# Assessment of Resources Available to Quantify Non-beneficial Consumptive Water Use by Riparian Vegetation in Nebraska

**Prepared for the**

**Riparian Vegetation Management Task Force**

**By**

**The Nebraska Department of Natural Resources**

Technical report number 2008-01

**December 15, 2008**

**Brian Dunnigan, Director**

**Integrated Water Management Division**

Jim Schneider – Division Head

**Contributing Authors**

Doug Hallum
Jason Alexander[1]
Amy Ostdiek
Terry Cartwright
Josh Lear
Mahesh Pun
Jesse Bradley
Dr. Scott Josiah[2]
Paul Koester
Dan Kloch

[1] – Hydrologist, US Geological Survey, Nebraska Water Science Center, 5231 South 19th, Lincoln, NE 68512-1271, jalexand@usgs.gov.
[2] – State Extension Forester, Nebraska Forest Service, 103 Plant Industry Building, P.O. Box 830815, Lincoln, NE 68583-0815, sjosiah2@unl.edu.

ERRATA — Assessment of Resources Available to Quantify Non-beneficial Consumptive Water Use by Riparian Vegetation in Nebraska, Nebraska Department of Natural Resources, Technical report number 2008-01, December 15, 2008

**Contributing Authors (Page ii):**

1) 1st footnote: replace "US Geological Survey" with "NDNR author, currently employed by the U.S. Geological Survey".

**Document Text:**

1) Page 44, first paragraph, first line; replace "Baird et al. (2007)" with "Baird et al. (2005)".
2) Page 44, last paragraph, first line; replace "Baird et al. (2007)" with "Baird et al. (2005)".
3) Page 44, last paragraph, last line; replace "Baird et al. (2007)" with "Baird et al. (2005)".
4) Page 47, second paragraph, item 2 of 4; replace "Baird et al. (2007)" with "Baird et al. (2005)".

**Bibliography:**

1) Add citation: Gurnell, A., 1997, The hydrological and geomorphological significance of forested floodplains: Global Ecology and Biogeography Letters, v. 6, p. 219-229.
2) Add citation: Kondolf, G.M., R. Kattelmann, M. Embury, and D.C. Erman, 1996, Status of Riparian Habitat. Chapter 36 in Sierra Nevada Ecosystem Project: Final Report to Congress, Vol II, Assesments and scientific basis for management options. Report No. 88, Centers for Water and Wildland Resources, University of California, Davis, p. 36-1 - 36-22.
3) Add citation: Naiman, R.J., DeCamps, H., and Pollack, M., 1993, The role of riparian corridors in maintaining regional biodiversity: Ecological Applications, v. 3, p. 209-12.

**TABLE OF CONTENTS**

LIST OF FIGURES ..... v

LIST OF TABLES ..... vi

1.0 INTRODUCTION ..... 7

2.0 PURPOSE ..... 9

3.0 STREAMSIDE VEGETATION AND THE RIPARIAN CORRIDOR ..... 10

4.0 WATER USE BY RIPARIAN VEGETATION ..... 13

5.0 ESTIMATING TRANSPIRATION OF WATER FROM RIPARIAN PLANTS ..... 16

5.1 Measurement of ET at the Individual Tree/Plant Scale ..... 16

5.1.1 Lysimeter and Small Plot Studies ..... 16

5.1.2 Xylem Sap Flow Measurements ..... 18

5.2 Measurement of ET at the Stand Scale ..... 19

5.2.1 Estimation of ET by Measurement of Pan Evaporation ..... 19

5.3 Measurement of Riparian ET from Diurnal Fluctuations in the Groundwater Table and Stream Discharge ..... 20

5.4 Measurement of ET at the Reach or Watershed Scale ..... 21

5.4.1 Reach and Catchment-Scale Water Budget ..... 21

5.4.2 Estimation of ET Using Remotely Sensed Data ..... 22

5.5 Common Theoretical Approaches to ET Estimation ..... 24

5.5.1 Calculation of ET Using the Energy Balance ..... 24

5.5.2 ET Approximation Using a Mass-Transfer Approximation ..... 26

5.6 Calculation of ET with Physically and Empirically-Based Equations ..... 27

5.6.1 Empirical Equations ..... 28

5.6.1.1 The Thornthwaite Equation ..... 28

5.6.1.2 The Blaney-Criddle Equation ..... 29

5.6.1.3 The Jensen-Haise Equation ..... 30

5.6.1.4 The Hargreaves Equation ..... 30

5.6.2 Physically-Based Equations ..... 31

5.6.2.1 The Penman Equation ..... 31

5.6.2.2 The Priestly and Taylor Equation ..... 32

5.6.2.3 The Penman-Monteith Equation ..... 33

6.0 WATER SALVAGE FROM VEGETATION REMOVAL: A HISTORICAL PERSPECTIVE ..... 35

7.0 PUBLISHED ESTIMATES OF WATER CONSUMPTION BY RIPARIAN VEGETATION IN NEBRASKA ....38

8.0 GROUNDWATER MODELING IN NEBRASKA AND CONSUMPTIVE USE BY RIPARIAN VEGETATION....41

8.1 Republican River Compact Accounting (RRCA) Model ....41

8.2 Cooperative Hydrology Study (COHYST) Models....42

8.3 Elkhorn-Loup Model (ELM) ....43

8.4 Uncertainty in Modeled ET Rates....43

9.0 IMPROVING GROUNDWATER MODELING IN NEBRASKA RELATED TO CONSUMPTIVE USE BY RIPARIAN VEGETATION.... 44

10.0 ET RESEARCH AND DATA NEEDS AND POTENTIAL AREAS OF IMPROVEMENT FOR GROUNDWATER MODELING IN NEBRASKA .... 46

11.0 CONCLUSIONS.... 48

BIBLIOGRAPHY....50

## LIST OF FIGURES

Figure 3-1. Spatial distribution of total species richness values for the state of Nebraska..... 10

Figure 5-1. Schematic diagrams of different types of lysimeters. .....17

Figure 5-2. Schematic diagram of constant heat method using xylem sap-flux sensors to estimate upward fluid velocities in woody plants as an estimate of transpiration rate. ..... 19

Figure 5-3. Diurnal fluctuations in the elevation of the groundwater table as related to daily transpiration by Alfalfa. ..... 20

Figure 5-4. Generalized schematic of reach scale water budget..... 22

Figure 5-5. Generalized schematic of the surface energy balance.....26

Figure 7-1. Locations of proposed and ongoing riparian *ET* research project within Nebraska. . 40

Figure 9-1. MODFLOW 96 traditional linear ET curve, MODFLOW 2000 segmented ET curve and modified segmented ET curve. ..... 44

## LIST OF TABLES

Table 3-1. Percent of land cover by cover class for the state of Nebraska. ..... 11

Table 4-1. Ranges of published values of annual consumptive use of water by common riparian and wetland vegetation. .....14

Table 7-1. Ongoing evapotranspiration related research studies within Nebraska.....39

## 1.0 INTRODUCTION

Subject to the requirements of the Nebraska Groundwater Management and Protection Act (act) (Neb. Rev. Stat. && 46-701 through 46-753), the Department of Natural Resources (DNR) and managing natural resources districts (NRDs) are required to develop integrated management plans (IMPs) for any river basin, subbasin, or reach whose hydrologically connected waters are designated as fully appropriated or overappropriated. In order to estimate the levels of appropriation of hydrologically connected waters, the DNR and NRDs build and operate several regional-scale numerical and analytical groundwater computer models. The basic framework of these models can be summarized by a generalized water budget equation for a reach of river:

$$I_{surf} + I_{ground} + P = O_{surf} + O_{ground} + ET + (V_2 - V_1) \qquad \textbf{(1)}$$

**Where:**

$\mathbf{I_{surf}}$, $\mathbf{I_{ground}}$ = volume of surface water and groundwater inflows

**P** = precipitation inputs

$\mathbf{O_{surf}}$, $\mathbf{O_{ground}}$ = volume of surface and groundwater outflows

**ET** = volume of water lost to evaporation and transpiration

$\mathbf{V_1}$, $\mathbf{V_2}$ = volume of water in basin at beginning and end of measurement time step ($V_2 - V_1$ = storage change)

Section 46-715.4(c) of the act requires the IMP to "identify the overall difference between the current and fully appropriated levels of development" which should "take into account cyclical supply, including drought…" The ET component of this equation represents a significant portion of the annual water budget and includes water consumed by both beneficial and non-beneficial vegetation. The designation as either beneficial or non-beneficial vegetation is related to its consumptive use of water being described with a corresponding designation of either beneficial or non-beneficial. Martin (2006) characterizes beneficial use as that supporting production of vegetation relating to "food, fiber, oil, landscape, turf, ornamentals, or forage" (p. 3) and non-beneficial use as that not attributable as beneficial.

As water supplies in Nebraska become further stretched to meet interstate compacts, maintain existing municipal and industrial demands, and satisfy increased agricultural demands in times of drought, it is essential to develop an understanding of those components of the budget that might help maximize our water supply. Water consumption (transpiration) by non-beneficial

vegetation has been identified as a component of water budgets that may have the potential to be converted to beneficial use. Section 2-958.02 of LB 701 designates two million dollars annually in 2007 and 2008 to “vegetation management programs that have as their primary objective improving the conveyance of streamflow in natural streams.” For the purposes of this report, the term “improving the conveyance” is believed to consist of two principal components relating to the quantity and quality of conveyance. The quantity component is believed to be synonymous with “increasing the amount of water supplied to the channel for conveyance,” and the quality component is taken to mean “improving the flow characteristics such that transit losses within the channel are minimized.” Although reduction of transpiration by vegetation within the stream corridor is not a specified goal of the funding, it is implied and a commonly cited goal in the funded grant proposals for FY 2007.

## 2.0 PURPOSE

The purpose of this report is to review and summarize published literature regarding consumptive use of groundwater by non-beneficial vegetation within and outside the state of Nebraska. While including discussion of vegetation classified as wetland (hydrophytes), this report focuses on vegetation within the corridors of natural streams.

This review begins with an assessment of vegetation types which occur within natural waterways, how water is consumed by this vegetation, and methods of estimating this consumption. It then includes an assessment of published reports documenting historical vegetation removal efforts whose main goal was to increase annual water yields in the form of stream flow. It summarizes published studies and ongoing efforts to estimate water consumption by riparian vegetation within Nebraska. Finally, the report reviews how streamside vegetation ET is currently modeled by DNR and NRDs, and compares these methods to the latest methods published in peer-reviewed journals and/or agency publications.

## 3.0 STREAMSIDE VEGETATION AND THE RIPARIAN CORRIDOR

LB701 authorizes the use of allocated funds for management of vegetation "within the banks of a natural stream or within one hundred feet of the banks of a channel of any natural stream." Streamside vegetation is often referred to as riparian vegetation and is the foundation of the riparian ecosystem. The word riparian relates to plant communities on the banks of natural watercourses, lakes or tidewaters (Merriam-Webster, 2003). Naiman et al. (1993) define the riparian corridor as the area of land that includes the stream channel and adjacent land above the high water mark such that vegetation can be influenced by a high water table or flooding. These areas can include the active floodplain of a river, as well as abandoned floodplains (terraces) containing riparian vegetation (Kondolf et al., 1996).

As the interface between the aquatic and terrestrial environments, riparian corridors are some of the most productive and diverse of terrestrial ecosystems (Naiman et al., 1993). While representing a relatively small proportion of the total landmass, riparian corridors fulfill a disproportionate volume of ecological functions; this is especially true in semi-arid and arid climates where stream corridors are often the only water source for tens of miles (Gurnell et al., 1997). Recent data published by CALMIT shows a strong association between the number of bird, reptile/amphibian, and mammalian species within the major river corridors of the state (Henebry et al., 2005) (figure 3-1). Additionally, four of five bird species listed as threatened or endangered by the Nebraska Game and Parks Commission use river corridors as habitat.

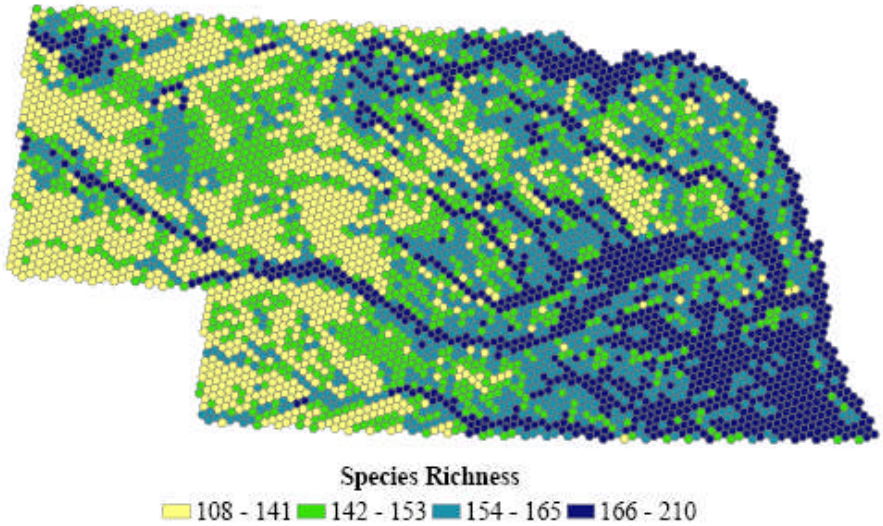


**Figure 3-1.** Spatial distribution of total species richness values for the state of Nebraska as modeled for the Nebraska GAP mapping project (Henebry et al., 2005). High values indicate number of modeled avian, reptile/amphibian, and mammalian species likely to occur within a 40 $km^2$ cell.

In addition to providing refuge and habitat for avian, mammalian and amphibian species, acting as a nutrient source and sink, and functioning as a stream temperature regulation mechanism, riparian corridors provide services to human communities. Riparian buffers reduce stream sedimentation, act as nutrient and contaminant filters, and provide property protection through bank stabilization (Kondolf et al., 1996; NRCS, 1999). Riparian corridors also provide important services to agriculture by acting as natural windbreaks and as the structure for important habitat and forage for native bee species which perform critical fertilization needs (Idso, 1981; USDA, 2006, 2007).

Riparian plant species occupy a total of 0.29 percent (Henebry et al., 2005) of the total landcover in the state of Nebraska (table 3-1). When grouped with other groundwater-consuming landcovers such wetlands and open water, these environments compose a total of 2.33 percent of the landcover of the state of Nebraska.

**Table 3-1.** Percent of land cover by cover class for the state of Nebraska. Riparian, wetland, and open water comprise less than 2.5% of the state land cover.

| Cover Class | Land Cover Name | $km^2$ | $Mile^2$ | Acre | Hectare | Percent |
|---|---|---|---|---|---|---|
| 1 | Ponderosa Pine Forests and Woodlands | 1070.61 | 413.36 | 264551.67 | 107060.67 | 0.53 |
| 2 | Deciduous Forest/Woodland | 3484.83 | 1345.50 | 861117.80 | 348483.33 | 1.74 |
| 3 | Juniper Woodland | 1022.11 | 394.64 | 252568.64 | 102211.29 | 0.51 |
| 4 | Sandsage Shrubland | 677.44 | 261.56 | 167398.85 | 67744.17 | 0.34 |
| 5 | Sandhills Upland Prairie | 45572.45 | 17595.62 | 11261155.26 | 4557245.13 | 22.74 |
| 6 | Lowland Tallgrass Prairie | 7301.69 | 2819.20 | 1804280.52 | 730169.19 | 3.64 |
| 7 | Upland Tallgrass Prairie | 7885.88 | 3044.75 | 1948635.58 | 788587.83 | 3.94 |
| 8 | Little Bluestem-Gramma Mixedgrass Prairie | 30324.11 | 11708.20 | 7493221.34 | 3032410.59 | 15.13 |
| 9 | Western Wheatgrass Mixedgrass Prairie | 207.59 | 80.15 | 51297.62 | 20759.49 | 0.10 |
| 10 | Western Shortgrass Prairie | 16752.67 | 6468.24 | 4139658.60 | 1675266.75 | 8.36 |
| 11 | Barren/Sand/Outcrop | 926.94 | 357.89 | 229051.36 | 92694.15 | 0.46 |
| 12 | Agricultural Fields | 73618.49 | 28424.25 | 18191454.91 | 7361848.53 | 36.74 |
| 13 | Open Water | 1296.87 | 500.72 | 320461.30 | 129686.58 | 0.65 |
| 14 | Fallow Agricultural Fields | 5299.77 | 2046.25 | 1309595.54 | 529976.52 | 2.64 |
| 15 | Aquatic Bed Wetland | 404.11 | 156.03 | 99856.69 | 40410.72 | 0.20 |
| 16 | Emergent Wetland | 2384.78 | 920.77 | 589289.61 | 238477.95 | 1.19 |
| 17 | Riparian Shrubland | 219.53 | 84.76 | 54247.90 | 21953.43 | 0.11 |
| 18 | Riparian Woodland | 357.56 | 138.05 | 88354.02 | 35755.74 | 0.18 |
| 19 | Low Intensity Residential | 877.54 | 338.82 | 216842.82 | 87753.51 | 0.44 |
| 20 | Commerical/Industrial/ Transportation | 686.36 | 265.01 | 169602.78 | 68636.07 | 0.34 |
| | **TOTAL** | **200371.32** | **77363.79** | **49512642.82** | **20037131.64** | **100.00** |

Other locations where riparian vegetation can be found include springs, seeps, and water resources infrastructure such as ditches, canals, ponds, and reservoirs. Examples of common, native Nebraskan riparian tree species include Eastern Cottonwood (*Populus deltoides*), Boxelder (*Acer negundo*), and Sandbar Willow (*Salix exigua*). Several invasive/noxious riparian species, including Tamarisk (hybrids of *Tamarix ramossissima* and *Tamarix chinesis*), Russian Olive (*Elaeagnus angustifolia*), and Phragmites (*Phragmites australis)* are also found in Nebraska (Rand, 1972; Johnsgard, 2001).

## 4.0 WATER USE BY RIPARIAN VEGETATION

Plants transpire water in order to absorb carbon dioxide which they use to create glucose, their energy source. Transpiration takes place during the daylight hours when light is absorbed to provide energy in the photosynthetic process. Osmotic pressures within the cells of roots allow a plant to absorb water from the surrounding substrate. This absorption causes increasing hydrostatic pressures within the root system, whereby, a negative pressure gradient is created in the leaves of the plant as the stomata open and close to absorb carbon dioxide gas from the atmosphere. When the stomata open, the plant releases water vapor, causing a decrease in pressure, which moves water up through the plant xylem through a process called transpirational pull (water flows from high to low pressure). Transpirational pull is accommodated by the electrostatic bonds (creating capillary forces) between water molecules. Plants regulate transpiration depending on several climatic and physiological factors including soil water availability, net solar radiation, relative humidity, soil and water salinity, and magnitudes of wind activity (USGS, 2007).

Riparian vegetation can be divided into two groups, obligate and facultative. Characteristics typical of obligate riparian vegetation include dependence on a high water table, tolerance to inundation and soil anoxia, tolerance to physical damage from flooding, tolerance to burial by sediment from floods, and ability to colonize and grow in substrates with few soil nutrients. Facultative vegetation can survive without access to saturated or near-saturated soil water levels. The boundaries between these two groups are not hard, and species considered obligate have been shown to tolerate seasonal fluctuations in the water table, including unsaturated conditions (Dahm et al., 2002).

Similarly, although phreatophytes are traditionally plant species that consume groundwater (i.e. Robinson, 1958), Naumberg et al. (2005) note that the term has little utility since all plants consume groundwater when it is within the reach of their roots. Furthermore, groundwater consumption, even among riparian obligate plant species, can be seasonal since groundwater table elevations can vary dramatically both seasonally and annually.

While riparian vegetation provides significant ecological and societal benefits, it consumes more water than other terrestrial vegetation species because it generally has constant access to saturated zone or capillary fringe water (Johns, 1989). In the arid climate of the southwestern United States, individual Cottonwood and Saltcedar trees have been shown to

consume nearly 90 in. of water annually (table 4-1) (Gatewood et al., 1950; Robinson, 1958); however, recent research has reported this volume to be rare, and site/stand specific (Cleverly et al., 2002; Glenn and Nagler, 2005; Nagler et al., 2005; Owens and Moore, 2007). In arid regions, Saltcedar trees are known to consume more water than native riparian vegetation (Carpenter, 1998; Weeks, et. al., 1987) and can grow in dense stands of up to 3000 trees per acre (Carpenter, 1998). They are capable of crowding out native species and creating a monoculture in the stream corridor.

**Table 4-1**. Ranges of published values of annual consumptive use of water by common riparian and wetland vegetation as compiled by Johns (1989). Ranges of values of annual consumptive use for Phragmites calculated from published rates in Burba (1999) and Cummings (2007).

| Common Name | Range of Annual Consumptive Use (inches) | Number of Studies | Study Locations | Methods |
|---|---|---|---|---|
| Arroweed | 96 | 1 | AZ | Tank |
| Cattail | 35-198 | 7 | AZ, CA, CO, MI, MN, NM, UT | Tank, Water Balance |
| Cottonwood | 39.3-92.7 | 7 | AZ, CA, CO, KS, NM, Saskatchewan | Tank, Diurnal Fluctuation, Gravimetric, Water Balance |
| Bermuda Grass | 28.8-73 | 1 | CA | Tank, Water Balance |
| Phragmites | 7.2-30.71 | 2 | NE | Lysimeter, Energy Balance, Leaf Porometer |
| Salt Grass | 6.2-48.8 | 11 | CA, CO, NM, NV, UT, WA | Tank, Water Balance, Lysimeter, Diurnal Fluctuation |
| Rush | 20.8-86.6 | 5 | CA, CO, MI, Saskatchewan | Tank, Water Balance, Diurnal Fluctuation |
| Russian Olive | 18.6-114.6 | 1 | NM | Lysimeter |
| Saltcedar (Tamarisk) | 11.8-86 | 16 | AZ, CA, CO, KS, NM, NV, UT, WA | Tank, ET Tent, Lysimeter, Water Balance, Leaf Area Model, Energy Balance, Gravimetric |
| Willow | 13.2-47.8 | 8 | CA, KS, NM, NV, UT, WA, Saskatchewan | Tank, Water Balance, Diurnal Fluctuation, Gravimetric - Portable Chamber |
| Riparian Woodland | 13.2-22.4 | 4 | AZ | Water Balance |

In addition to local climate, the number of plants per unit area, presence or absence of other species, and relative depth to groundwater may all be controlling factors relating to actual water use in a given location. Therefore, the volume is likely somewhat lower for riparian stands in the more humid and seasonal climate of Nebraska, though little research has been completed within the state to quantify annual water consumption by riparian vegetation, leaving its significance with respect to water supplies and stream conveyance open to speculation.

## 5.0 ESTIMATING TRANSPIRATION OF WATER FROM RIPARIAN PLANTS

Evaporation is the process whereby liquid water is converted to water vapor and removed from the evaporating surface (lake, river, soil, wet vegetation, concrete etc.). Transpiration is the vaporization of liquid water from plant tissue to the atmosphere via small openings in the plant leaf called stomata. These two processes are collectively referred to as evapotranspiration (*ET*). Evaporation and transpiration occur simultaneously, and are difficult to separate or estimate accurately. There is no method for directly measuring *ET,* and as a result *ET* is often estimated from the residual of measurements of several other climatic and environmental variables. This difficulty in direct measurement arises because *ET* is a complex function of several climatic and botanical factors which vary spatially and temporally. Climatic variables include solar radiation, relative humidity, wind speed and run, and temperature. Differences in stomata resistance, water need, aerodynamic resistance, and soil type, because of age, structure, composition, and density of riparian plant stands, as well as geographic setting, have profound effects on actual *ET* under a given set of climatic conditions (Nagler et al., 2005).

Three methods are generally referenced for measuring evapotranspiration: (1) mass-balance (2) energy budget (3) mass-transfer (Johns, 1989). These methods have been used to derive and calibrate physical and empirical equations for estimation of *ET*. Regardless of the method used, estimation of *ET* requires foresight into the scale of interest. Wilcox et al. (2006) cite four general scales used in the literature for riparian vegetation *ET* studies: (1) tree scale (2) stand scale (3) small catchment scale (large enough to incorporate channel and groundwater flow processes) (4) landscape scale (watersheds of 20 $km^2$ or greater). Below we summarize several methods of estimating evapotranspiration from riparian plants and provide some notes on the general scale of their application. This summary is intended as a review, but is not intended as an exhaustive methods guide. Dunne and Leopold (1978), Johns (1991), Allen et al. (1998), and Nichols et al. (2004) provide more in-depth reviews of methods of ET estimation.

### 5.1 Measurement of ET and the Individual Tree/Plant

#### 5.1.1 Lysimeter and Small Plot Studies

The preferred method of measuring *ET* directly is by constructing a finely tracked water balance for a single plant and its associated rooting medium. In order to mimic actual field conditions, the soil profile, plant type, canopy elevation, and vegetation density should be the

same as the surrounding vegetation (Allen et. al., 1998). The general form of a plant-scale water budget is:

$$ET = PPT + I - Q_{g\text{-}out} + \Delta S \qquad \textbf{(2)}$$

**Where:**

***ET*** = evapotranspiration

**PPT** = precipitation within the measurement area

**I** = irrigation

$\mathbf{Q_{g\text{-}out}}$ = groundwater discharge out of the lysimeter (drainage)

**ΔS** = change in storage (soil moisture.)

If precipitation and irrigation area are monitored, *ET* is the result of the two remaining variables: (1) drainage and (2) change in storage, or soil moisture. To measure these terms, a lysimeter (porous-bottomed tank) is buried in the ground and is generally large enough not to restrict the growth and development of the plant of interest (Dunne and Leopold, 1978) (figure 5-1).

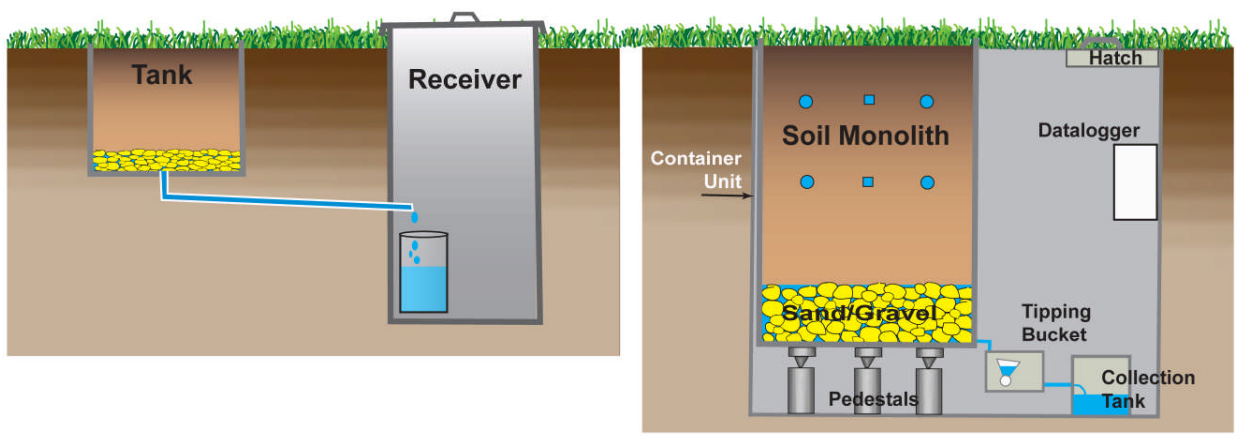


**Figure 5-1.** Schematic diagrams of different types of lysimeters: (a) drainage (Perkins, 1999) and (b) weighing (Meissner and Seyfarth, 2004).

In the absence of a weighing mechanism, change in storage is assumed to be zero, and the lysimeter will track drainage out of the bottom of the tank. If the lysimeter has a weighing mechanism, changes in storage are tracked by the change in mass of the tank. *ET* can be statistically correlated to nearby climatic measurements to construct empirical relations or generate crop coefficients for existing physical or empirical equations.

While a lysimeter has high temporal resolution (hours to days), it has low spatial resolution (limited to the tree or a small vegetated plot). However, because of their accuracy, lysimeters are useful as a research tool, and are the typical reference for calibration of other less-direct methods (Allen et. al., 1998). The same water balance equation and experimental design can be used on a single tree using a small plot with uniform soil conditions. In soil plots with shallow soils, drainage must be monitored; for deep soils drainage is assumed to be 'zero' (Dunne and Leopold, 1978).

### 5.1.2 Xylem Sap Flow Measurements

Transpiration as a singular process can be approximated by measuring the flux of fluid within the xylem of woody plants. Sap flux measurements use thermal dissipation theory to calculate the velocity of fluid between two probes fitted with thermocouples and inserted into a tree stem, one above the other (Smith and Allen, 1996). The upper probe is heated and the temperature compared to the lower probe, a thermal dissipation equation applied, and a fluid velocity obtained (figure 5-2).

Sap flow measurements can be taken on several trees within a stand and applied over the time scale of an hour, then related to nearby climatic measurements (Wullschleger et al., 1998). An advantage of sap flow measurements is the ability to obtain transpiration by several different species within a stand under the same environmental and climate conditions. Thus, sap flow measurements can be applied at the individual tree or at the stand scale using several measurements.

Although the most direct measure of fluid flow in a tree, sap flow measurements encounter the problem of only measuring *transpiration*; evaporation must be a separate estimate. Thus, sap flux can greatly underestimate *ET*, even when combined with other measures (Wilson et al., 2001; Ford et al., 2007). In addition, radial variations in sap-flux velocity can introduce large degrees of uncertainty to the transpiration approximation (Nadezhdina et al., 2002).

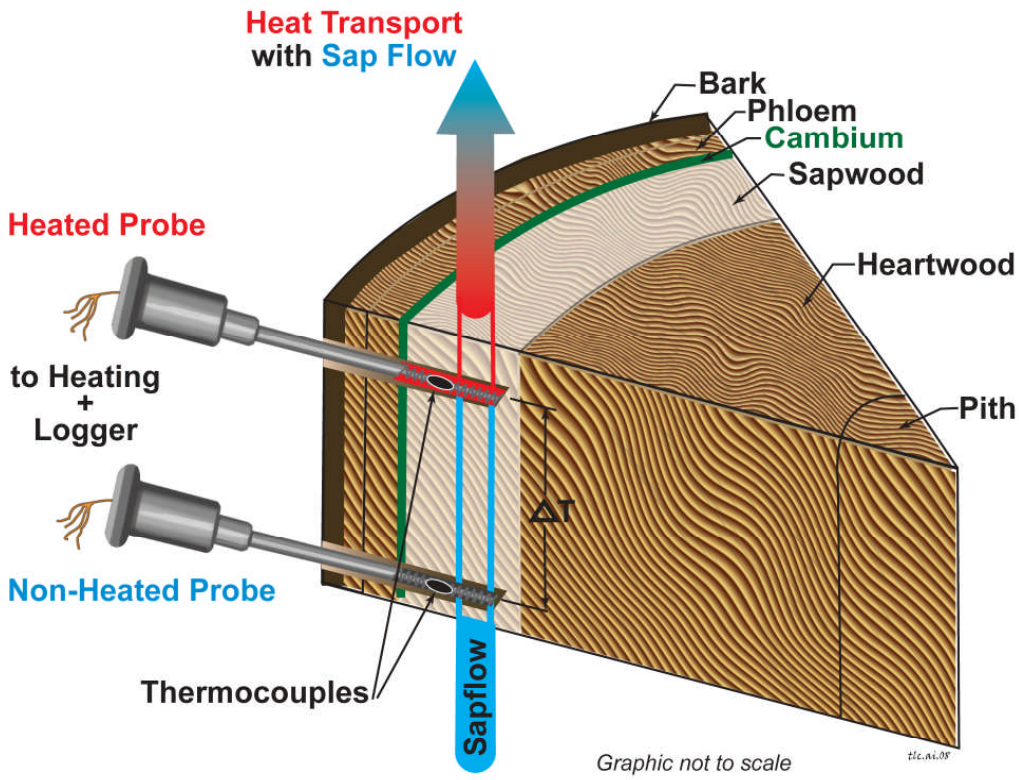


**Figure 5-2.** Schematic diagram of constant heat method using xylem sap-flux sensors to estimate upward fluid velocities in woody plants as an estimate of transpiration rate (www.geographie.uni-mannheim.de/inst/lpg/motzer/abstract.htm).

## 5.2 Measurement of ET at the Stand Scale

### 5.2.1 Estimation of ET by Measurement of Pan Evaporation

Measurement of evaporation from a free water surface can be accomplished using a U.S. Weather Bureau Class A evaporation pan by tracking the volume of water in the pan over time. In conjunction with a well-instrumented climate station, evaporation from a pan can be closely tracked and related to other climatic variables, such as temperature, with fine temporal resolution. Although it is not a direct measurement of transpiration, pan evaporation measurements integrate several climatic factors and are a reasonable way of obtaining an index of potential *ET* (Dunne and Leopold, 1978). In turn, pan-estimated potential *ET* can be related to *ET* for a specific plant species (or composition of several species) through empirically-based coefficients, usually obtained from other methods such as lysimeters or plot-scale water budgets.

### 5.3 Measurement of Riparian ET from Diurnal Fluctuations in the Groundwater Table and Stream Discharge

Groundwater consumption by vegetation during daylight hours was recognized early in the 20th century as causing a signature diurnal fluctuation in the water table observed in nearby monitoring wells (White, 1932) (figure 5-3).

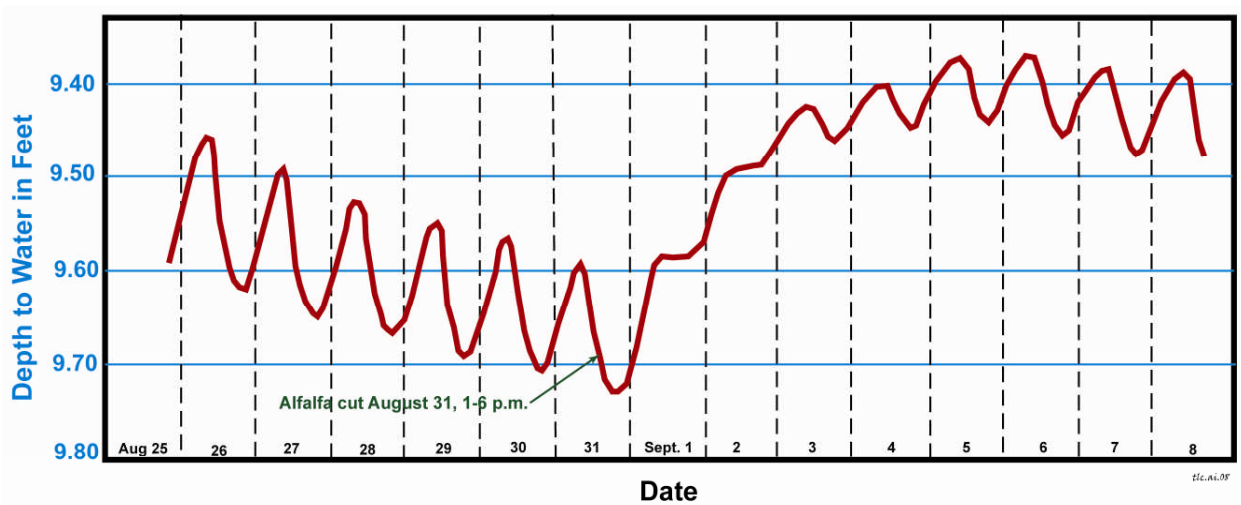


**Figure 5-3.** Diurnal fluctuations in the elevation of the groundwater table as related to daily transpiration by Alfalfa. Note the two-day hiatus from fluctuations, and groundwater elevation rise after the alfalfa was cut (White, 1932).

These fluctuations are similar to the behavior of the groundwater table when an irrigation well pump is being turned on and off, and are caused by the daytime transpiration of groundwater by riparian vegetation (Butler et. al., 2007). White (1932) devised a method of estimating groundwater consumption by vegetation using the equation:

$$ET_g = S_y (r_{+/-} s) \qquad \textbf{(3)}$$

**Where:**

**$ET_g$** = evapotranspirative consumption of groundwater

**$S_y$** = the specific yield of the surrounding aquifer and soil

**r** = the net inflow calculated from groundwater recovery during night

**s** = net change in water table elevation over one day

Butler et al. (2005) used the method of White (1932) in several test sites in the western United States, including a test site in the Arkansas River valley of Kansas. Butler et al. (2005) found that the method of White (1932) effectively estimated water use for vegetation growing in riparian zones underlain with sands and gravels because the readily available specific yield ($S_y$) is similar to porosity, which could be estimated with some certainty. However, in finer grained substrates, Butler et al. (2005) noted that the difficulty in obtaining the $S_y$ estimate could reduce the reliability of the method. Butler et al. (2005) cautioned against applying single well estimates of *ET* for reach-scale assessments because the variability in substrate, land use practices, and vegetation composition could substantially alter the calculated magnitude of *ET*.

Reigner (1966) used diurnal fluctuations in the discharge records of Dilldown Creek, PA, to estimate baseflow depletions from riparian vegetation. He used multiple regression analysis to relate the magnitude of the daily depletion (downward dip in the diurnal fluctuation) to the local vapor pressure deficit and mean daily stream flow. Reigner (1966) estimated the largest daily portion of streamflow lost was 23 percent and the largest total loss was 0.44 $ft^3$/second. The largest loss, however, was only 50 percent of the estimated potential *ET* (see below) for that day.

## 5.4 Measurement of ET at the Reach or Watershed Scale

### 5.4.1 Reach and Catchment-Scale Water Budget

Although extremely measurement intensive, *ET* can be calculated as the residual of a comprehensive water balance constructed for a small drainage basin, or a reach of river (figure 5-4). This method follows a general water budget equation usually applied at the monthly timescale:

$$ET = PPT + Qg_{in} - Qg_{out} - Qsurf_{out} + \Delta S \qquad \textbf{(4)}$$

**Where:**

**PPT** = precipitation into the basin or reach

**Qg-in** = groundwater discharge into the basin or reach

**Qg-out** = groundwater discharge out of the basin or reach

**$Qsurf_{out}$** = surface water discharge out of the measurement area

**ΔS** = change in storage within the basin or reach

This equation assumes the basin is closed, with no surface water discharges from other basins (no ditches, canals, etc.). All of the above variables are measured except for *ET*, which is the residual of the equation. If irrigation from groundwater pumping was to be added, it would be fractioned into additional losses as a groundwater extraction, and a groundwater addition from the unconsumed portion that returns to the aquifer. While this method applies to a larger area, there is uncertainty in each measurement needed, especially in the components that can have extreme spatial variability, such as soil moisture or groundwater conductance (Dunne and Leopold, 1978). Several intensive, reach-scale water budgets have been constructed to evaluate riparian *ET* in the desert southwestern United States. We discuss some of these studies in further detail below.

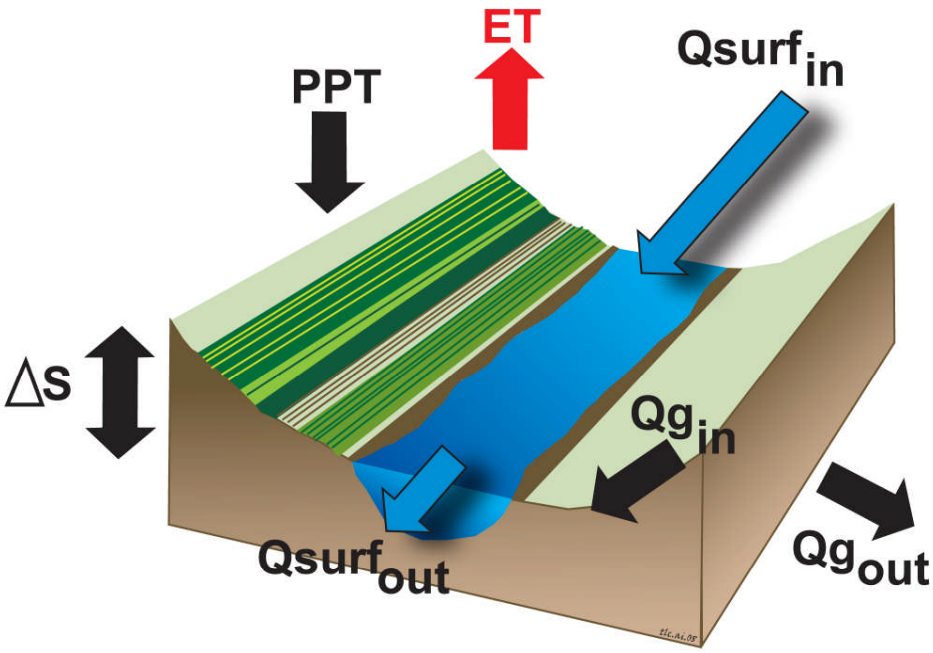


**Figure 5-4.** Generalized schematic of reach scale water budget. At the watershed scale, Qsurf$_{in}$ is not considered unless a canal or trans-basin diversion discharges into the watershed.

### 5.4.2 Estimation of ET using Remotely Sensed Data

Estimation of riparian *ET* using the energy budget, Bowen ratio, FAO-Penman-Monteith equation, or other empirical equations can produce reasonable magnitudes at the scale of a local river reach, however these estimations are not representative of several miles/kilometers of river corridor. In the past, the most spatially-robust measures of riparian *ET* were developed through basin-scale or extended reach-scale mass-balance studies. Although these studies have been

shown to produce reliable estimates of riparian *ET*, they are expensive, measurement and labor intensive, and require several years of data collection to develop baseline *ET* estimations.

With the continuing increase in computing power, use of remotely sensed data have made estimating *ET* over larger regions or large reaches of river easier. The U.S. National Aeronautics and Space Administration (NASA) obtains and provides multi-spectral imagery of the earth's surface to the general public as part of its Earth Observing System (EOS) program. Currently, NASA operates four satellites which have multi-spectral sensors on-board that provide imagery for use in *ET* studies. The Landsat 5 and Landsat 7 satellites each have 16-day orbits, offset by 8 days, and provide spectral data with 15 to 120 m resolution every 16 days for the United States. The Aqua and Terra satellites have daily orbits and each carries a moderate resolution imaging spectroradiometer (MODIS) sensor. These satellites provide 16-day composite data for the total earth surface at 250 to 500 m resolution.

Several algorithms have been developed to estimate *ET* from satellite data. Two common vegetation algorithms are the Normalized Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI), which utilize ratios of difference between the red and near infra-red spectral bands within individual data grid cells. To estimate *ET*, the satellite imagery must be statistically related to or calibrated with ground-based *ET* estimates. Recently, Nagler et al. (2005) estimated riparian *ET* for the Middle Rio Grande, Upper San Pedro, and Lower Colorado Rivers by statistical correlation of EVI, NDVI, and Land Surface Temperature (LST) estimates from MODIS with several ground-based *ET* measurements from eddy-covariance and Bowen stations. Nagler et al. (2005) found that the approximately 70 percent of the variability could be explained by NDVI and EVI, but that the MODIS LST estimates were too coarse to estimate *ET* in the narrow riparian corridor.

For smaller river corridors, the MODIS cell size of 250 m can be too large to accurately isolate *ET*. Bastiaanssen et al. (1992) developed the Surface Energy Balance Algorithm for Land (SEBAL) model, which uses the thermal infrared spectral channel from Landsat imagery. Bastiaanssen et al. (2005) showed that SEBAL could estimate *ET* to within +/- 15 percent at the scale of 100 hectares. Allen et al. (2007) developed the Mapping Evapotranspiration at high Resolution with Internalized Calibration (METRIC) model, using the SEBAL algorithm. METRIC has been shown to estimate *ET* to within 4 to 20 percent of lysimeter study estimates at the 120 m scale (Allen et al., 2007).

*ET* algorithms have also been developed for non-satellite based remote sensing tools. Loheide and Gorelick (2005) developed the local-scale, high-resolution evapotranspiration mapping algorithm (ETMA) for the forward-looking infrared (FLIR) camera. The FLIR captures thermal infrared data at the scale of 10-100 m. Loheide and Gorelick (2005) showed that the ETMA algorithm estimated *ET* to within 10 percent of $ET_p$ (from FAO-Penman-Monteith method), but did not report the accuracy of the ETMA relative to a more robust measure of *ET* such as an eddy-covariance or Bowen system. Cooper et al. (2000) used ground-based Light Detection and Ranging (LiDAR) imaging to estimate *ET* over 5600 m areas over a 500 m range. Cooper et al. (2000) showed that the LiDAR estimated to within 10-15 percent of sap-flux *ET* measurements.

## 5.5 Common Theoretical Approaches to ET Estimation

### 5.5.1 Calculation of ET Using the Energy Balance (Hornberger et al., 1998; Campbell, 1998)

When the sun's energy (shortwave radiation) hits the earth's surface, some is reflected, some is absorbed by the ground (soil/rock), some is input to the air (sensible heat), and the rest in input into water (latent heat). The latent energy (heat) that is used to convert liquid water to water vapor is removed from the system as the water vapor moves from the surface into the atmosphere, but is then converted back to thermal energy as the water re-condenses.

The rate of evaporation can be described in terms of an energy balance (figure 5-5), the basic equation is:

$$\frac{\Delta Q}{\Delta t} = R_n - G - H - E_l \qquad \textbf{(5)}$$

**<u>Where:</u>**

***Q*** = the amount of energy stored in a control volume per unit area of surface

***t*** = time

$\boldsymbol{R_n}$ = the net solar radiation (input minus reflected radiation)

***G*** = energy output through conduction to the ground

***H*** = net output of sensible heat (energy used to change temperature)

$\boldsymbol{E_l}$ = output of latent heat (internal energy of mass released or absorbed during a phase change

The equation can be rearranged such that it is a solution for latent heat flux:

$$E_l = R_n - G - H - \frac{\Delta Q}{\Delta t} \qquad \textbf{(6)}$$

Latent heat flux ($E_l$) is related to the rate of evapotranspiration through the latent heat of vaporization (a constant):

$$et = \frac{E_l}{\rho_w \lambda_v} \qquad \textbf{(7)}$$

**<u>Where:</u>**

$et$ = evapotranspiration rate (units of length/time)

$\rho_w$ = density of water (constant)

$\lambda_v$ = latent heat of vaporization (constant)

Therefore, with substitution of **(6)** into **(7),** the equation becomes:

$$et = \frac{R_n - G - H - \frac{dQ}{dt}}{\rho_w \lambda_v} \qquad \textbf{(8)}$$

$R_n$ and $G$, are measured values, while $H$ is either estimated using eddy covariance (correlation) methods, the Bowen ratio, or calibrated satellite thermal imaging data (discussed below). Because dQ/dt is an energy storage term, over a 24-hour period it is considered to be 0; however, this term is also the budget closure term, and can be used as an estimate of the measurement error of the energy budget. Because the energy balance is calculated using measurement of climatic variables from an instrumented station, the method applies to the scale of the fetch (distance to the upwind turbulent boundary) of the station, and the *ET* estimate applies to the stand of vegetation within the boundary layer. The calculation of fetch is dependent on the height of the canopy and the average wind speed, and is based on turbulent transfer theory that is outside the scope of this document.

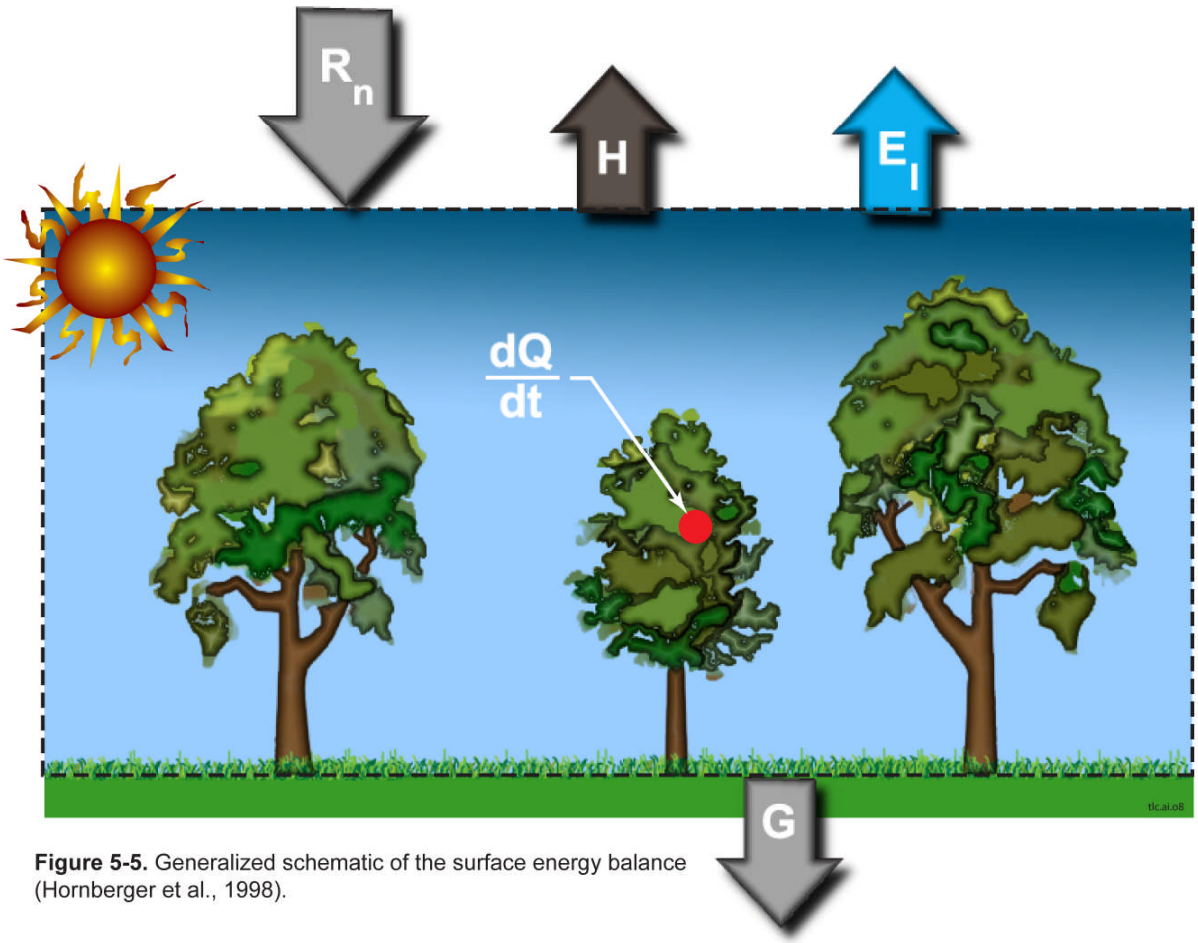


**Figure 5-5.** Generalized schematic of the surface energy balance (Hornberger et al., 1998).

### 5.5.2 ET Approximation Using a Mass-Transfer Approximation (Johns, 1989; Hornberger et al., 1998; Campbell, 1998)

Another method of estimating *ET* is through mass-transfer, which uses approximations of heat and vapor flux from the surface into the atmosphere through turbulent air transfer (eddies) over a large, homogeneous surface. Under steady-state conditions, the transfer of water vapor to the atmosphere can be approximated by the Bowen Ratio (*B*) (Bowen, 1926):

$$B = \frac{PC_p}{\lambda_v \varepsilon} \frac{(T_s - T_a)}{(e_s - e_a)} = \frac{H}{E_l} \qquad \textbf{(9)}$$

**<u>Where:</u>**

***P*** = atmospheric pressure

$\boldsymbol{C_p}$= specific heat of air (constant)

$\boldsymbol{\varepsilon}$ = ratio of molecular weight of water to molecular weight of dry air

$\boldsymbol{T_s}$ = temperature at the ground surface

$\boldsymbol{T_a}$ = temperature at some elevation above the surface

$\boldsymbol{e_s}$ = vapor pressure at the surface

$\boldsymbol{e_a}$ = vapor pressure at some elevation above the surface

$\boldsymbol{\lambda_v}$ = latent heat of vaporization

Since $P$, $C_p$, $\lambda_v$, $\varepsilon$, are all constants ($P$ is a constant per elevation), as a surface becomes warm and dry ($T_s$ increases and $e_s$ decreases), the ratio increases, leading to an increase in the sensible heat flux (temperature) relative to latent heat flux (energy/water). Thus, the larger the Bowen ratio, the greater the flux of available water between the ground and air. Typical ranges of the Bowen ratio are between 0.1 (over the ocean) and up to 10 for hyper arid, desert environments. If measurements of $T$ and $e$ at two heights, and $R_n$ and G are made at a microclimate station, then $ET$ can be approximated using the energy balance by substituting $E_lB$ for $H$ in **(6)**:

$$E_l = \frac{R_n - G}{1 + B} \qquad \textbf{(10)}$$

$E_l$ can then be translated to ET using equation **(7)**. Like the energy balance, the mass-transfer approximation is applicable within a boundary layer of the vegetation stand where the instrumentation is located. For a review of the Bowen method and associated instrumentation, see Campbell (1998).

### 5.6 Calculation of ET with Physically and Empirically-Based Equations

Several physically and empirically-based equations have been developed for estimating evapotranspiration using meteorological data. These equations commonly estimate what is referred to as potential evapotranspiration ($ETp$), which is water transpired in a defined time by a short green crop, shading the ground, of uniform height, with adequate water in the soil. An empirically-based cropping coefficient ($K_c$) is then applied to scale $ET_p$ to a specific plant cover. Recently, the term and concept of reference evapotranspiration ($ET_r$) has replaced the term potential evapotranspiration, especially with regards to the Penman-Monteith equation (Suat and

Harman, 2003). The concept of $ET_r$ reduces the ambiguity in the initial calculation by specifying the "short green crop" to be a grass or alfalfa plot (Allen et al., 1998).

Several predictive *ET* equations have been developed using statistical correlation of micrometeorological with vegetation lysimeter data, or calibrating physically-based equations with lysimeter *ET* data and/or microclimatic measurements. For a complete review of physically and empirically-based *ET* estimation equations, see Nichols et al. (2004), Allen et al. (1998), Jensen et al. (1990), and Dunne and Leopold (1978).

### 5.6.1 Empirical Equations

Empirical equations have the advantage of practicality because they commonly only require one or two meteorological measurements. Empirical equations developed to use solar radiation and/or temperature as the main variable include: Thornthwaite (Thornthwaite and Mather, 1955), Blaney-Criddle (Soil Conservation Service, 1970), Jensen-Haise (Jensen and Haise, 1963), and Hargreaves (Hargreaves, 1985). Since temperature is the most widely available meteorological parameter, these equations are convenient and widely applicable, although their uncertainty can be large (Allen et al., 1998).

#### 5.6.1.1 The Thornthwaite Equation

The Thornthwaite equation directly relates evapotranspiration to the mean monthly temperature and daylight duration with the result termed potential evapotranspiration (Thornthwaite and Mather, 1955, Thornthwaite, et. al, 1957). Intuitively, it is reasonable to expect that the potential evapotranspiration will be higher when temperature is higher and there are more daylight hours, assuming that soil moisture storage is constant. Accordingly, potential evapotranspiration is calculated as (Lu, et. al., 2005):

$$ET_p = 1.6 L_d \left( \frac{10T}{I} \right)^a \qquad \textbf{(11)}$$

**<u>Where:</u>**

$\boldsymbol{ET_p}$ = potential evapotranspiration rate

$\boldsymbol{L_d}$ = daylight duration (sunrise to sunset / 12 hours)

$\boldsymbol{T}$ = monthly mean air temperature

$\boldsymbol{a} = 6.75\text{x}10^{-7} I^3 - 7.71\text{x}10^{-5} I^2 + 0.01791 I + 0.49239$

***I*** = annual heat index, computed by:

$$I = \sum_{j=1}^{12} \left( \frac{T_j}{5} \right)^{1.514} \qquad \textbf{(12)}$$

**Where:**

$\boldsymbol{T_j}$ = mean air temperature during month *j*

***j*** = month (1,…,12)

Given monthly mean temperatures from actual measurements, a reasonable estimate of the potential evaporation and other water budget components for each month of the year can be calculated (Calvo, 1986). The Thornthwaite method performs best in humid climates when long-term averages are used and the formula is calibrated and verified using locally measured data (Lu, et. al., 2005).

#### 5.6.1.2 The Blaney-Criddle Equation

The Blaney-Criddle equation is another temperature-based method for estimating evapotranspiration. The result of this method is reference crop evapotranspiration ($Et_r$) expressed as a monthly average. The Blaney-Criddle method assumes calculation of water use by vegetation consists of a seasonal factor ($p$) times a monthly consumptive use factor ($0.46T_{mean}$ + 8), and is expressed as:

$$ET_r = p(0.46T_{mean} + 8) \qquad \textbf{(13)}$$

**Where:**

$\boldsymbol{ET_r}$ = reference crop evapotranspiration rate

***T*** mean = mean daily temperature in degrees Celsius

***p*** = mean percentage of daylight hours

The Blaney-Criddle methodology is applied in Nebraska through use of the Nebraska NRCS Consumptive Use Calculator for the purpose of assessing depletions or accretions to the regional water budget (NRCS, 2001). The document identifies thirty common practices needing evaluation that may impact Platte River streamflow. Since the assumptions incorporated in the Blaney-Criddle method are similar to those in Thornthwaite, its application is similarly restricted

to basic (monthly averaged) estimates for years typical of long term average climatic conditions (Nichols, et. al., 2004).

#### 5.6.1.3 The Jensen-Haise Equation

The Jensen-Haise (1963) equation uses temperature *and* solar radiation measurements, a different approach than Thornthwaite or Blaney-Criddle, which use the length of daylight as a proxy for the solar radiation term. The Jensen & Haise (1963) equation was derived from 35 years of evapotranspiration and soil sampling data of the arid western United States (Jensen, et.al., 1990), so its use with respect to the high plains may be additionally justified. The method relies on monthly mean values for daily solar radiation and temperature. The U.S. Bureau of Reclamation (1994) expresses the equation as follows:

$$\lambda ETr = C_T(T_{mean} - T_X)R_s \qquad \textbf{(14)}$$

**Where:**

$\boldsymbol{ET_r}$ = reference crop evapotranspiration rate

$\boldsymbol{C_T}$ = temperature coefficient

$\boldsymbol{T_{mean}}$ = mean daily air temperature

$\boldsymbol{T_X}$ = intercept of the temperature axis (calculated for each weather station)

$\boldsymbol{R_s}$ = measured solar radiation

This method is used as a reference to check the values calculated from the more rigorous Penman methodology used in the U.S. Bureau of Reclamation's AgriMet Program (U.S. Bureau of Reclamation, 1994).

#### 5.6.1.4 The Hargreaves Equation

The Hargreaves model is the result of 8 years of lysimeter data collection on cool-season Alta fescue grass in Davis California (Jensen, et.al., 1990) with modifications (Hargreaves and Samani, 1985), and takes the form:

$$ETr = 0.00023R_a\delta_t^{1/2}(T_{mean} + 17.8) \qquad \textbf{(15)}$$

**Where:**

$\boldsymbol{ET_r}$ = reference crop evapotranspiration rate

$\boldsymbol{R_a}$ = measured solar radiation

$C_T$ = temperature coefficient

$\delta_t$ = difference between mean monthly maximum and minimum temperatures

$T_{mean}$ = mean air temperature

Relative humidity is not explicitly noted in the equation; it is included implicitly through the difference in maximum and minimum temperature. The temperature difference ($\delta_t$) demonstrates a linear relationship with respect to relative humidity (Hargreaves and Samani, 1982). The goal of this method is to provide an approach that does not need a local calibration and performs as well as more data intensive methods while requiring fewer measurements. Hargreaves and Samani (1985) demonstrated strong correlation with both measured lysimeter data and the Penman method as modified by Doorenbos and Pruitt (1977).

### 5.6.2 Physically-Based Equations

Physically-based equations typically require several meteorological measurements and are commonly cited as producing the most accurate estimates of $ET_p$. Physically-based *ET* equations include: Penman (Penman, 1948), Priestly-Taylor (Priestly and Taylor, 1972), and Penman-Monteith (Monteith, 1965). Penman (1948) describes evaporation of water from an open water surface, while the more sophisticated Penman-Montieth (Montieth, 1965) is used to provide evapotranspiration estimates in areas with vegetation. The Priestly-Taylor equation calculates the evaporation or the potential evapotranspiration as a function of the latent heat of vaporization and the heat flux in a water body (Jacobs, et.al., 2002; Mosner and Aulenbach, 2003).

#### 5.6.2.1 The Penman Equation

The Penman (1948) equation uses temperature, solar radiation, wind run and humidity, combining the energy balance with a turbulent mass transfer function to describe evaporation from an open water surface. The equation is:

$$E_{mass} = \frac{mR_n + \rho_a c_p (\delta e) g_a}{\lambda_v (m + \gamma)} \quad \textbf{(16)}$$

**<u>Where:</u>**

$\boldsymbol{E_{mass}}$ = Open water surface evaporation rate

$\boldsymbol{m}$ = Slope of the saturation vapor pressure curve

$\boldsymbol{R_n}$ = Net irradiance

$\boldsymbol{\rho_a}$ = density of air

$\boldsymbol{c_p}$ = heat capacity of air

$\boldsymbol{g_a}$ = atmospheric conductance

$\boldsymbol{\delta e}$ = vapor pressure deficit

$\boldsymbol{\lambda_v}$ = latent heat of vaporization

$\boldsymbol{\gamma}$ = psychrometric constant

This equation assumes that net heat exchange with the ground is insignificant, and that a unit area does not exchange heat or vapor with surrounding areas. The original equation was revised in 1956 by Penman to make adjustments to the wind function (Jacobs, et.al. 2002).

#### 5.6.2.2 The Priestly and Taylor Equation

The Priestly and Taylor equation as presented by Mosner and Aulenbach, (2003):

$$ET_p = 1.26\left(\frac{s}{s} + \gamma\right)\left(\frac{Qn - Qx}{L}\right)^a \qquad \textbf{(17)}$$

**<u>Where:</u>**

$\boldsymbol{ET_p}$ = potential evapotranspiration

$\boldsymbol{s}$ = slope of saturated vapor pressure gradient

$\boldsymbol{\gamma}$ = psychrometric constant

$\boldsymbol{Q_n}$ = Net radiation

$\boldsymbol{Q_x}$ = change in heat stored

$\boldsymbol{L}$ = latent heat of vaporization

This equation defines the relationship between the radiation term and the aerodynamic term as a constant, in this case 1.26. Conceptually, a constant of 1.0 represents an equilibrium condition, where the actual vapor pressure approaches the saturation vapor pressure (Jacobs, et. al., 2002). Remotely sensed data can be used to determine many of the input variables for the Priestly and Taylor equation (Nourbaeva, et.al.). Moges, et. al. (2002) indicates that the Priestly and Taylor method, when combined with a simple correction, will reliably result in equivalent potential evapotranspiration to Penman-Montieth.

### 5.6.2.3 The Penman-Monteith Equation

The Penman-Monteith equation is a derivation of the original Penman equation described above. This version incorporates factors to apply the equation over a variety of vegetative covers (Jacob, et. al., 2002 and Walter, et.al., 2000).

In 1998, the Food and Agriculture Organization of the United Nations (FAO) recommended discontinuation of the use of all previously endorsed predictive *ET* equations and endorsed a modified version of the Penman-Monteith (Monteith, 1965), referred to as the FAO-Penman-Monteith equation:

$$ET_o = \frac{0.0408\Delta(R_n - G) + \gamma \frac{C_n}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d * u_2)} \qquad \textbf{(18)}$$

**<u>Where:</u>**

$\mathbf{ET_o}$ = reference evapotranspiration

$\mathbf{R_n}$ = net radiation at the crop surface

**G** = soil heat flux density

$\mathbf{C_n}$ = reference crop, time-step-specific numerator constant.

**T** = mean daily air temperature at 2 m height

$\mathbf{u_2}$ = wind speed at 2 m height

$\mathbf{e_s}$ = saturation vapor pressure

$\mathbf{e_a}$ = actual vapor pressure

$\mathbf{e_s} - \mathbf{e_a}$ = vapor pressure deficit

$\boldsymbol{\Delta}$ = slope vapor pressure curve

$\gamma$ = psychrometric constant

$\mathbf{C_d}$ = reference crop time-step-specific denominator constant.

The FAO-Penman-Monteith equation has been accepted as the most widely (globally) accurate equation for estimating *ET* (Allen et al., 1998). Although populating all of the above variables with field data increases the precision of the calculation, the FAO-Penman-Monteith is designed to be solved using standard climate records of solar radiation, air temperature, humidity, and wind speed. These more common parameters can then be related to the above list

of variables through a series of empirically-based standardized tables and/or functions developed for different regions of the world (Allen et al., 1998).

## 6.0 WATER SALVAGE FROM VEGETATION REMOVAL: A HISTORICAL PERSPECTIVE

Studies within the United States of water yields (streamflow) resulting from vegetation removal originated with studies of forestry practices in experimental forests in the southeast, northeast, Pacific northwest and Rocky Mountain regions (Bosch and Hewlett, 1982). These catchment-scale experiments focused on upland coniferous and hardwood trees and sought to determine the effects of various degrees of forest cutting on runoff hydrology, seasonal and annual water yields, and water quality (Hoover, 1944; Lieberman, 1947; Hursh, 1947; Hibbert, 1969). Hydrologic response from vegetation removal in these experiments was mixed, though increases in annual water yield through a reduction in precipitation interception by forest canopy, a reduction in transpiration, and an increase in runoff due to decreased soil infiltration capacities were common. Hewlett and Hibbert (1961) summarized all forest cutting experiments in the Coweeta Experimental Forest, North Carolina, reporting negligible gains of water in basins whose forest cover was reduced less than 20 percent. The persistence of the gains in water yield was shown to be proportional to the rate of recovery of the replacement vegetation, which was subsequently dependent on the climate regime following cutting (Bosch and Hewlitt, 1982; Burt and Swank, 1991).

By the mid-20$^{th}$ century, a growing body of literature was identifying stream-bank vegetation as a potentially large consumer of groundwater, citing the high amplitude fluctuations in the groundwater table in wells adjacent to streams (figure 8-1) (i.e. Meinzer, 1927, Troxell, 1936; Young and Blaney, 1942). Dunford and Fletcher (1947) cleared vegetation within 15 vertical feet of the stream bottom, amounting to 12 percent of a 22-acre forested catchment of the Coweeta Experimental Forest, and monitored changes in the diurnal fluctuation of streamflow. After cutting was complete, they concluded that water yield may be increased by eliminating transpiration from vegetation on the stream bank. Hewlitt and Hibbert (1961) later showed that the gains reported by Dunford and Fletcher (1947) were within the error of the measurement methods.

Intensive, field-based studies of individual plant and site-scale consumptive use of groundwater by riparian vegetation indicated that significant volumes of water could be yielded by removing riparian vegetation along the streambanks of rivers (Gatewood et al., 1950; Robinson, 1958; McDonald and Hughes, 1968). These projects were mainly based in the desert

southwestern U.S. where rapid development and an arid climate were increasing demand, similar to Nebraska's situation today. The large estimates of potential for water yields published by these studies led to federally-sponsored research efforts focused on measuring water yields associated with riparian vegetation removal.

Bowie and Kam (1968) removed 22 acres of woody and herbaceous vegetation along a 1.5 mile reach of Cottonwood Wash, Mohave County, Arizona and used a water-budget method to estimate changes in ET. Initial vegetation control was attempted using a chemical defoliant. The defoliant caused a rapid but short-lived decrease in ET. Complete eradication through physical removal, chemical herbicide, and burning was later attempted and maintained for two years. After eradication, Bowie and Kam (1968) observed decreases in the diurnal fluctuation in the groundwater table in the early growing season, and reported a decrease in ET from 18 percent of the inflow (80 acre-feet) to 12 percent of the inflow (42 acre-feet). However, the resulting reported streamflow gains that could be measured within their experimental framework were below 1.5 $ft^3$/ second. The annual growing season (March-October) gains of 38 acre-feet averaged approximately five percent of the daily stream flow. The uncertainty of the measurements was not reported.

Culler et al. (1970) cleared nearly 5,500 acres of riparian trees along a heavily-instrumented 15-mile reach of the Gila River in Arizona over an eight year study period. Culler et al. (1982) used the water-budget *ET* data to calibrate empirical *ET* equations and estimate total annual changes in *ET* over the study period. Prior to removal of riparian vegetation, Culler et al. (1982) estimated *ET* to be between 25 and 56 inches. After removal, estimated reductions averaged 19 in. Although the estimated reductions in *ET* were large, Culler et al. (1982) did not report yields in streamflow directly related to the removal, but a change from a negative to a positive trend in groundwater table elevations for the early growing season, and anecdotal evidence of river reaches gaining small amounts of flow were reported, but not quantified. Culler et al. (1982) acknowledged that the cleared condition was temporary and used calibrated *ET* equations to estimate the use of water by the most common replacement vegetation; the *ET* of replacement vegetation was estimated to be equal or greater to the vegetation removed.

In an effort to estimate potential water salvage, Mower et al. (1964) calculated the water use of bottomland grasses and Tamarix along a 51-mile stretch of the Pecos River in New Mexico using four different ET estimation methods. Mower (1964) estimated an annual average

potential salvage of 28,000 acre-feet if Tamarix were completely eradicated and replaced with grasses. Hughes (1970) performed an economic feasibility analysis along the same stretch of the Pecos to see if the cost of Tamarix eradication and maintenance would pay off in water yields valued at market rates. Hughes (1970) estimated 28,000 acre-feet of water salvage from Tamarix eradication, and showed that eradication and maintenance was economically feasible even at the lower limiting value of water at the time.

Weeks et al. (1987) later reported that 21,500 acres of Tamarix had been cleared from the Pecos River floodplain between 1967 and 1974 along the reach described by Mower et al. (1964). Using eddy-covariance techniques and an energy budget, Weeks et al. (1987) estimated water use by the remaining stands of Tamarix and the replacement grasses in the removed segments. Weeks et al. (1987) estimated Tamarix annually consumed 0.3 meters (11.8 in.) more water than the replacement grasses, which should have resulted in an annual salvage of 10,000 to 20,000 acre-feet. However no base-flow changes in the Pecos River could be linked to the removal. The absence of a response in annual baseflows led Weeks et al. (1987) to conclude that the increase in baseflows was either masked by the increase in local groundwater pumping, or that the vegetation in a streamside buffer of woody vegetation simply consumed more water.

## 7.0 PUBLISHED ESTIMATES OF WATER CONSUMPTION BY RIPARIAN VEGETATION IN NEBRASKA

Many intensive research experiments dealing with water consumption by riparian vegetation illustrated in table 4-1 have been conducted in the arid states of Arizona, New Mexico, Nevada, and Utah (i.e. Gatewood et al., 1950; Robinson, 1958; Mower et al., 1964; Collings and Myrick, 1966;. Bowie and Kam, 1968; McDonald and Hughes, 1968; Culler et al., 1970; Van Hylckama, 1980; Culler et al., 1982; Weeks et al. 1987; Carman, 1993; Cooper et al., 2000; Scott et al., 2000; Cleverly et al., 2002; Dahm, 2002; Scott et al., 2004; Nagler et al., 2005). It is no coincidence that these states are also extremely dry, have long growing seasons, and have faced severely limited water supplies for decades.

Nebraska by comparison has few published estimates of riparian vegetation water consumption. Dirmeyer (1975) estimated that the expansion of woodlands along the Platte was responsible for roughly one million acre-feet of water consumption between April and October. Nagel and Dart (1980) constructed a computational model based on a modified Blaney-Criddle formula to make comparative estimates of evapotranspiration on a monthly basis in the central Platte River between 1938 and 1977, a period of rapid woodland expansion. Nagel and Dart (1980) estimated that evapotranspiration rates in 1977 (35.5 in.) were approximately the same as those in 1938 (37.3 in.), citing that the wider, shallow, and open channel of the Platte in the 1930s evaporated approximately as much water as the riparian trees in 1977 transpired. Nagel and Dart (1980) noted that there were limitations to the model, but the estimation showed that removal of riparian woodlands would likely yield negligible volumes of water.

More recently, Landon et al. (2006) estimated *ET* in the central Platte River using eddy covariance and energy balance at two locations within riparian woodlands from 2002 to 2004. At both sites, annual *ET* ranged from approximately 21 in. to 26 in., roughly equivalent to the annual rainfall at each site. Landon et al. (2008) estimated that central Platte River riparian forest site *ET* averaged approximately 23 inches from 2002 to 2006. Landon et al. (2006, 2008) used the climate data from each site and a modified Penman equation to estimate *ET* over the same time period and found that the Penman equation substantially overestimated *ET* relative to the magnitudes measured using eddy covariance. Burba et. al. (1999) used the Bowen ratio-energy balance to estimate *ET* for *Phragmites australis*, *Scirpus acutus*, and open water in a north central Nebraska wetland from June to October, 1994. Evapotranspiration estimates ranged from

9.45 in.-30.71 in. for the duration of the study (table 4-1). Cummings (2007) estimated transpiration for *Phragmites australis* at three locations in the central Platte River valley using lysimeters and stomatal conductance measurements and found that approximately 195,000 gallons (~7 inches) of water per acre were used during the growing season.

Several *ET* research studies are proposed or underway within the state of Nebraska (table 7-1). These projects are focused in the Republican River basin and the central Platte River, and include the study by Landon et al. (2006) described above (figure 7-1).

The ongoing and proposed *ET* projects in the Republican River coincide with invasive riparian vegetation removal efforts associated with LB 701. If successful, these projects will begin to produce the most reliable estimates of consumptive use of groundwater by riparian vegetation to date.

**Table 7-1**. Ongoing evapotranspiration related research studies within the state of Nebraska.

| Author | Agency | Description |
|---|---|---|
| Hergert, et. al. 2006 | NPNRD, SPNRD - UNL | Demonstrate and adapt remote sensing technology to produce and utilize consumptive water use maps for the Nebraska Panhandle |
| Irmak, A., et. al. 2008 | USGS - UNL | Satellite-based Energy Balance to Assess Riparian Water Use |
| Irmak, S., et. al. 2006 | UNL | Use of Remotely Sensed Data for Improved Quantification of Evapotranspiration for Water Management in Nebraska |
| Irmak, S., et. al. 2007 | CPNRD - UNL | Measurement of growing season actual crop evapotranspiration and crop coefficients, and dormant season evaporative losses for key vegetation surfaces in the Central Platte Natural Resources District |
| Irmak, S., et. al. 2008 | CPNRD - UNL | Water use, surface energy balance, and vegetation dynamics of Phragmites (Phragmites australis) in the Central Platte River Valley |
| Landon, et. al. 2002 | COHYST - USGS | Evapotranspiration Rates from Riparian Woodlands, Platte River since 2002 |
| Martin, et. al. 2007 | NDNR - UNL | Estimation of Evapotranspiration from Riparian and Invasive Species Using Remote Sensing and in Situ Measurements in the Republican River Basin |
| Rus and Landon, 2006 | CPNRD - USGS | Water consumption of Central Platte River grasslands |
| Scott, et. al., 2007 | IANR/NU Rural Initiative - UNL | Riparian Water Use Modeling |
| Singh, et. al. 2007 | UNL | Application of SEBAL for mapping evapotranspiration and estimating surface energy fluxes in south central Nebraska |

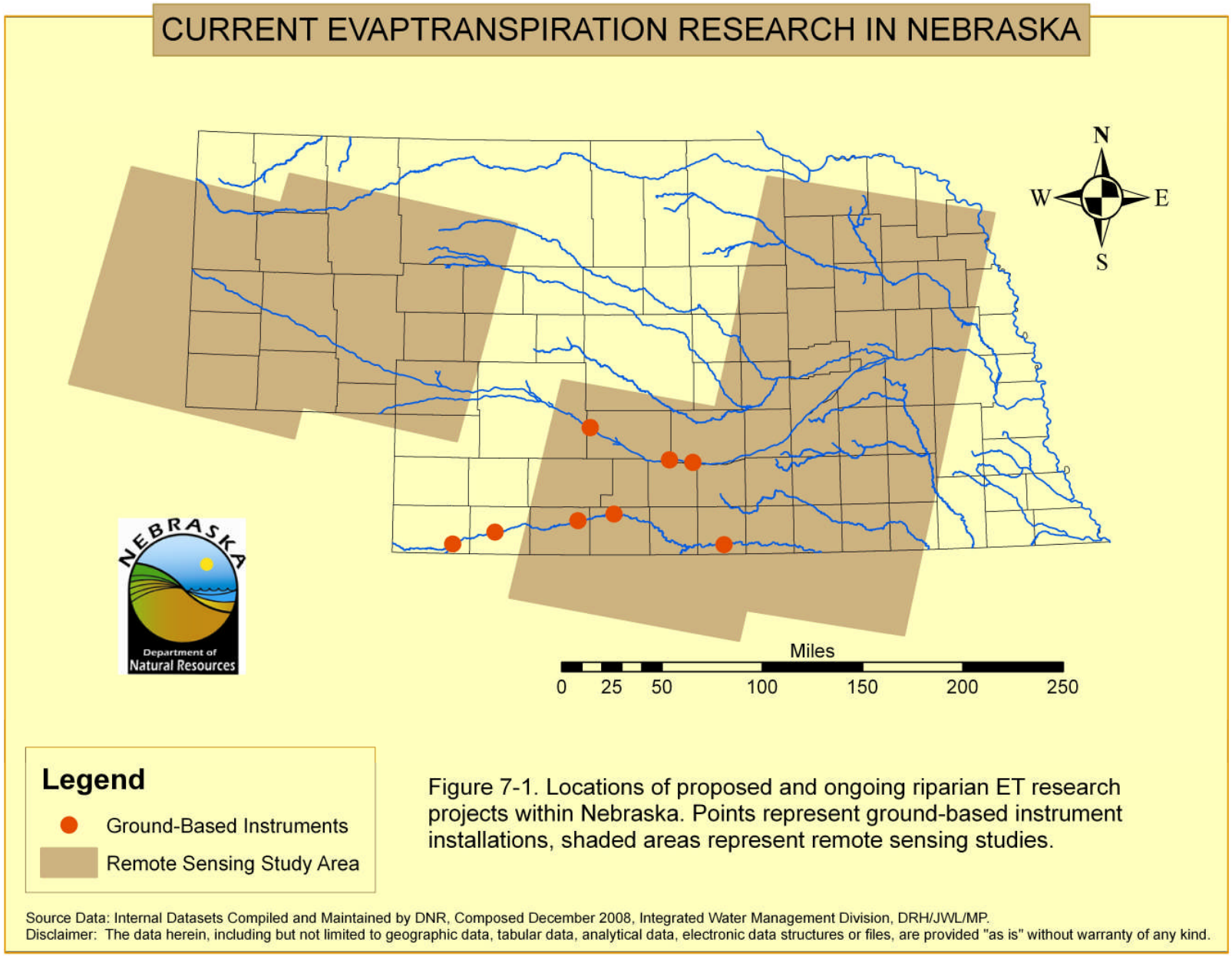


Figure 7-1. Locations of proposed and ongoing riparian ET research projects within Nebraska. Points represent ground-based instrument installations, shaded areas represent remote sensing studies.

Source Data: Internal Datasets Compiled and Maintained by DNR, Composed December 2008, Integrated Water Management Division, DRH/JWL/MP.
Disclaimer: The data herein, including but not limited to geographic data, tabular data, analytical data, electronic data structures or files, are provided "as is" without warranty of any kind.

## 8.0 GROUNDWATER MODELING IN NEBRASKA AND CONSUMPTIVE USE BY RIPARIAN VEGETATION

The DNR and several NRDs within the state use numerical groundwater models to simulate the groundwater flow system and aid in the approximation of water budgets within and between state river basins. The framework of each model is based on layered cellular arrays with numerical simulations based on the MODFLOW groundwater modeling code (McDonald and Harbaugh, 1988; 1996). Currently, three large groundwater modeling studies are used within Nebraska to help guide management decisions: (1) the Republican River Compact Accounting Model (RRCA), (2) Platter River COoperative HYdrology STudy (COHYST), and (3) the Elkhorn – Loup Modeling study (ELM). Groundwater evapotranspiration due to riparian and wetland vegetation in each model are calculated using a linear function (figure 15-1A) whereby maximum and minimum *ET* rates within a cell are a function of the elevation of groundwater. Maximum *ET* occurs at or above the elevation of the '*ET surface'*, and *ET* is zero below a specified elevation referred to as the 'extinction depth'. The methods for defining these surfaces are somewhat arbitrary, and the RRCA, COHYST, and ELM models define these surfaces differently.

A numerical groundwater model constructed by Chen and Shu (2006) poses a hypothetical scenario that indicates seasonally pumping wells may affect evapotranspiration of groundwater in the central Platte and Republican river valleys from 2 to 9.4 percent of the pumping volume. The study assumed a linear ET function similar to those describe previously, and an irrigation season lasting 90 days.

### 8.1 Republican River Compact Accounting (RRCA) Model

Land surface elevation within the RRCA model is based on the average of all nodes within a model grid cell from the USGS National Elevation Dataset 30 meter resolution land surface data grid (Spalding, per. Comm.). The *ET* surface within all model cells, except stream cells, is equivalent to the land surface within that cell. Within stream cells of RRCA, the *ET* surface is assigned to be 5 ft. above the stream top. The *ET* rate in each cell is determined by interpolation and extrapolation of *ET* estimates performed using data from weather stations, multiplied by the area of phreatophytes within the cell to obtain an *ET* volume for each monthly stress period. The extinction depth used in the RRCA model is 10 feet below the ET surface.

### 8.2 Cooperative Hydrology Study (COHYST) Models

Within the COHYST program, three overlapping model units were created from eastern Wyoming to Columbus, Nebraska named the Eastern (EMU), Central (CMU), and Western (WMU) model units.

Within the Western Model Unit, groundwater evapotranspiration areas were defined within a 1 to 2-mile wide corridor around the North and South Platte rivers, and areas of numerous natural lakes and wetlands in the Sand Hills. Tributary evapotranspiration and small lakes were considered negligible. *ET* from groundwater was initially estimated as the difference between average lake evaporation values (1946-1955) and average precipitation values, multiplied by a coefficient from an unpublished study by the USGS. These values were later increased to 16 in/yr and 15 in/yr for the western and eastern portions of the WMU respectively. Maximum *ET* rates occurred when water levels reached or exceeded the *ET* surface (as with RRCA and ELM), which was defined as the elevation halfway between the mean land surface elevation in a model cell and the minimum land surface elevation in the same cell. Within the Sand Hills this elevation was arbitrarily lowered by 10 ft. during the calibration of the model to optimize water levels. Extinction depths were set to 7 ft. below the *ET* surface along the North and South Platte, and to 5 ft. elsewhere in the model.

*ET* areas in the CMU were defined using 1997 land use mapping data. *ET* was simulated within a model cell if more than 25 percent of the cell was classified as open water, riparian forest/woodlands, wetland and dryland alfalfa (sub-irrigated). Maximum *ET* from groundwater was estimated in the CMU as the difference between average lake evaporation values (1946-1955) and average precipitation values, multiplied by a coefficient from an unpublished riparian *ET* study by the USGS. These calculations resulted in maximum *ET* values of 17 in/yr in the sand hill lakes area and 13 in/yr in the rest of the model domain. The *ET* surface was approximated as the elevation that is halfway between the average elevation within a 160-acre cell, and the minimum elevation within the same cell. The extinction depth was set to 7 ft for riparian and wetland areas, and 3 ft in other areas.

*ET* areas in the EMU were defined as cells where the groundwater elevation was, on average, 10 ft or less below the ground surface based on long-term depth-to-water data or if the cell was occupied by 25 percent or more of wetlands, riparian forest, wetlands, dryland alfalfa

(sub-irrigation), or open water. Maximum *ET* was defined using the same methods as in the CMU resulting in values ranging from 7 to 13 in/yr. The *ET* surface and extinction depths were determined using the same methods as in the CMU.

### 8.3 Elkhorn-Loup Model (ELM)

Elevation data within ELM are based on 30 meter digital elevation model. The *ET* surface was calculated as the 25$^{th}$ percentile of the land surface elevation within each model grid cell. *ET* was only allowed in model grid cells where wetlands and lakes existed according to the U.S. Fish and Wildlife Service National Wetland Inventory (2005). The ET extinction depth was assumed to be uniform, at a depth of 5 ft. The maximum *ET* rate in each cell was extrapolated from measured values and soil moisture budget calculations performed near Gothenburg and Odessa in the Platte River valley (Landon, et. al., 2006). Extrapolation was conducted assuming a direct relationship to mapped evaporation rates from the U.S. Weather Bureau lake evaporation map (U.S. Weather Bureau, 1959).

### 8.4 Uncertainty in Modeled ET Rates

Although the maximum net *ET* (*ET* minus rainfall) varies up to 10 in/yr across the COHYST modeling area, gross, or total *ET*, varies significantly less; between 30 and 36 in/yr. Maximum gross *ET* occurs in the CMU and minimum gross values occur in the WMU. This distribution could reflect differences in the methodologies used to develop the *ET* modeling packages or approaches to model calibration. Values for the RRCA and ELM models have not yet been compiled and published.

## 9.0 IMPROVING GROUNDWATER MODELING IN NEBRASKA RELATED TO CONSUMPTIVE USE BY RIPARIAN VEGETATION

Baird et al. (2007) note that the two largest sources of error in traditional approaches to *ET* modeling are: (1) the use of a single *ET* curve to represent both evaporation and transpiration regardless of the species assemblages present and their vigor and density and (2) using one assumed shape for the curve relating *ET* to groundwater elevation for all species assemblages. Banta (2000) replaced the linear shape with a segmented shape, changing the *ET* flux rate over certain ranges, but leaving the max *ET* constant above a particular groundwater elevation (figure 15-1B).

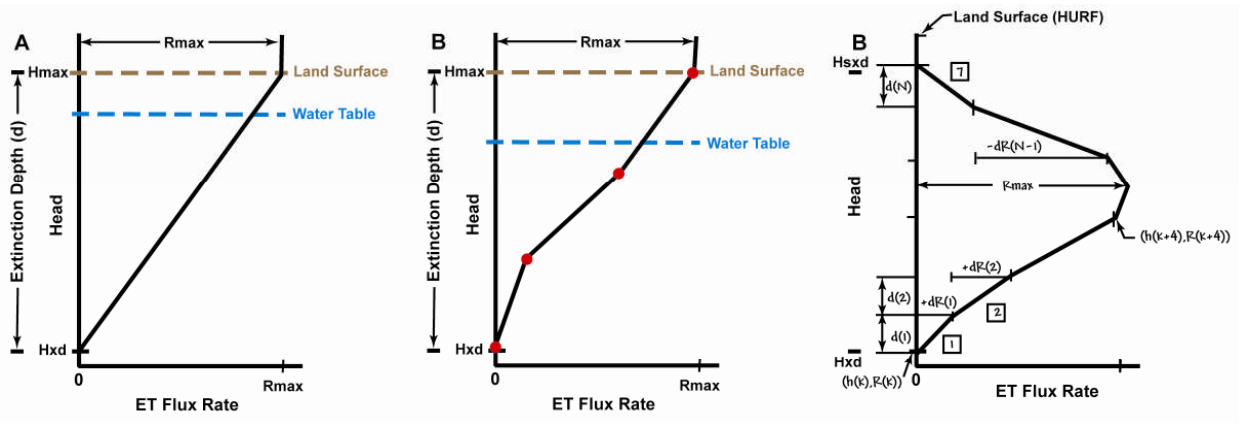


**Figure 9-1.** (A) MODFLOW 96 traditional linear ET curve (B) MODFLOW 2000 ET curve published by Banta (2000) and (C) modified ET curve published by Baird et al. 2007.

Baird et al. (2007) significantly refined the *ET* package in MODFLOW by: (1) creation of plant functional groups (PFGs), which group plants by species that exhibit similar responses to environmental conditions, and plant function subgroups (PFSGs), which further group plants into assemblages with similar community traits such as density, soil salinities, rooting depths, and water tolerance; (2) reshaping transpiration curves for riparian vegetation relating *ET* to groundwater elevation (figure 15-1C); (3) applying several different transpiration curves for different PFSGs within a single model cell; (4) quantification of fractional coverage of riparian zones within larger model cell and introduction of seasonal fractional coverage; (5) application of multiple surface elevations per cell by allowing the assignment of unique elevation for each PFG or riparian polygon within a cell. Baird et al. (2007) showed that the modified *ET* package

(called RIP-*ET*), produced both higher and lower magnitudes of *ET* relative to traditional and adjusted methods in two large-scale groundwater models where it was tested.

## 10.0 ET RESEARCH AND DATA NEEDS AND POTENTIAL AREAS OF IMPROVEMENT FOR GROUNDWATER MODELING IN NEBRASKA

Accurate, peer-reviewed and published estimates of water consumption by riparian vegetation are not common within the state of Nebraska. Preliminary data by Landon et al. (2006 and 2008) for the central Platte River indicate that reference *ET* calculations overestimate actual *ET* from riparian vegetation. Groundwater models in Nebraska typically use maximum potential *ET* values that are obtained using either calculated differences between lake evaporation and precipitation or reference *ET* calculated from empirical equations. Reliable methods for determining the groundwater portion of evapotranspiration are not commonly available in Nebraska. Maximum *ET* values across the COHYST study area suggest that gross maximum *ET* values range between 30 and 36 in/yr, up to 12 in/yr higher than the average gross values reported by Landon et al. (2006) and 7 to 13 in/yr higher than the 2002 to 2006 average reported by Landon et al. (2008). Although attempts to refine *ET* surface elevations are made and some differentiation in this surface is made between open water, alfalfa, and riparian plants, neither the COHYST nor RRCA models make explicit cell elevation corrections for riparian zones, contain refined *ET* curves, or explicitly assign *ET* based on plant types or characteristics. Further, it seems that *ET* has been used as a calibration factor in the modeling schemes, suggesting *ET* is not being modeled as a reality-based process, but rather as a residual component of the water budgets. An example of the error that has resulted from this is the fact that within the COHYST models, maximum *ET* is larger in the CMU and EMU (~35 in/yr) than for the WMU (~30 in/yr), which is in the most arid region of the three.

These facts suggest that there is potential for error (either positive or negative) within the groundwater budgeting models used across the state. If this error is in the positive, the results would lead the managers of water resources to believe that large amounts of groundwater could be salvaged through reduction of water consuming plants along the riparian corridor; if negative, the results would suggest that riparian *ET* is an afterthought in the total water budget.

Improvement of water budgets begins with better constraint of riparian *ET* within Nebraska. Research needs that would allow for better model inputs and model calibration of riparian *ET* include:

1. Development of physiologically-based riparian *ET* functions for common riparian plant assemblages at several locations within several river basins across the state

with priority in fully and overappropriated basins; relation of riparian *ET* amongst different plant groups to groundwater elevation where feasible.

2. Improved DEM resolution within fully and overappropriated basins; focused topography data would be best improved in areas where ET is considered to have a significant groundwater component.
3. If significant differences exist between plant assemblages from #1, then improved mapping of riparian plant composition in fully and overappropriated basins would be necessary to further fractionalize *ET* by plant groups within riparian *ET* zones.

Ongoing or proposed riparian *ET* research projects cover significant areas of the Republican and central Platte rivers. Additional riparian *ET* research could focus on the Nebraska panhandle area, the most arid component of the COHYST area. Potential areas for improvement of the riparian *ET* component of state groundwater models include:

1. Inclusion of refined riparian *ET* functions once new maximum *ET* values have been published; published curves could be used to test initial sensitivity.
2. Elevation corrections within model cells where possible or upon the availability of new, higher resolution elevation data; elevation correction by Baird et al. (2007) could be used to test initial sensitivity.
3. Inclusion of fractional *ET* curves where possible or necessary (CALMIT – GAP composition data).
4. Modeling of riparian *ET* as a process with maximum values, rather than as a calibration factor.

## 11.0 CONCLUSIONS

Riparian corridors are some of the most productive and diverse of terrestrial ecosystems. They provide refuge and habitat for animals, store nutrients, and regulate stream temperature. Riparian corridors also provide value to private and public interests; acting as natural windbreaks, reducing stream sedimentation, providing habitat and forage for native bee species, acting as nutrient and contaminant filters, and providing property protection through bank stabilization.

Invasive trees may consume more water than native riparian vegetation and are capable of crowding out native species and creating a monoculture in the stream corridor. Local climate, the number of plants per unit area, species assemblages, and depth to groundwater control groundwater use in a given location.

Reasonable estimation of *ET* in Nebraska can be accomplished by numerous methods, including empirically-based equations as well as physically-based equations calibrated with field measurements. Whether *ET* rate is estimated based on empirical or physically based equations – there is an associated degree of unquantified uncertainty.

Within the riparian corridor, open water and active channel probably evaporate as much water as riparian vegetation intercepts and transpires. *ET* from areas affected by invasive species, when replaced with native grasses over substantial areas and maintained to prevent regrowth of invasives, may be reduced. The effects of reducing *ET* over large areas are difficult to quantify, as several components of the hydrologic cycle must be accurately assessed to reliably estimate effects on streamflow, these include: soil moisture storage, groundwater storage, changes to recharge, changes to runoff, and timing of effects relating to each component.

Current numerical modeling efforts rely on ET rate, surface elevation, and extinction depth to approximate evapotranspiration of riparian vegetation; addressing uncertainties associated with each of these values will improve confidence in modeling results. Surface elevation is typically based on 30m or 10m DEM, which have an associated uncertainty of +/- 10 ft. Modeled extinction depth is typically from 3-10 ft., well within the surface elevation uncertainty. Improved conceptual understanding of ET function relating to plant physiology can be used to develop new evapotranspiration packages for the various models.

Improving estimation of evapotranspiration can be accomplished in several ways. Empirical estimates can be improved through continued and expanded local data collection, and

relating collected field data to other modeling studies and measured data will yield more accurate, physically-based estimates. In addition, surface elevation uncertainty can be refined through acquisition of improved topographic data to improve simulation of *ET* in groundwater modeling studies.

Numerous studies relating to quantification of riparian and invasive species ET are ongoing in many areas in Nebraska, indicating that reliable physically-based evapotranspiration estimates will be available for locations in the Platte and Republican River valleys.

Continued study is needed to ensure that changes through time are recorded and analysis relating to the accuracy of initial studies can be assessed and improvements made. Quality measurement and continuous measurement will be critical to ensure reliable modeling and management of available resource to minimize non-beneficial consumptive use of groundwater.

**Bibliography**


Allen, R.G., L.S. Pereira, D. Raes, and M. Smith, 1998, *Crop evapotranspiration –guidelines for computing crop water requirements – FAO irrigation and drainage paper 56*, Food and Agriculture Organization of the United Nations, Rome.

Allen, R.G., M. Tasumi, A. Morse, R. Trezza, J.L. Wright, W. Bastiaanssen, W. Kramber, I. Lorrite-Torres, and C.W. Robinson, *in press*, Satellite-based Energy Balance for Mapping Evapotranspiration with Internalized Calibration (METRIC), *Journal of Irrigation and Drainage Engineering*.

Amlin, N.M., and S.B. Rood. 2002. Comparative tolerances of riparian willows and cottonwoods to water-table decline. *Wetlands*. 22:338-346.

Baird, K.J., J.C. Stromberg, and T. Maddock III. 2005. Linking riparian dynamics and groundwater: an ecohydrologic approach to modeling groundwater and riparian vegetation. *Environmental Management*. 36:551-564.

Banta, E.R., 2000, *MODFLOW-2000: The U.S. Geological Survey modular groundwater model: Documentation of packages for simulating evapotranspiration with a segmented function (ETSI) and drains with return flow (DRTI)*, U.S. Geological Survey Open-File Report 00-466.

Bastiaanssen, W.G.M., C.W.J. Roest, H. Pelgrum, and M.A. Abdel Khalek, 1992, Monitoring of the irrigation performance on the basis of actual evapotranspiration: Comparison of satellite data and simulation model results, *Advances in planning, design and mangment of irrigation system as related to sustainable land use*, Center for Irrigation Engineering and ECOWARM, Leuven, Belgium, pp. 473-483.

Bastiaanssen, W.G.M., E.J.M Noordman, H. Pelgrum, G. Davids, B.P. Thoreson, and R.G. Allen, 2005, SEBAL model with remotely sensed data to improve water-resources management under actual field conditions, *Journal of Irrigation and Drainage Engineering*, 131:85-93.

Black, Peter E. 2007. Revisiting the Thornthwaite and Mather Water Balance. *Journal of the American Water Resources Association* (JAWRA) 43(6):1604-1605. DOI: 10.1111/j.1752-1688.2007.00132.x

Bosch, J.M., and J.D. Hewlett, 1982, A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration, *Journal of Hydrology*, 55:3-23.

Bowie, J.E., and W. Kam, 1968, *Use of water by riparian vegetation Cottonwood wash, Arizona*, U.S. Geological Survey Water Supply Paper 1858.

Bowen, I.S., 1926, The ratio of heat losses by conduction and by evaporation from any water surface, *Phys. Rev.*, 27: 779-787.

Burba, G.G., S. Verma, and J. Kim, 1999, *A Comparative Study of Surface Energy Fluxes of Three Communities (Phragmites Australis, Scirpus Acutus, and Open Water) in a Prairie Wetland Ecosystem*, WETLANDS, Vol. 19, No. 2, pp. 451-457, The Society of Wetland Scientists.

Burt, T.P., and W.T. Swank, 1992, Flow frequency responses to hardwood-to-grass conversion and subsequent succession, *Hydrological Processes*, 6:179-188.

Butler, J.J., G.J. Kluitenberg, D.O. Whittenmore, S.P. Loheide II, W.Jin, M.A. Billinger, and X. Zhan, 2007, A field investigation of phreatophyte-induced fluctuations in the water table.

Calvo, J.C., 1986, An Evaluation of Thornthwaite's water balance technique in predicting stream runoff in Costa Rica, Journal – des Sciences Hydrologiques, Vol. 31, No 1.

Campbell Scientific, 1998, *Bowen ratio instrumentation instruction manual*, www.**campbell**sci.com/documents/**manual**s/**bowen**.pdf.

Carpenter, A., 1998, Element Stewardship Abstract for *Tamarix ramosissima* Lebedour, *Tamarix pentandra* Pallas, *Tamarix chinesis* Loureiro, and *Tamarix parviflora* De Candolle, The Nature Conservancy, Arlington, Virginia.

Chen, X., and Shu, L., 2006, Groundwater evapotranspiration captured by seasonally pumped wells in river valleys, Journal of Hydrology 318, 334-347.

Cleverly, J.R., C.N. Dahm, J.R. Thibult, D.J. Gilroy, and J.E. Allred-Coonrod, 2002, Seasonal estimates of actual evapotranspiration from *Tamarix ramosissima* stands using 3-dimensional eddy covariance, *Journal of Arid Environments*, 52:181-197.

Collings, M.R., and R.M. Myrick, 1966, *Effects of Juniper and Pinyon eradication on streamflow from Corduroy Creek basin, Arizona*, U.S. Geological Survey Professional Paper 491-B.

Cooper, D.I., W.E. Eichinger, J. Kao, L. Hipps, J. Reisner, S. Smith, S.M. Shcaeffer, and D.G. Williams, 2000, Spatial and temporal properties of water vapor and latent energy flux over a riparian canopy, *Agricultural and Forest Meteorology*, 105:161-183.

Culler, R.C., 1970, *Objectives, methods, and environment- Gila River phreatophyte project, Graham County, Arizona*, U.S. Geological Survey Professional Paper 655-A.

Culler, R.C., R.L. Hanson, R.M. Myrick, R.M. Turner, and F.P. Kipple, 1982, *Evapotranspiration before and after clearing phreatophytes, Gila River floodplain, Graham County, Arizona*, U.S. Geological Survey Professional Paper 655-P.

Cummings, A.M., 2007, Seasonal Dynamics of Total Non-Structural Carbohydrates in Rhizomes of *Phragmites Australis* and Transpiration Rates in Stands Along the Platte River in South-Central Nebraska, *A Thesis Presented to the Graduate Faculty of the Department of Biology and the Faculty of the Graduate College,* University of Nebraska, Kearney, NE, 134 pp.

Dahm, C.M., J.R. Cleverly, J.E. Allredd-Coonrod, J.R. Thibault, D.E. McDonnell, and D.J. Gilroy, 2002, Evapotranspiration at the land/water interface in a semi-arid drainage basin, *Freshwater Biology*, 47:831-843.

DeLoach, J. 1997. Effects of Biological Control of Saltcedar (Tamarix ramosissima) on Endangered Species: Biological Assessment. U.S. Department of Agriculture, Temple, Texas.

Doorenbos, J.; Pruitt, W.O. Crop water requeriments. Rome: FAO, 1977. 179p. Irrigation and Drainage Paper, 24

Dunford, E.G., and P.W. Fletcher, 1947, Effect of removal of streambank vegetation upon water yield, *Transactions of the American Geophysical Union*, 28:105-110.

Dunne, T., and L.B. Leopold, 1978, *Water in Environmental Planning*, W.H. Freeman and Company, 818 pp.

Ford, C.R., R.M. Hubbard, B.D. Kloeppel, and J.M. Vose, 2007, A comparison of sap flux-based evapotranspiration estimates with catchment-scale water balace, *Agricultural and Forest Meteorology*, 145:176-185.

Gatewood, J.S., T.W. Robinson, B.R. Colby, J.D. Hem, and L.C. Halpenny, 1950, *Use of water by bottom-land vegetation in lower Safford Valley, Arizona*, U.S. Geological Survey Water-Supply Paper 1103.

Glenn, E.P., and P.L. Nagler, 2005, Comparative ecophysiology of saltcedar (*Tamarix Ramosissima*) and native trees, *Journal of Arid Environments*, 61:419:446.

Hargreaves, G.H., and Z.A. Samani, 1985, Reference crop evapotranspiration from temperature, *Applied Engineering in Agriculture*, 1:96-99.

Hart, C.R., and A. McDonald, 2003, *Pecos River Ecosystem Monitoring Project*, Texas Cooperative Extension, The Texas A&M University System

Henebry, G.M., B.C. Putz, M.R. Vaitkus, and J.W. Merchant, 2005, The Nebraska Gap Analysis Project Final Report, School of Natural Resources, University of Nebraska-Lincoln

Hewlett, J.D., and A.R. Hibbert, 1961, Increases in water yield after several types of forest cutting, *Quarterly Bulletin of International Association of Scientists and Hydrologists*, 6:5-17.

Hibbert, A.R., 1969, Water yield changes after converting a forested catchment to grass, *Water Resources Research*, 5:634-640.

Hornberger, G.M., J.P. Raffensperger, P.L. Wiberg, and K.N. Eshleman, 1998, *Elements of Physical Hydrology*, The Johns Hopkins University Press, 302 pp.

Hoover, M.D., 1944, Effects of removal of forest vegetation upon water yields, *Transactions of the American Geophysical Union*, 6:967-977.

Hughes, W.C., 1970, Economic feasibility of increasing Pecos basin water supplies through reduction of evaporation and evapotranspiration, University of New Mexico, Water Resources Research Institute, Report No. 9, 32 pp.

Hursh, C.R., 1947, Water resource management, *North Carolina Engineer*.

Irmak, S., and D.Z. Haman, 2003, Evapotranspiration: potential or reference?, University of Florida, http://edis.ifas.ufl.edu/AE256.

Jacobs, J.M., Mergelsberg, S.L., Lopera, A.F., and Myers, D.A., 2002, *Evapotranspiration from a wet Prairie Wetland Under Drought Conditions: Paynes Prairie Preserve, Florida, USA*, Wetlands, Vol. 22, No. 2, June 2002, pp. 374-385.

Jensen, M., and H. Haise, 1963, Estimating evaporation from solar radiation, *Journal of Irrigation and Drainage*, 89:15-41.

Jensen, M.E., R.D. Burman, and R.G. Allen (editors), 1990, *Evapotranspiration and Irrigation Water Requirements*, American Society of Civil Engineers, Manual and Report No. 70, 360 pp.

Johns, E.L. (editor), 1989, *Water use by naturally occurring vegetation including an annotated bibliography*, American Society of Civil Engineers, New York.

Landon, M.K., D.L. Rus, B.J. Dietsch, M.R. Johnson, and K. Eggemeyer, 2006, Evapotranspiration rates of riparian woodlands in the northern high plains, Platte River, Nebraska, *Midwest Groundwater Conference*, Lincoln, Nebraska.

Landon, M.K., D.L. Rus, B.J. Dietsch, M.R. Johnson, and K.D. Eggemeyer, 2008, Evapotranspiration rates from riparian forests, Platte River, Nebraska, 2002-2006: U.S. Geological Survey Scientific Investigations Report 2008-5228, in press.

Lieberman, J.A., 1947, Water resource and watershed management research in the southeast, *Journal of the American Water Works Association*, 39:443-454.

Loheide, S.P., and S.M. Gorelick, 2005, A local-scale, high-resolution evapotranspiration mapping algorithm (ETMA) with hydroecological applications at riparian meadow restoration sites, *Remote Sensing of the Environment*, 98, 182-200.

Lu, J., Sun, G., McNulty, S.G., Amatya, D.M., A COMPARISON OF SIX POTENTIAL EVAPOTRANSPIRATION METHODS FOR REGIONAL USE IN THE SOUTHEASTERN UNITED STATES, *Journal of the American Water Resources Association*, Vol. 41, NO: 3, 621-633, 2005

Martin, D., 2006, *Water Use in Agricultural Watersheds*, Department of Biological Systems Engineering, University of Nebraska – Lincoln, http://watercenter.unl.edu/WRRI/WaterResearch/MartinWaterUse.pdf

Mcdonald, C.C., and G.H. Hughes, 1968, *Studies of consumptive use of water by phreatophytes and hydrophytes near Yuma, Arizona*, U.S. Geological Survey Professional Paper 486-F.

Meissner, R. and Seyfarth, M., 2004, *Measuring water and solute balance with new lysimeter techniques*, SuperSoil 2004: 3rd Australian New Zealand Soils Conference, 5 – 9 December 2004, University of Sydney, Australia, Published on CDROM. Website www.regional.org.au/au/asssi/

Meinzer, O.E., 1927, *Plants as indicators of ground water*, U.S. Geological Survey Water-Supply Paper 577.

Moges, S.A., Katambara, Z., and Bashar, K., 2002, Decision Support System for Estimation of Potential Evapotranspiration in Pangani Basin, *3rd WaterNet/Warfsa Symposium, Water Demand Management for Sustainable Development*, University of Dar es Salaam, 30-31 October, 2002, Dar es Salaam, Tanzania.

Monteith, J.L., 1965, Evaporation and environment, *Sym. Soc. Exp. Biol*, 19:205-234.

Mosner, M.S., and Aulenbach, B.T., 2003, Comparison of Methods used to Estimate Lake Evaporation for a Water Budget of Lake Seminole, Southwestern Georgia and Northwestern Florida, in *Proceedings of the 2003 Georgia Water Resources Conference*, April 23-24, 2003, University of Georgia, Kathryn J. Hatcher, ed., Institute of Ecology, The University of Georgia, Athens, Georgia.

Mower, R.W., J.W. Hood, R.L. Cushman, R.L. Borton, and S.E. Galloway, 1964, *An appraisal of potential ground-water salvage along the Pecos River, between Acme and Artesia New Mexico*, U.S. Geological Survey Water Supply Paper – 1659.

Nadezhdina, N., J. Cermak, and R. Ceulemans, 2002, Radial patterns of sap flow in woody stems of dominant and understory species: scaling errors associated with positioning of sensors, *Tree Physiology*, 22:907-918.

Nagel, H.G., and M.S. Dart, 1980, Platte River evapotranspiration: A historical perspective in Central Nebraska, *Transactions of the Nebraska Academy of Sciences*, 8:55-76.

Nagler, P.L., R.L. Scott, C. Westenberg, J.R. Cleverly, E.P. Glenn, and A.R. Huete, 2005, Evapotranspiration on western U.S. rivers estimated using the Enhanced Vegetation Index from MODIS and data from eddy covariance and Bowen ratio flux towers, *Remote Sensing of the Environment*, 97:337-351.

Nichols, J., W. Eichenger, D.I. Cooper, J.H. Prueger, L.E. Hipps, C.M.U. Neale, and A.S. Bawazir, 2004, Comparison of evapotranspiration estimation methods for a riparian area, U.S. Bureau of Reclamation, Hydroscience and engineering technical report No. 436, 46 pp.

Nourbaeva, G., Kazama, S. and Sawamoto, M., *Assessment of Daily Evapotranspiration Using Remote Sensing Data*, ISEIS – Environmental Informatics Archives, School of Civil Engineering, Tohoku University, 6 Aoba-yama, Sendai, 980-8579, Japan

NRCS, 2001, *Consumptive Use Calculator: Evapo-Transpiration Calculations for Cover Types in a Non-Stressed Environment*, U.S. Department of Agriculture – Nebraska Natural Resource Conservation Service, 54 pp.

Owens, M.K., and G.W. Moore, Saltcedar water use: realistic and unrealistic expectations, *Rangeland Ecology and Management*, 60:553-557.

Penman, H.L., 1948, Natural evapotranspiration from open water, bare soil and grass, *Proceedings of the Royal Society of London*, Series A, col. 193, pp. 120-145.

Perkins, Donald, 1999, Use and construction of a lysimeter to measure evapotranspiration Last updated 28 January 2006, http://www.llansadwrn-wx.co.uk

Priestly, C.H.B., and R.J. Taylor, 1972, On the assessment of surface heat flux and evaporation using large-scale parameters, *Monthly Weather Reviews*, 100:81-92.

Purvis, J.C., 1961, Graphical Solution of the Penman Equation for Potential Evapotranspiration, *Monthly Weather Review*, 089:192-196, docs.lib.noaa.gov/rescue/mwr/089/mwr-089-06-0192.pdf.

Reigner, I.C. 1966. A method of estimating streamflow loss by evapotranspiration from the riparian zone. Forest Science. 12:130-139.

Robinson, T.W., 1958, *Phreatophytes*, U.S. Geological Survey Water Supply Paper 1423.

Scott, R.L., W.J. Shuttleworth, D.C. Goodrich, and T.M. Maddock, 2000, The water use of two dominant vegetation communities in a semiarid riparian ecosystem, *Agricultural and Forest Meteorology*, 105:241-256.

Scott, R.L., E.A. Edwards, W.J. Shuttleworth, T.E. Huxman, C. Watts, and D.C. Goodrich, 2007, Interannual and seasonal variation in fluxes of water and carbon dioxide from a riparian woodland ecosystem, *Agricultural and Forest Meteorology*, 122:65-84.

Shafroth, P.B., J.R. Cleverly, T.L. Dudley, J.P. Taylor, C. Van Riper III, E.P. Weeks, and J.N. Stuart. 2005. Control of Tamarix in the western United States: Implications for water salvage, wildlife use, and riparian restoration. Environmental Management. 35:231-246.

Smith, D.M., and S.J. Allen, 1996, Measurement of sap flow in plant stems, *Journal of Experimental Botany*, 47:1833-1844.

Stromberg, J.C., S.J. Lite, R. Marler, C. Paradzick, P.B. Shafroth, D. Shorrock, J.M. White, and M.S. White. 2007. Altered stream-flow regimes and invasive plant species: the Tamarix case. Global Ecology and Biogeography. 16:381-393.

Stromberg, J., 1998. Dynamics of Fremont cottonwood (Populus fremontii) and saltcedar (Tamarix chinensis) populations along the San Pedro River, Arizona. Journal of Arid Environments. 40:133-155.

Thornthwaite, C.W., and J.R. Mather, 1955, *The water balance*; United States Department of Agriculture: Laboratory of Climatology. Publication No. 8, Centerton, N.J.

Thornthwaite, C.W., Mather, J.R., and Carter, D.B., 1957, *Instructions and Tables for Computing Potential Evapotranspiration and the Water Balance*; Climatology, Vol. 10, No. 3, Centerton, N.J.

Troxell, H.C., 1936, The diurnal fluctuations in the groundwater and flow in the Santa Ana River and its meaning, *Transactions of the American Geophyiscal Union*, 17:496-504.

U.S. Bureau of Reclamation, 1994, revised 2008, *Computation of the 1982 Kimberly-Penman and the Jensen-Haise Evapotranspiration Equations as Applied in the U.S. Bureau of Reclamation's Pacific Northwest AgriMet Program*

U.S. Department of Agriculture, 2006, Improving forage for native bee crop pollinators, *Agroforestry Notes*, 33.

U.S. Department of Agriculture, 2007, Enhancing nest sites for native bee crop pollinators, *Agroforestry Notes*, 34.

U.S. Geological Survey, 2007, The Water Cycle: Transpiration, http://ga.water.usgs.gov/edu/watercycletranspiration.html.

U.S. Soil Conservation Service, 1970, *Irrigation Water Requirements*, U.S. Department of Agriculture, Technical Release No. 21.

U.S. Weather Bureau, 1959, *Evaporation Map for the United States***,** U.S. Weather Bureau Technical Paper 37, plate2.

Van Hylckama, T.E.A., 1980, *Weather and evapotranspiration studies in a Saltcedar thicket, Arizona*, U.S. Geological Survey Professional Paper 491-F.

Walter, I. A., Allen, R. G., Elliott, R., Jensen, M. E., Itenfisu, D., Mecham, B., Howell, T.A., Snyder, R., Brown, P., Echings, S., Spofford, T., Hattendorf, M., Cuenca, R. H., Wright, J. L., and Martin, D., 2000. *ASCE's Standardized Reference Evapotranspiration Equation*. Proc. 4th Dec. Nat. Irrig. Symp. Phoenix, Arizona. Amer. Soc. Ag. Eng., pp 209-215.

Weeks, E.P., H.L. Weaver, G.S. Campbell, and B.D. Tanner, 1987, *Water use by saltcedar and replacement vegetation in the Pecos River floodplain between Acme and Artesia, New Mexico*, U.S. Geological Survey Professional Paper 491-G.

White, W.N., 1932, *A method of estimating ground-water supplies based on discharge by plants and evaporation from soil*, U.S. Geological Survey Water-Supply Paper 659.

Wullschleger, S.D., F.C. Meinzer, and R.A. Vertessy, 1998, A review of whole-plant water use studies in trees, *Tree Physiology*, 18:499-512.

Young, A.A., and H.F. Blaney, 1942, Use of water by native vegetation: California Department of Public Works, *Division of Water Resources Bulletin 50*, 154 pp.