)

DESIGN BY: Jeff Finch & Brett Towler

NOTE: Parts of this design are taken from LM1830 data sheets (National Semiconductor)

FLOW METER CIRCUIT DIAGRAM