



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

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Abstract:

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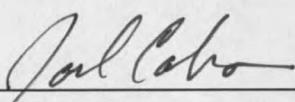
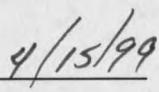
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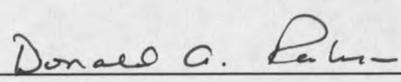
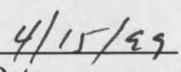
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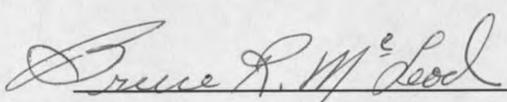
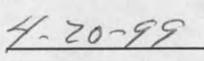
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ABSTRACT

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 *Typha 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 Pruitt, 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;

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

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:

$$R_n + G + H + A_n + LE + P = \Delta S \quad (2.2)$$

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;  $\Delta S$  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  $3\mu\text{m}$ , 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 ( $\alpha$ ) 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.

$$S_n = S_t ( I - \alpha ) \quad (2.3)$$

where  $S_n$  net incoming short wave radiation;  $S_t$  is the total incoming short wave radiation;  $\alpha$  is the reflection coefficient.

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

$$L_n = L_i - L_o \quad (2.4)$$

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.

$$R_n = S_n + L_n \quad (2.5)$$

*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* ( $\Delta S$ ). 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:

$$LE = \Delta S - R_n - A_n - P - H - G \quad (2.6)$$

Ignoring  $\Delta S$  and  $P$ , and using the convention that a loss from the system is positive the equation becomes:

$$LE = R_n - A_n - H - G \quad (2.7)$$

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.

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

### 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.

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

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

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

where  $ET_o$  is potential evapotranspiration in mm/day;  $\Delta$  is the slope of the saturation vapor pressure-temperature curve in mbar/K;  $\gamma$  is the psychrometric 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

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

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

$$G = (T_a - T_p)C_s \quad (2.12)$$

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 3/4 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).

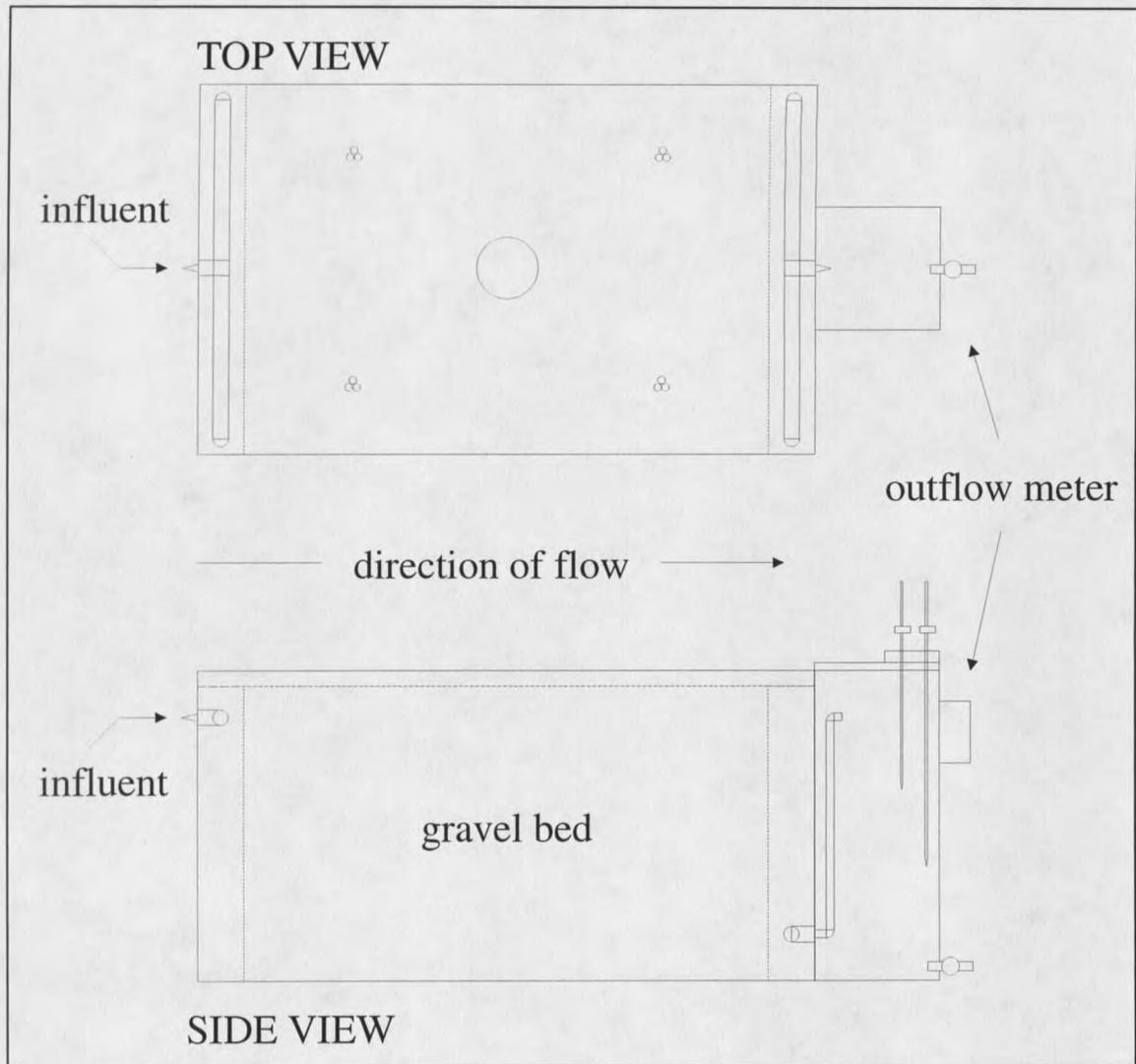


Figure 3.1. General schematic for bench-scale constructed wetland cells and outflow meters. (Not to scale.)

### 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  $\frac{1}{2}$  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.







































































































































































