Evapotranspiration Estimates with Emphasis on Groundwater Evapotranspiration in Texas

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Prepared for the Texas Water Development Board

December 2005

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Executive Summary

Accurate estimation of groundwater evapotranspiration (ET) is important for reliable assessment of groundwater resources. The purpose of this study was to (1) compile existing information on ET rates and processes, focusing primarily on groundwater ET from databases and literature; (2) evaluate relationships between vegetation types in different settings and ET rates; and (3) translate information collated in this study on groundwater ET rates and processes into the Groundwater Availability Modeling (GAM) program. This report describes the results of a reconnaissance study to assess the state of knowledge on ET and to determine approaches for providing reliable ET data for the Groundwater Availability Modeling (GAM) program.

ET rates measured from a variety of different approaches were compiled from the literature. Examples of techniques used to estimate ET include water balance, lysimeters, micrometeorological techniques such as Bowen Ratio and Eddy Covariance, and water table fluctuations. Information on ET in Texas is generally limited to meteorological stations used to estimate potential ET (PET) in different parts of the state. There are four Eddy Covariance stations and three Bowen Ratio stations on the Edwards Plateau to evaluate the impact of vegetation on ET. Weighing and nonweighing lysimeters are being monitored in Bushland and Uvalde to estimate ET of crops. None of these measurements provide estimates of groundwater ET. Groundwater ET occurs primarily in riparian buffer strips adjacent to streams. There is no monitoring of ET in riparian zones in Texas. Most detailed information on riparian ET is available from micrometereological stations installed in riparian zones adjacent to the San Pedro River in Arizona and the Rio Grande in New Mexico.

ET rates in the literature range from 46 to 1839 mm/yr (1.8 to 72.4 in/yr). There is no systematic variation in ET rates among different vegetation types including riparian, trees, shrubs, and grasses. Within riparian zones, ET rates are generally higher in obligate phreatophytes such as cottonwood and willows than in facultative phreatophytes such as mesquite and saltcedar. These differences in ET rates generally reflect differences in leaf area and plant density rather than a fundamental difference in ET rates related to plant type such as cottonwood or saltcedar. Sites where ET was partitioned into groundwater ET indicate that even in riparian zones where vegetation has access to groundwater, ET rates generally range from 30 to 50 percent of PET. ET rates from previous GAM models ranged from 2 to 96 percent of groundwater discharge. The proposed approach for simulating ET in GAMs includes (1) setting an extinction depth based on combined depth of root zone and thickness of capillary fringe (based on soil type), (2) increasing ET linearly from zero for most vegetation types at the extinction depth to the vegetation ET rate over the thickness of the root zone, and (3) again increasing ET approximately linearly over the thickness of the capillary zone. ET at the surface

is set at the PET rate. A map of long-term average annual PET is available for Texas. Information on crop coefficients for riparian vegetation to reduce PET to actual ET is provided. Data requirements for this approach for modeling ET include PET, distribution of riparian vegetation or wetland vegetation in areas of shallow water tables, vegetation coefficients for identified plant types, soil textures for estimating thickness of capillary fringe and capillary zone, and rooting depths for specified plant types in the area soils. Application of this approach to simulating ET in future GAMs should result in more reliable ET rates and more comparable ET rates among GAMs. This consistent approach may result in improved predictions of groundwater capture resulting from increased groundwater development and lowering of water tables below root extinction depths.

There are a number of limitations to this study. The primary limitation is the lack of ET measurements in riparian vegetation in Texas. In contrast, surrounding states such as New Mexico, Arizona, and Oklahoma have several micrometeorological stations for monitoring ET. In addition, New Mexico plans to install about 35 new stations along the Rio Grande in a recently funded study. The lack of a detailed map of the distribution of riparian vegetation in the state is a severe limitation also. Another limitation is the questionable applicability of ET data from semiarid regions such as Arizona and New Mexico to east Texas where the climate is much more humid. Although the primary objective of this study was to assess groundwater ET, most studies do not partition ET into unsaturated zone and groundwater components.

This reconnaissance study highlights gaps in our knowledge in estimating groundwater ET for the GAM program that should be addressed in future studies. A map of riparian vegetation should be developed at an appropriate resolution for the GAM program. Monitoring of ET should be conducted in riparian zones in different climatic regions in the state. Different approaches for monitoring ET should be compared, such as micrometeorological approaches, water table fluctuations, and sap flow measurements. Optimal approaches should be chosen, and a network of stations should be established in the state. At least 20 to 30 micrometeorological stations would be required to cover representative climate, soil, and plant types in the state. Water table fluctuations should be monitored adjacent to surface water gauging stations to assess groundwater-surface water interactions and to use this approach to estimate ET. Sap flux measurements can be done in different vegetation types to estimate ET. Isotope studies can be conducted to determine the source of the evaporating water. Modeling approaches for estimating ET should also be investigated and validated with ground-based measurements. Satellite-based approaches for monitoring ET should also be evaluated and compared with ground-based data. Satellite approaches could be used to upscale ground-based measurements. Such information would advance our understanding of ET rates, processes, and controls and would be invaluable for optimal management of water resources in Texas.

1.0 Introduction

Evapotranspiration (ET) is the transport of water between the Earth's surface and the atmosphere accompanied by a change in phase from liquid or solid (sublimation) at or below the surface, to vapor in the atmosphere. Evapotranspiration includes evaporation from bare soil or open water surfaces and transpiration from plants. Transpiration is evaporation that occurs through the stomates of plants. Stomates are microscopic holes in the leaves or needles of vegetation, through which water is lost in the process of obtaining carbon dioxide for growth.

Evapotranspiration generally constitutes the second largest component of the water budget, after precipitation. Groundwater ET, caused primarily by deep-rooted phreatophytes, is a significant component of groundwater discharge for many aquifers. Phreatophyte is defined as a deep-rooted plant that obtains its water from the water table or the layer of soil just above it (Merriam-Webster Online Dictionary, 2005). Accurate assessment of groundwater resources requires a thorough understanding of ET rates and processes. Spatiotemporal variability in ET rates needs to be incorporated into Groundwater Availability Models (GAMs) to better predict available groundwater resources. Most groundwater ET occurs in riparian buffer strips adjacent to streams. The distribution of vegetation types and riparian zones is described in Appendix 1.

The purpose of this study was to (1) compile existing information on ET rates and processes, focusing primarily on groundwater ET, using data based on physical, chemical, isotopic, and modeling techniques by examining databases and literature; (2) evaluate relationships between vegetation types in different settings and ET rates; and (3) translate information collated in this study on groundwater ET rates and processes into the GAM program.

1.1 Water Resources

Water resources management is a critical issue in Texas because of diminishing supplies and projected rapid increases in population growth (21 million in 2000 to 40 million in 2050: TWDB, 2002). To manage future water resources it is critical to understand the various components of the groundwater budget. The general water budget can be represented as:

$$P + Q_{on}^{sw} + Q_{on}^{gw} - ET^{sw} - ET^{uz} - ET^{gw} - Q_{off}^{sw} - Q_{off}^{gw} - Q^{bf} - Q_{gw}^{pu} = \Delta S^{sw} + \Delta S^{uz} + \Delta S^{gw} \quad (1)$$

where P is precipitation, Q is flux, sw is surface water, gw is groundwater, uz is unsaturated zone, ET is evapotranspiration, pu is pumping, ΔS is change in water storage, bf is baseflow, and on and off refer to flow into and out of the area being considered (Scanlon and others, 2002). This general budget shows that ET can occur from surface water, unsaturated zone, and groundwater. This study focuses on the groundwater budget:

$$R - Q^{pu} - Q^{bf} - ET^{gw} + Q_{on}^{gw} - Q_{off}^{gw} = \Delta S^{gw} \quad (2)$$

where R is recharge. Developing a consistent methodology for simulating groundwater ET in the GAM program should increase confidence in water availability estimates. Model calibration using groundwater head data alone cannot distinguish between different modes of groundwater discharge; that is, the same head distribution can be obtained if groundwater is discharged through ET or baseflow to streams. Reducing uncertainty in ET estimates may improve recharge and baseflow simulation. Improved estimates of the extinction depth used in MODFLOW for ET simulation should be extremely useful in evaluating the impacts of increased groundwater development and declining water tables on groundwater ET. If the water table falls below the extinction depth specified in MODFLOW, groundwater ET becomes zero and water that previously was evapotranspired would be available for use. Therefore, water availability may increase as a result of reduced discharge through ET. Development of a database of groundwater ET rates for different vegetation and climates will provide actual ET data for comparison with model results from the GAM program.

Other programs in Texas that can benefit from information on ET include brush control and instream flow. The brush control program in Texas is being conducted to reduce ET by removing brush and thus make more water available for groundwater recharge and streamflow (Dugas and others, 1998; Thurow and others, 2000; 2001). Saltcedar has been removed along the Pecos River in west Texas, and studies of the effects of vegetation removal are ongoing (Clayton and others, 2000; Hart and others, 2005). Accurate information on ET is required to assess potential impacts of brush control on the water cycle. This study should provide relevant information for the brush control program. Accurate information on groundwater ET is also required to evaluate instream flows. Assessing minimum flow requirements of streams to meet human and ecosystem needs is the topic of a recent National Academy of Sciences panel in Texas (NRC, 2005). Improved understanding of groundwater discharge through ET would help constrain estimates of baseflow discharge to streams.

1.2 Scope of Work

The scope of the study includes three primary tasks, and the groups responsible for those tasks are listed below:

Task 1. Compilation of all existing information on ET rates (UT Bureau of Economic Geology)

Task 2. Relation of ET rates to vegetation parameters (UT School of Biological Sciences)

Task 3. Assessment of how ET processes and rates can be incorporated into GAMs (INTERA)

Task 1 includes development of a database on ET rates, study area locations, techniques used to estimate ET rates, annual precipitation, and vegetation type based on information in the literature and databases. Scaling issues related to ET are also evaluated within this task. Conceptual models of ET processes were developed for different settings. Gaps and limitations associated with existing data are determined as part of this task. Task 2 involves relating ET rates to various vegetation parameters based on literature review. Differences in ET rates between obligate and facultative phreatophytes were evaluated. Various remote sensing approaches for classifying phreatophytic vegetation were examined. Information on rooting characteristics of different vegetation types and the degree to which rooting depths of vegetation vary in response to declining water tables were examined. Task 3 involves translating information on ET processes and rates into GAMs. Critical parameters include ETmax (maximum ET rate at the surface), ET extinction depth, and rooting depths of vegetation.

2.0 Task 1a. Collate Existing Data on ET Rates from the Literature and Databases

A database was developed that includes information on ET rates in settings similar to those in Texas. The database was developed after reviewing approximately 200 published papers and reports on ET. Only data that included ET rates for long time periods such as growing season or annual periods were included in the final database (Appendix 2, Figure 2.1). Although information on ET for the entire year is preferable, many studies only report total ET for the growing season. It is not possible to readily convert rates based on growing season to those based on an entire year without information on nongrowing season ET rates. The latter varies with precipitation rates during the nongrowing season. We were not able to find any information on nongrowing season ET in the literature, but discussions with Dr. Russ Scott (USDA, Arizona) provided some comparisons. For example, ET for a mesquite site in Arizona in 2003 for the growing season was 676 mm (26.7 in) (Appendix 2), whereas ET for the entire year was 744 mm (29.3 in); therefore, the nongrowing season ET was 68 mm (2.7 in) and precipitation during the nongrowing season was 60 mm (2.4 in). During 2004, ET for the growing season was 615 mm (24.2 in) and for the entire year was 721 mm (28.4 in); therefore, 106 mm (4.17 in) ET occurred during the nongrowing season. Rainfall during the nongrowing season at this site in 2004 was 110 mm (4.33 in). Therefore, ET in this region during the nongrowing season is almost equivalent to precipitation during the nongrowing season (Scott, pers. comm., 2005). The database generally includes information on the following categories where the information was available: ET rates, study year(s), notes on whether the ET rate represents total ET (ET), groundwater ET (GW ET), or potential ET (PET), study area location, technique used to estimate ET, vegetation, annual precipitation, and reference information. Most information on ET rates was obtained from published papers.

2.1 Techniques for Estimating Evapotranspiration

The ET database (Appendix 2) includes rates based on a variety of different techniques. A brief review of these techniques is given to provide background for understanding the database. The various techniques include

1. meteorological approaches
2. soil moisture balance
3. lysimeters
4. sap flow sensors (transpiration)
5. water table fluctuations
6. optical remote sensing
7. modeling
8. stable isotopes

Meteorological approaches include measurement of parameters to estimate reference crop evapotranspiration (ET_o) and multiplying ET_o times a crop coefficient to estimate actual evapotranspiration. The term potential ET (PET) is also used to describe reference crop ET; however, there are ambiguities in the definitions of PET (Allen and others, 1998). The two terms, reference crop ET and PET, are used interchangeably in this study. The reference crop ET represents the evaporative power of the atmosphere and is only controlled by climatic parameters. The reference crop is generally grass with a fixed crop height (0.12 m, 0.39 ft), an albedo of 0.23, a surface resistance of 0.70 s/cm (1.78 s/in), and not water limited (Allen and others, 1998).

$$ET = K_c \, ET_o \tag{3}$$

where ET is actual ET of the crop, K_c is crop coefficient (dimensionless), and ET_o is reference crop ET.

$$K_c = ET_c / ET_o \tag{4}$$

Crop coefficients are determined from measuring ET for a crop and ET_o for reference grass. Crop coefficients should take factors such as soil moisture, crop maturity, wind, and relative humidity into account.

$$K_c = K_{cb}K_s + K_w \tag{5}$$

where K_c is the crop coefficient for a particular crop, K_{cb} is basal crop coefficient for the particular crop, K_s is the factor related to water stress, and K_w is the factor to account for the increased evaporation from wet soils following a rain or irrigation event (Borrelli and others, 1998). K_{cb} is a function of mean minimum relative humidity and strength of wind. When stress due to lack of soil moisture is ignored, the crop is assumed to have adequate soil moisture for maximum growth. The factor K_w varies with soil type and with the number of times wet surfaces are developed.

The most widely used approach for estimating reference crop ET is the Penman-Monteith equation (equation 3, Allen and others, 1998):

$$ET_0 = \frac{1}{\lambda} \frac{\Delta(R_n - G) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)} \qquad (6)$$

where λ is latent heat of vaporization, Δ represents slope of saturation vapor pressure temperature relationship, R_n is net radiation, G is soil heat flux, (e_s - e_a) represents vapor pressure deficit of the air, ρ_a is mean air density at constant pressure, c_p is specific heat of the air, γ is psychometric constant, and r_s and r_a are (bulk) surface and aerodynamic resistances. The Food and Agriculture Organization (FAO) Penman-Monteith equation (7) is derived from equation (6) by incorporating equations for aerodynamic and surface resistance:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \qquad (7)$$

where ET_o is reference crop ET, T is mean daily air temperature (2 m height, deg. C), and u_2 is wind speed at 2 m (6.6 ft) height. Required measurements to estimate ET_o include solar or net radiation (sunshine), air temperature, relative humidity, and wind speed. The measurements should be made at 2 m (6.6 ft) (or converted to that height) above an extensive surface of green grass, shading the ground and not short of water.

The Penman-Monteith equation shows that the main factors controlling ET are energy supply such as solar or net radiation and water supply. Evapotranspiration for reference crops is controlled by climatic factors. Atmospheric demand is controlled by vapor pressure deficit, wind speed, and atmospheric stability. Surface resistance is affected by plant stomates (transpiration), leaf area index, soil surface dryness, and surface roughness.

Micrometeorological approaches for measuring ET include the Bowen Ratio Energy Budget and Eddy Covariance approaches (Evett, 2000). Both approaches are based on the energy balance equation:

$$R_n = H + \lambda ET + G \qquad (8)$$

where R_n is net radiation measured with a net radiometer, H is sensible heat flux or energy used to heat the air, λET is latent heat flux or energy used to evaporate water, λ is latent heat of vaporization of water, and G is soil heat flux or energy used to warm the soil, measured with soil heat flux plates or soil temperature profiles. The Bowen ratio is the ratio of sensible to latent heat flux, $\beta = H/\lambda ET$, and can be calculated as a constant times the vertical gradient in air temperature divided by that of water vapor pressure.

$$ET = 1/\lambda(R_n - G)/(\beta + 1) \quad (9)$$

Time increments should be no longer than 1 hour. Vertical gradients of temperature and vapor pressure are often quite small and therefore sensitive to instrument bias (Tanner, 1960; Stannard, 1993; and Shuttleworth, 1991).

The Eddy Covariance or Eddy Correlation method is based on the concept that if eddies with an upward velocity are correlated with humidities that are on average higher than humidities with downward moving eddies, then the net flux of water vapor is upward (Evett, 2000).

$$ET = \left(\frac{M_w}{M_a P}\right)\rho_a \overline{w}' \overline{e}_a' \quad (10)$$

where the overscores indicate time averages of vertical wind speed, w', and water vapor pressure, e_a', the primes indicate instantaneous deviations from the mean, P is atmospheric pressure, ρ_a is air density, and M_w and M_a are molecular weights of water and air. Precise and rapid (10 Hz) measurement of wind speed and direction and water vapor are required. Instrumentation can include a sonic anemometer for wind speed and direction and sonic temperature and a Krypton hygrometer for atmospheric water vapor. Instruments are usually installed at a height of 1 to 2 m (3.3 to 6.6 ft) above the plant canopy. Instruments are expensive and fragile, although durability has been greatly improved in recent years (Tanner, 1988; Stannard, 1993).

Soil water balance monitoring can also be used to estimate ET:

$$ET = P - R_0 - D - \Delta S \quad (11)$$

where P is precipitation, R_0 is runoff, D is drainage below the root zone, and ΔS is change in soil water storage. P and R_0 are zero during dry periods and ET can be estimated by subtracting drainage from change in soil water storage. In arid regions, drainage is often approximately zero, and ET is approximated by changes in soil water storage between rains. On an annual basis, changes in soil water storage are generally zero, and ET can be estimated from P - R_0 - D. Soil water content can be measured periodically with a neutron probe or with time domain reflectometry. Groundwater ET can be estimated using a simple water balance approach when runoff and drainage are negligible; that is, if ET rates exceed precipitation + ΔS on an annual basis, then the difference can be assigned to groundwater ET (Scott and others, 2000a, b).

Lysimeters are containers filled with disturbed or undisturbed soil, with or without vegetation, which are hydrologically isolated from the surrounding soil for purposes of measuring the components of the water balance:

$$\Delta S = P - ET - D \quad (12)$$

where ΔS is change in soil water storage, P is precipitation, ET is evapotranspiration from vegetated lysimeters, and D is drainage (Allen and others, 1991). Many lysimeters have an elevated rim around their edges that precludes runon and runoff. All lysimeters are designed to allow collection and measurement of drainage. Nonweighing or drainage lysimeters measure only drainage; precipitation and water storage must be measured separately. Weighing lysimeters are generally used for accurate measurements of E or ET. Weight changes correspond to changes in soil-water storage. Increases in soil-water storage correspond to precipitation and decreases in soil-water storage correspond to E, T, or D. Lysimetry has been used primarily to determine crop coefficients for agricultural research (Dugas and others, 1985; Howell and others, 1985; Allen and others, 1991).

Plant transpiration can be measured using the heat pulse velocity method. The instantaneous velocity of sap moving within the xylem of a plant is measured (Marshall, 1958; Cohen and others, 1981). A probe is inserted in the stem of the plant. The probe generally consists of two needles; a line heater and a thermocouple junction. The line heater generates a heat pulse and the rate of dissipation of heat or time required for the pulse to travel a given distance and the amplitude of the pulse are measured by the thermocouples. These data are used to estimate the velocity of sap within the xylem. The results can be scaled up to a canopy level.

Water table fluctuations are used to estimate groundwater ET (White, 1932; Loheide and others, 2005).

$$ET = SY(24R + NF) \tag{13}$$

where SY is aquifer specific yield, R is hourly rise of water table between midnight and 4 am and NF is net fall of water table during 24 hr period. Assumptions include high air permeability from surface to water table, no water use by vegetation between midnight and 4 am, and roughly constant groundwater supply from below. Water table fluctuations are generally small and may be impacted by barometric pressure effects even in unconfined aquifers. Gas bubbles below the water table can expand and contract making data analysis difficult.

Optical remote sensing has been used to estimate regional ET using the Surface Energy Balance for Land (SEBAL) model developed by Bastiaanssen and others (2002) and the two source model (Anderson and others, 2004). A brief review of the SEBAL approach is provided in this section. SEBAL is based on the estimation of ET as a residual term in the energy balance equation (8). The term $R_n - G$ represents the available energy, which is subdivided between λE and H. Net radiation (R_n) is estimated from the remotely sensed surface albedo and surface temperature, along with solar radiation calculated from standard astronomical formulae (Iqbal, 1983). The soil heat flux (G) is estimated from semi-empirical relationships, which include net radiation, surface albedo, surface temperature, and vegetation index. The specific equations used in SEBAL to estimate R_n and G can be found in Bastiaanssen and others (1998a, b).

ET can also be estimated using various modeling approaches. Land atmosphere models, watershed models, water balance models, and groundwater models can be used to estimate ET. Examples of watershed models include Soil Water Assessment Tool. Water balance models include unsaturated zone models such as HYDRUS-1D (Simunek and others, 1998) and UNSAT-H (Fayer, 2000) HYDRUS-1D and UNSAT-H use PET based on climate data and partition it into potential evaporation and potential transpiration. Fluxes occur at the potential rate when head at the surface node is between 0 and a prespecified lower value. Below this prespecified head value potential evaporation is reduced based on soil moisture availability and potential transpiration is distributed based on rooting depth and reduced based on soil moisture availability. When the head reaches a lower bounding value, that is, wilting point of vegetation, the boundary condition changes from a constant flux (PET) to a constant head, and evapotranspiration is controlled by the rate at which water can be transmitted to the soil surface.

Stable isotopes of oxygen and hydrogen can be used to distinguish different sources of ET if these sources have different isotopic signatures (Brunel and others, 1995; Dawson and Ehleringer, 1993; Walker and Richardson, 1991). The relative contribution of evaporation and transpiration to ET can be evaluated using stable isotopes of oxygen and hydrogen because transpiration does not fractionate isotopes (Hsieh and others, 1988).

2.2 Riparian ET Programs in Surrounding States

ET programs in surrounding states are very advanced. Numerous studies have been conducted on riparian ET along the Rio Grande in New Mexico. Currently about 10 micrometeorological stations are monitoring riparian ET under different plant functional types (cottonwood, saltcedar, and Russian olive) and different conditions (flooded and unflooded) (Cleverly and others, 2002; Dahm and others, 2002). This program will be expanded to include an additional 30 to 35 micrometeorological stations to monitor riparian ET through the New Mexico Experimental Program to Stimulate Competitive Research (EPSCoR) (Bowman, pers. comm., 2005). This program also includes evaluation of satellite based approaches for estimating ET by validating the results with ground-based measurements. Water table level fluctuations are also being monitored adjacent to stream gauges to assess groundwater-surface water interactions and assess riparian ET.

Arizona also has an intensive program to quantify riparian ET that includes micrometeorological stations (Bowen Ratio and Eddy Covariance systems) in mesquite and sacaton grass sites and sap flux measurements in cottonwood and willow sites (Scott and others, 2000a, b, 2004, 2005). Water table fluctuations are also being monitored to compare this approach for estimating ET. ET is subdivided into unsaturated and groundwater components at these sites. The ground-based data are used to develop empirical relationships between riparian ET and vegetation indices from satellite data (Normalized Difference Vegetation Index, NDVI; and Enhanced Vegetation Index, EVI). (Nagler and others, 2005a, b).

The Oklahoma Mesonetwork (Brock and others, 1995) is a permanent system of 115 stations that measures a suite of meteorological and surface components across all of Oklahoma, with an average spacing interval of 30 km (18.6 mi) between sites. Each site measures solar radiation, air pressure, precipitation, wind speed and direction at 10 m (32.8 ft), air temperature and relative humidity at 1.5 m (3.3 ft), and bare soil and soil temperature at a 10 cm (3.9 in) depth. The mesonet was installed during 1992 and became operational on 1 January 1994. The Oklahoma Atmospheric Surface-Layer Instrumentation System (OASIS; Brotzge 1999) enhanced 89 of the mesonet sites with new sensors to enable routine measurements of the surface energy budget. Net radiation, ground heat flux, sensible heat flux, and skin temperature are measured. Latent heat flux is estimated as the residual of the surface energy balance. In addition, soil matric potential is measured at 5, 25, 60, and 75 cm (2.0, 9.8, 23.6, and 29.5 in) depths.

These systems provide examples of the types of data required to address riparian ET. Each program includes multiple approaches that span a range of space scales and can be used to evaluate the reliability of different techniques.

2.3 Summary of Database Results

Evapotranspiration rates were quite variable and ranged from 46 to 1839 mm/yr (1.81 to 72.4 in/yr) (Appendix 2). There is no systematic variation in ET rates among different vegetation types (riparian, trees, shrubs, crops, etc) (Figure 2.2). Each technique provides a range of ET rates for the vegetation types (Figure 2.3). Within categories there is some systematic variation in ET rates, for example between obligate and facultative phreatophytes in riparian vegetation as discussed in section 3.1. Cleverly and others (2002) showed that ET for unflooded saltcedar was 60% of that for flooded saltcedar based on data from 1999. More recent data (2000 to 2004) indicate that ET in unflooded saltcedar averages 73% of that in flooded salt cedar. Differences between flooded and unflooded saltcedar do not seem to apply to cottonwood where ET for the flooded sites averages 85% of that in the unflooded sites. ET is generally not correlated with precipitation (Figure 2.4). Some studies only report potential ET or reference crop ET. A limited number of studies report ET and PET for the same region. ET and PET data from New Mexico indicate that ET represents 50 to 134 percent of PET for various riparian sites near the Rio Grande from 2001 to 2004 (Cleverly, pers. comm., 2005). Estimates of ET and PET are also available for sites in Arizona (Scott, pers. comm., 2005). These data indicate that ET ranges from 55 to 65 percent of PET for a mesquite site for 2001 to 2003.

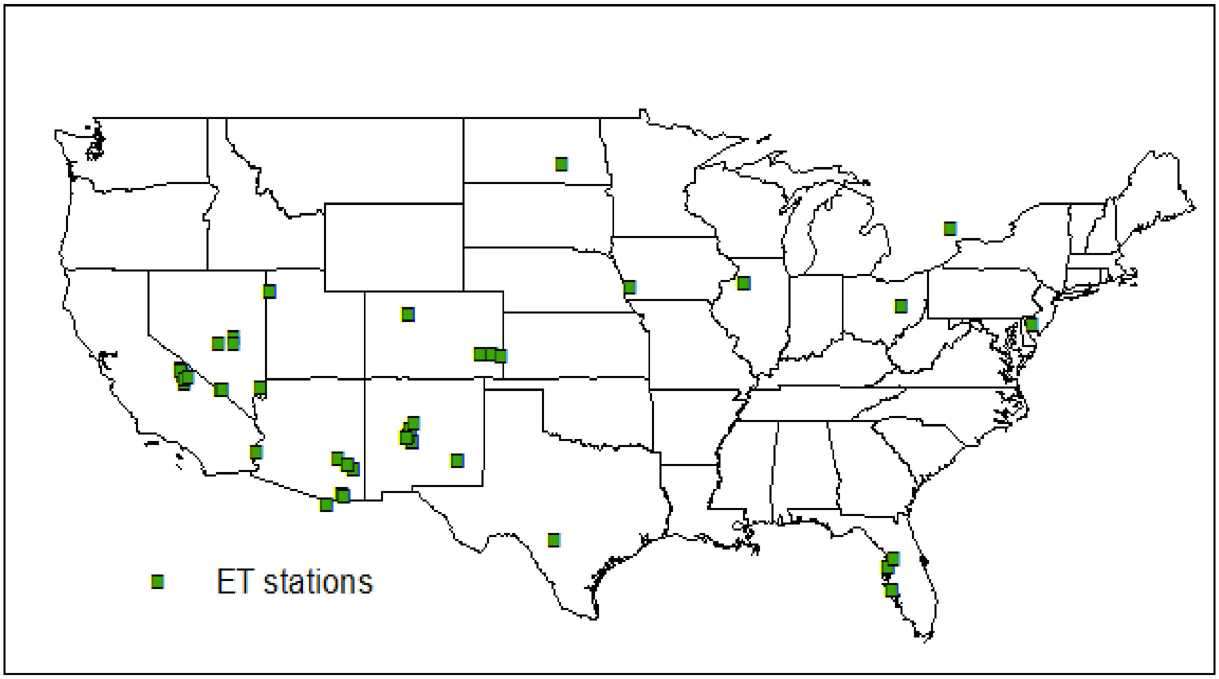

Figure 2.1 Distribution of sites in the U.S. that correspond to ET rates provided in Appendix 2. Sites are not numbered because many locations represent multiple studies.

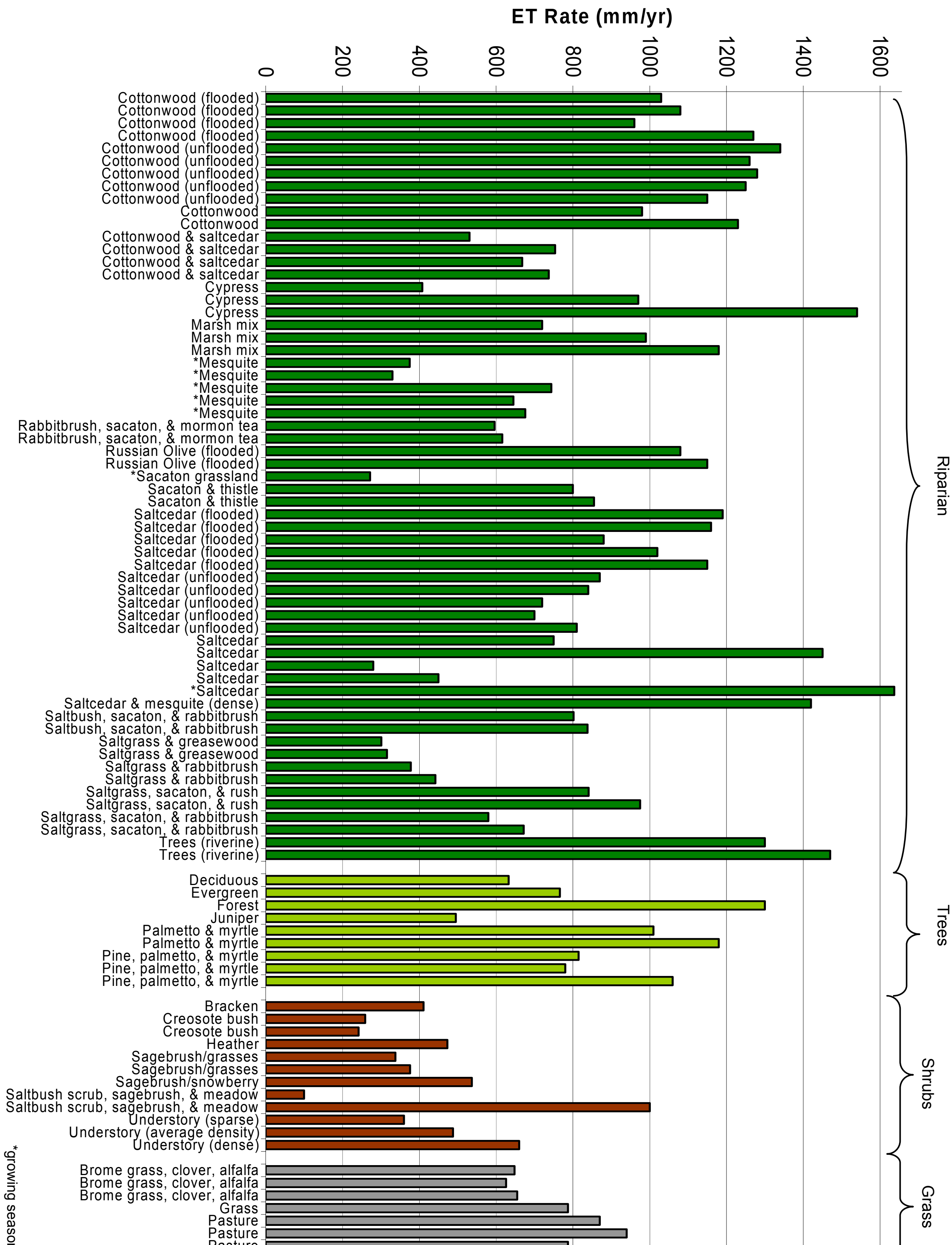

Figure 2.2. ET rates for various vegetation types based on data from Appendix 2.

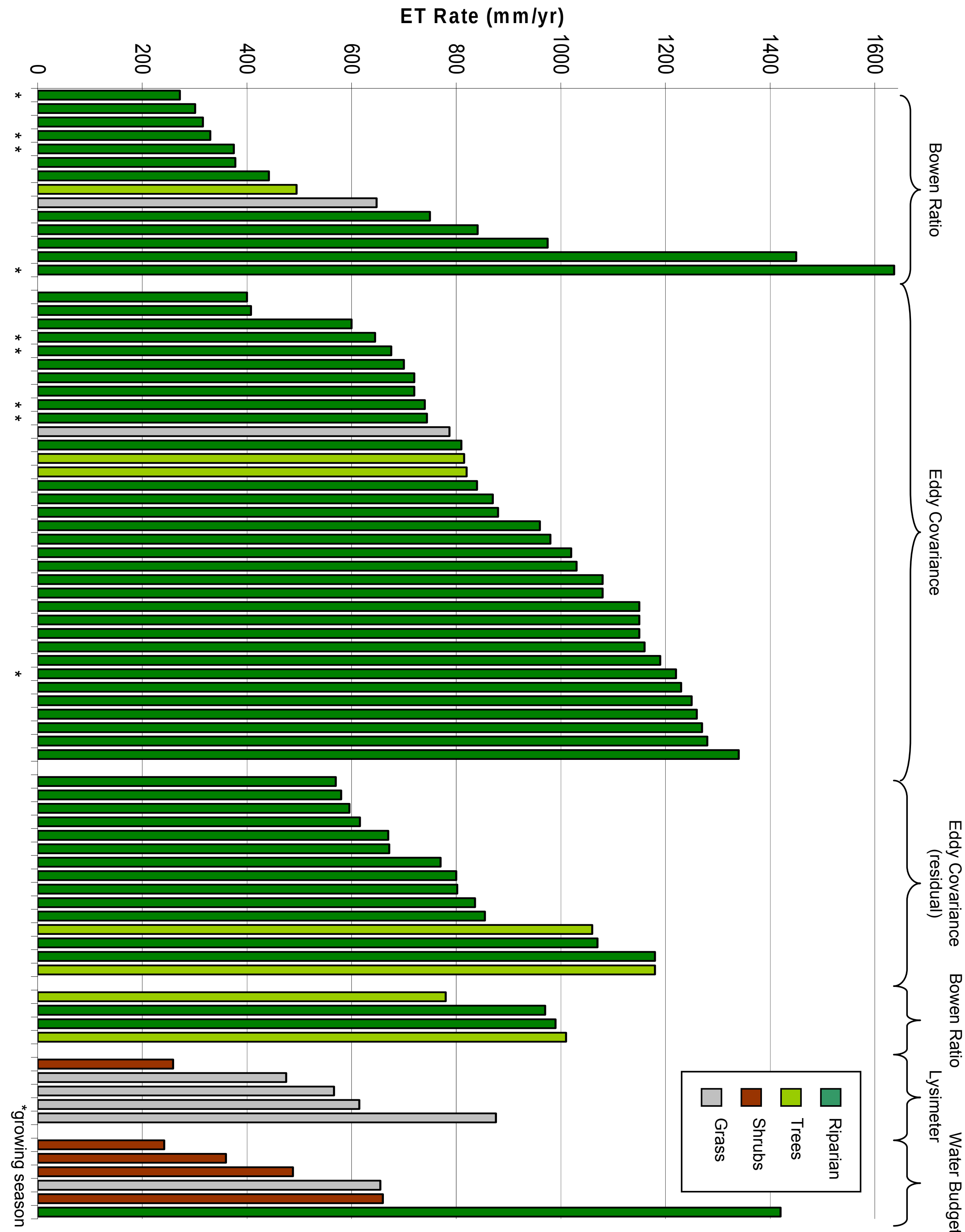

Figure 2.3. Range of ET rates based on data from different measurement techniques using data from Appendix 2.

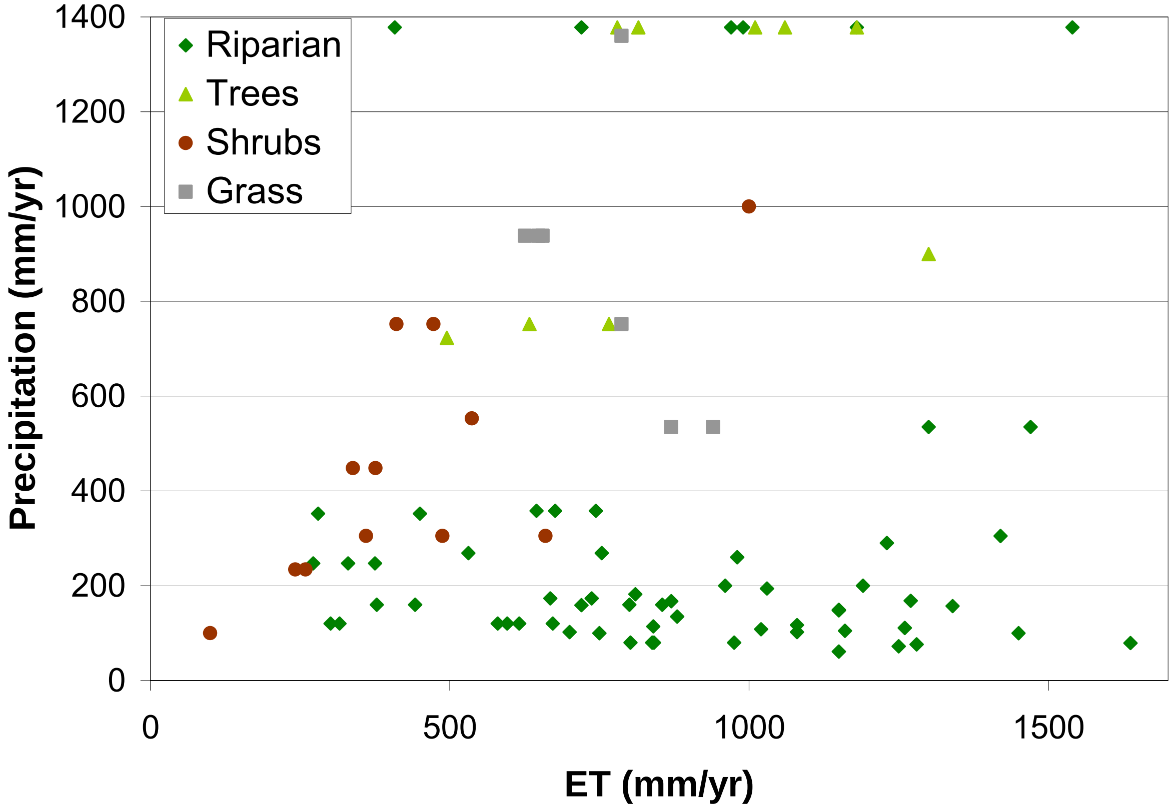

Figure 2.4. Relationship between ET and precipitation.

Groundwater ET is the parameter of most interest for groundwater modeling. Most studies measure total ET which includes ET from surface water, unsaturated zone, and/or groundwater. Studies by Scott and others (2004, 2005) separate ET into a groundwater component by subtracting precipitation and soil water storage from ET, termed precipitation excess ET. Groundwater ET varies from 61 to 75 percent of ET and 34 to 44 percent of ET_0 at a mesquite site in Arizona (Scott and others, 2004, 2005). Therefore, these data suggest that if information is only available on PET from climate records, groundwater ET should represent only a fraction of PET.

2.4 Task 1b. Evaluate Scaling Issues Related to ET

The spatial scales covered by different techniques varies from point scales based on monitoring sap flow in individual trees and weighing lysimeter data to larger scales covered by water table fluctuations and micrometeorological approaches. The micrometeorological approaches provide ET estimates for the fetch area of the instrument that depends on the height of the instrument and wind directions, generally on the scale of 100 to 300 m (328 to 984 ft). Various remote sensing approaches can be used to regionalize smaller scale estimates, using truck, airplane, or satellites as platforms (Norman and others, 2003; Kustas and others, 1999). Many studies have evaluated upscaling and downscaling between point based and regional estimates (Anderson and others, 2003; Kustas and others, 2003). The various approaches for estimating ET complement each other in the spatial scales represented. It is important to combine data using different approaches to develop a comprehensive understanding of ET processes and rates at different scales.

The database includes ET estimates based on various measurement approaches and covers a wide range in scales. Comparison of ET estimates based on the SEBAL satellite data and lysimeter data in the Bear River Basin in Idaho showed that the SEBAL estimates were within ± 16 percent for monthly ET values and within ± 4 percent for seasonal values (Allen and others, 2001). Programs have been developed for aggregating and disaggregating remote sensing based estimates to the fetch area of micrometeorological based methods with good success (Anderson and others, 2003, 2004).

2.5 Task 1c. Develop Conceptual Models of ET Processes in Different Settings

Developing realistic conceptual models of ET is an essential prerequisite for accurately modeling ET in Groundwater Availability Modeling (GAM) studies. Conceptual models of ET may vary with climate, vegetation, and hydrology. Most groundwater ET should occur where water tables are shallow, generally adjacent to streams where riparian vegetation is dominant. Information on the distribution of riparian vegetation in Texas is limited. Various sources of vegetation maps in Texas are described in Appendix 1; however, the resolution of these state-wide vegetation maps is generally not high enough to show narrow riparian buffer strips along some streams. Riparian vegetation is often dominated by phreatophytes, which are defined as vegetation that obtains water from groundwater. Phreatophytes are subdivided into obligate phreatophytes that need access to groundwater or facultative phreatophytes that use groundwater but do not depend on groundwater and can obtain water from other sources, for example unsaturated zone or surface water. Because obligate phreatophytes should have access to groundwater, one would expect that they might evaporate at close to the potential rate. However, data from the literature indicate that ET rates from phreatophytes are often only 30 to 50 percent of PET (Scott and others, 2005; Landon, pers comm., 2005).

One approach to estimating groundwater ET in Texas would be to apply a fraction of PET to riparian zones and areas where water tables are shallow. PET networks have been established in many areas of Texas (Figure 2.5).

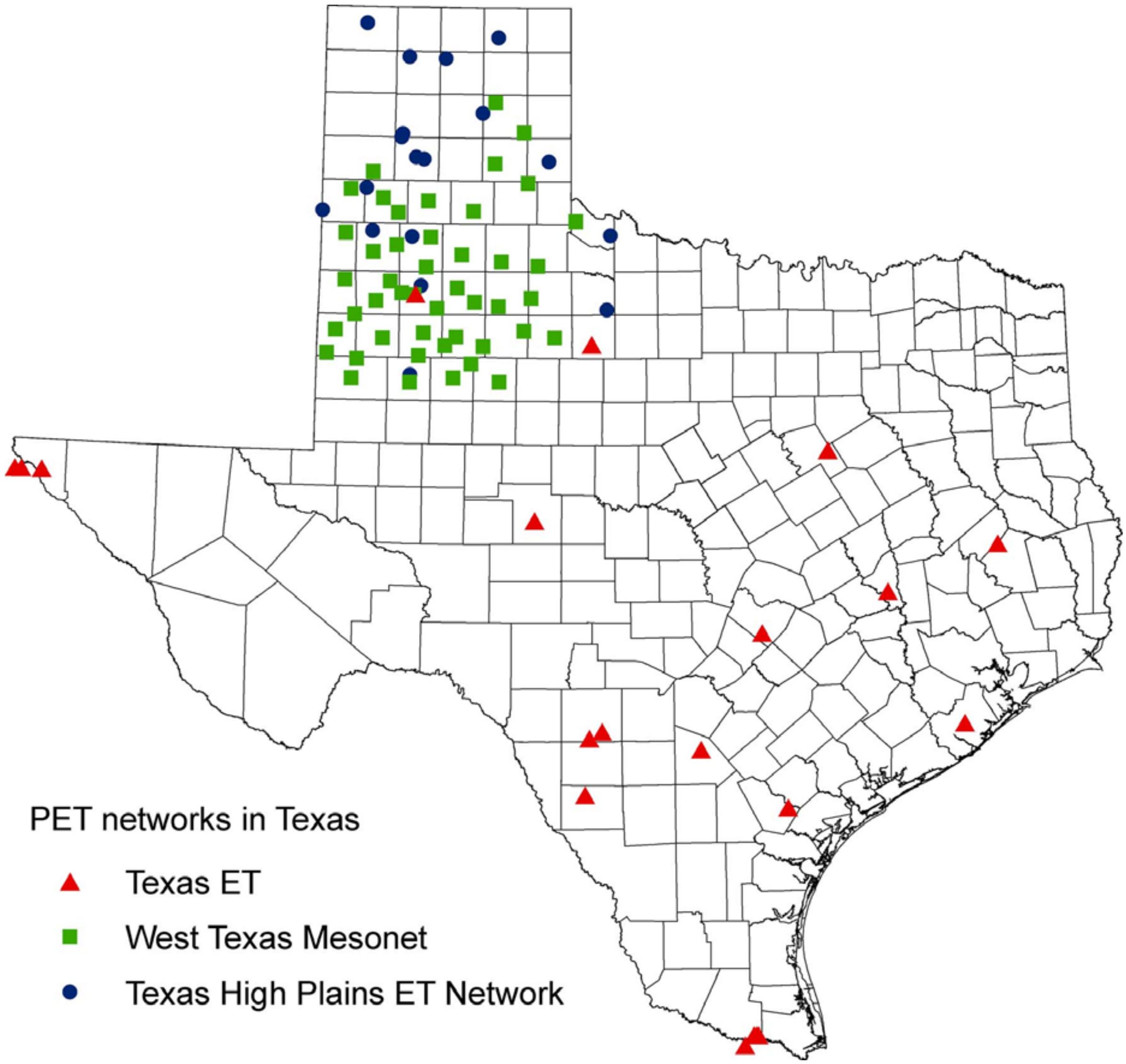

Figure 2.5. Location of PET networks in Texas.

Web sites containing information about PET stations in Texas include:

Texas High Plains ET Network: http://txhighplainset.tamu.edu/

TexasET: http://texaset.tamu.edu/

West Texas Mesonet: http://www.mesonet.ttu.edu/

The Texas MesoNet: http://www.met.tamu.edu/texnet/mesonet.html

A map of long-term (30 yr) annual ET for a grass reference crop (ET_o) was developed by Borrelli and others (1998) based on climatic data (Figure 2.6, Table 2.1). Tables of crop coefficients (K_c) for specific locations are tabulated in Borrelli and others, 1998. Table 2.1 provides basal crop coefficients for common crops grown in Texas (Borrelli and others, 1998 modified from Soil Conservation Service, 1993). These values assume that the soil surface is dry. All parts of the state have a wind run less than 400 km/day (250 mi/day) except for the extreme northern Panhandle during the months of March and April; therefore, only coefficients for moderate wind run are presented here (coefficients for strong wind run can be found in Borelli and others, 1998). Although ET rates are not correlated with precipitation (Figure 2.7), reference crop ET (equivalent to PET) is inversely proportional to precipitation and decreases from west to east in Texas. Crop coefficients are also provided in Borrelli and others (1998) for the main crops in Texas based on data from Soil Conservation Service (1993) and Jensen (1990) (Table 2.2). Some information is also provided in Borrelli and others (1998) for riparian vegetation based on literature values.

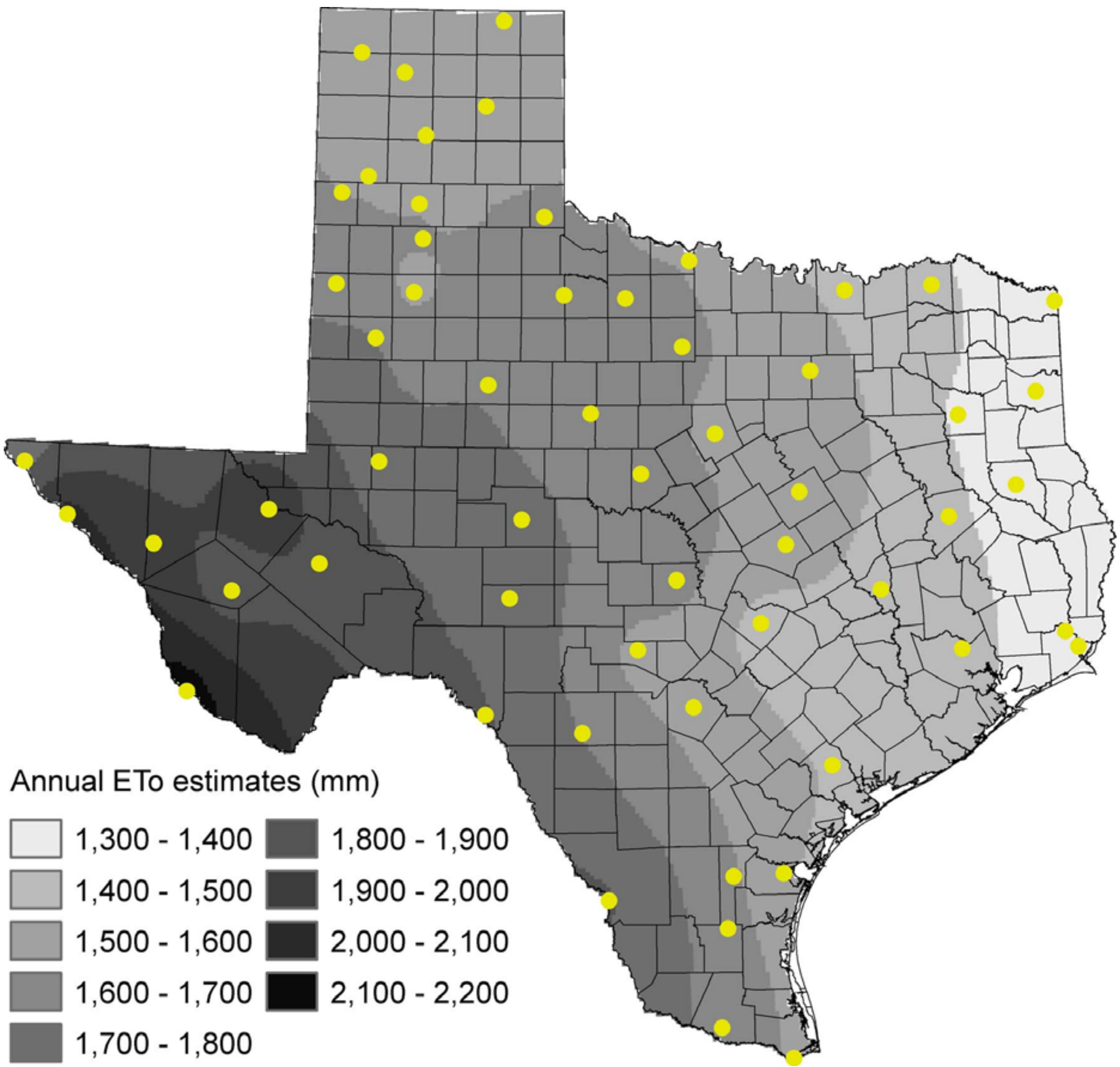

Figure 2.6. Long-term (30-yr) annual grass reference crop ET (ET_o) based on calculations using the Penman-Monteith equation for 58 sites in Texas and 7 sites in neighboring states (Borrelli and others, 1998). Values for each location are provided in Table 2.1.

Table 2.1. Annual grass reference crop evapotranspiration (ET_o) (mm/yr) plotted in Figure 2.6 from Borrelli and others, (1998).

Location	*Latitude*	*Longitude*	*Annual (ET_0) (mm/yr)*	*Annual (ET_0) (in/yr)*	*Location*	*Latitude*	*Longitude*	*Annual (ET_0) (mm/yr)*	*Annual (ET_0) (in/yr)*
Abilene	32.43	-99.68	1631	64.2	Morton	33.72	-102.76	1661	65.4
Alice	27.75	-98.07	1623	63.9	Nacogdoches	31.61	-94.65	1382	54.4
Amarillo	35.23	-101.7	1516	59.7	Pampa	35.53	-100.96	1532	60.3
Austin	30.3	-97.7	1463	57.6	Paris	33.66	-95.56	1417	55.8
Beaumont	30.11	-94.16	1349	53.1	Pecos	31.42	-103.49	1986	78.2
Brownfield	33.18	-102.27	1704	67.1	Perryton	36.4	-100.75	1529	60.2
Brownsville	25.9	-97.43	1590	62.6	Plainview	34.19	-101.72	1608	63.3
Brownwood	31.82	-99.09	1676	66.0	Port Arthur	29.95	-94.02	1308	51.5
Childress	34.42	-100.24	1623	63.9	Presidio	29.56	-104.37	2164	85.2
College Station	30.61	-96.29	1471	57.9	San Angelo	31.37	-100.5	1727	68.0
Corpus Christi	27.77	-97.5	1506	59.3	San Antonio	29.46	-98.5	1570	61.8
Crockett	31.32	-95.46	1412	55.6	Seymour	33.59	-99.26	1615	63.6
Dalhart	36.06	-102.51	1567	61.7	Sherman	33.64	-96.61	1466	57.7
Del Rio	29.39	-100.91	1808	71.2	Snyder	32.72	-100.91	1694	66.7
Dumas	35.87	-101.97	1560	61.4	Sonora	30.57	-100.64	1760	69.3
El Paso	31.8	-106.4	1758	69.2	Stephenville	32.22	-98.2	1570	61.8
Falfurrias	27.23	-98.14	1648	64.9	Temple	31.09	-97.39	1554	61.2
Fort Davis	30.59	-103.89	1816	71.5	Texarkana	33.44	-94.08	1369	53.9
Fort Hancock	31.29	-105.86	2027	79.8	Tulia	34.54	-101.77	1595	62.8
Fort Stockton	30.89	-102.88	1875	73.8	Tyler	32.34	-95.3	1389	54.7
Fort Worth	32.83	-97.05	1570	61.8	Uvalde	29.21	-99.79	1699	66.9
Friona	34.64	-102.72	1600	63.0	Van Horn	31.04	-104.83	1935	76.2
Graham	33.1	-98.58	1628	64.1	Victoria	28.85	-96.92	1496	58.9
Guthrie	33.63	-100.39	1702	67.0	Waco	31.62	-97.22	1580	62.2
Hereford	34.82	-102.4	1588	62.5	Wichita Falls	33.97	-98.48	1595	62.8
Houston	29.98	-95.37	1438	56.6	Roswell	33.37	-104.53	1678	66.1
Kerrville	30.05	-99.14	1565	61.6	Oklahoma City	35.4	-97.6	1417	55.8
Laredo	27.52	-99.49	1811	71.3	Tulsa	36.2	-95.9	1335	52.6
Llano	30.75	-98.68	1646	64.8	Fort Smith	35.33	-94.37	1315	51.8
Lubbock	33.65	-101.82	1575	62.0	Little Rock	34.73	-92.23	1303	51.3
Marshall	32.54	-94.36	1374	54.1	Shreveport	32.47	-93.82	1351	53.2
McAllen	26.22	-98.23	1669	65.7	Lake Charles	30.12	-93.22	1392	54.8
Midland	31.93	-102.2	1732	68.2					

Table 2.2. Basal crop (K_{cb}) coefficient at peak season with moderate wind for a grass reference crop (ET_o). Moderate wind is defined as mean wind run ≤ 400 km/day (250 mi/day). *Humid*, mean minimum relative humidity ≥ 70 percent; *arid*, mean minimum relative humidity ≤ 20 percent (Borelli and others, 1998)

Crop	*Climate*	K_{cb}
Grain, small	Humid	1.05
	Arid	1.15
Oats	Humid	1.05
	Arid	1.15
Peanuts	Humid	0.95
	Arid	1.05
Sorghum	Humid	1.00
	Arid	1.10
Soybeans	Humid	1.00
	Arid	1.10
Winter Wheat	Humid	1.05
	Arid	1.15
Spring Wheat	Humid	1.05
	Arid	1.15

Reference crop ET can be compared with long-term mean annual precipitation in Texas (Figures 2.7 and 2.8). Precipitation increases from west to east across Texas whereas reference crop ET generally decreases (Figure 2.8). Therefore, differences between annual precipitation and annual ET_o decrease from west to east.

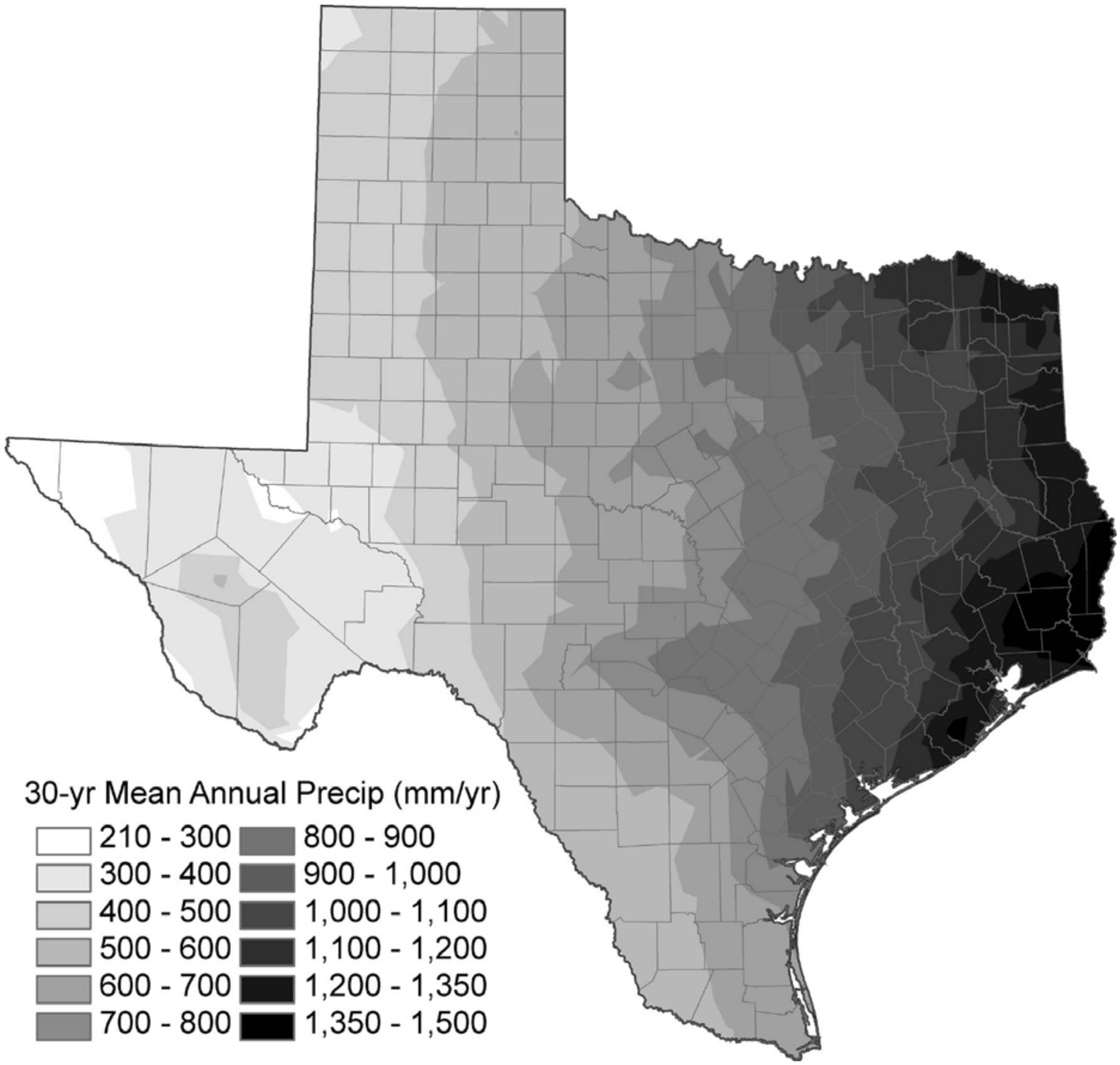

Figure 2.7. Long-term (1961 to 1990) mean annual precipitation from PRISM study (Daly and others, 1994).

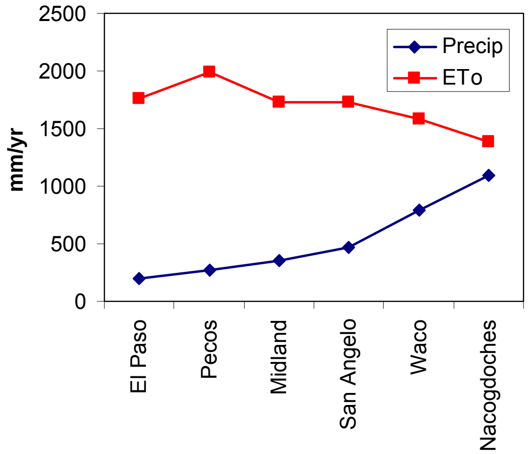

Figure 2.8. Relationship between long-term (1961 to 1990) mean annual precipitation and reference crop ET from west to east at selected stations in Texas.

2.6 Task 1d. Determine Gaps in our Knowledge of ET Processes and Rates and Recommend Appropriate Techniques for Filling these Gaps

Most groundwater ET occurs along riparian zones; however, vegetation maps for Texas are generally not at a high enough resolution to show the distribution of riparian vegetation (Appendix 1). Maps of riparian vegetation should be developed. Remote sensing approaches could be used to map riparian vegetation (Appendix 1).

Information on ET in Texas is generally limited to data from PET networks. The lysimeter program at the US Dept. of Agriculture, Agricultural Research Service in Bushland Texas includes four large weighing lysimeters (9 m^2, 29.5 ft^2 diameter), one smaller grass weighing lysimeter (2.25 m^2, 7.4 ft^2 diameter), and 45 smaller nonweighing lysimeters (0.75 m^2, 2.5 ft^2 diameter) with four soil types (http://www.cprl.ars.usda.gov/swmru_research.htm). These studies focus on developing crop coefficients for irrigated and nonirrigated crops such as cotton, wheat, and sorghum. A new lysimeter program in Uvalde includes four weighing lysimeters (http://uvalde.tamu.edu/staff/piccinni/index.html). Unlike New Mexico and Arizona and other states, Texas does not have any program to address riparian ET. Future studies should include monitoring programs of riparian ET, such as micrometeorological data like Eddy Covariance or Bowen Ratio systems, and water table fluctuations. Water table fluctuations could be monitored adjacent to stream gauging stations to assess groundwater surface water interactions and the impact of riparian ET on these interactions. Remote sensing approaches can be applied using optical data to provide regional estimates of ET with no requirements for ground based data. However, ground referencing of ET estimates based on remote sensing with micrometeorological data and lysimeter data would increase reliability and confidence in estimates based on remote sensing.

3.0 Task 2. Relate ET Rates to Vegetation Parameters

3.1 Obligate Versus Facultative Phreatophytes – Comparison of ET Rates from the Literature

Direct measurements of ET from a variety of plant associations in riparian areas are now available from a number of sites in the southwestern US. Although these measurements have not been made in Texas, these studies allow linkages between measured ET rates in riparian zones with specific ecosystem parameters such as plant functional groups like obligate versus facultative phreatophytes, and community/ecosystem parameters such as total leaf area and plant density. The most recent estimates of ET in riparian areas are from a network of towers in semi-arid regions of New Mexico and Arizona. Continuous ET is currently measured from nine flux towers, using the eddy covariance and Bowen ratio techniques, established in major vegetation types on the Middle Rio Grande (Cleverly and others, 2002; Coonrod and McDonnell, 2001; Dahm and others, 2002), Upper San Pedro River (Scott and others, 2000a, b, 2004, 2005), and Lower Colorado River (DeMeo, 2003). Vegetation types range from near monocultures of cottonwood (*Populus fremontii*) with understory (Cleverly and others, 2002), saltcedar (*Tamarix ramosissima*) with and without understory (Cleverly and others, 2002), mesquite (*Prosopis velutina*) with understory, and mixed stands of cottonwood, willow (*Salix* spp.), and saltcedar.

3.2 Remote Sensing Approaches for Classifying Phreatophytic Vegetation

Various remote sensing approaches for classifying phreatophytic vegetation are described in Appendix 1. Appendix 1 was developed under a contract with Texas Commission for Environmental Quality and is listed separately.

3.3 Canopy-Scale Measurements

In Arizona and New Mexico, direct measurements of ET suggest that cottonwood and willow stands, which are both considered obligate phreatophytes, generally have the highest annual ET rates (1100 to 1300 mm/yr, 43.3 to 51.2 in/yr) in areas where water is continually available (Nagler and others, 2005a, b) which are generally consistent with the ranges found in Appendix 2 (960 to 1340 mm/yr, 37.8 to 52.8 in/yr). Facultative phreatophytes such as mesquite and saltcedar have stand ET rates ranging from 400 to 1100 mm/yr (15.7 to 43.3 in/yr) (mesquite) and 300 to 1300 mm/yr (11.8 to 51.2 in/yr) (saltcedar) (Nagler and others, 2005a, b). The values reported in Appendix 2 for mesquite range from 330 to 744 mm/yr (13.0 to 29.3 in/yr). Riparian areas dominated by sacaton grasses (*Sporobolus wrightii*) (500 to 800 mm yr, 19.7 to 31.5 in/yr), arrowweed (*Pluchea sericea*) (300 to 700 mm/yr, 11.8 to 27.6 in/yr), saltgrass or rabbitbrush typically have the lowest ET rates (Nagler and others, 2005a, b).

The above differences in ET rates may reflect a fundamental relationship between ET and total leaf area, which is a function of tree density and height (Nagler and others, 2005a, b). Cottonwood and willow are broadleaf species with generally large leaf areas and associated high ET rates. These are generally considered pioneer species that can take advantage of available water. In contrast, mesquite and saltcedar are more drought adapted and can maintain productivity under low water availability conditions but cannot produce large leaf areas to take advantage of large water supplies; hence the generally lower ET rates. The salinity of the substrate is also an important factor. Therefore, in areas of mixed vegetation measured ET along riparian corridors varies more predictably with total leaf area (Nagler and others, 2005a, b), rather than whether the stand is made up of obligate versus facultative phreatophytes. Dense stands with high leaf area index (LAI) have the highest rates of ET, regardless of vegetation type. Leaf area index is defined as the one sided green leaf area per unit ground area in vegetation. For example, ET measurements above saltcedar stands on the Middle Rio Grande were in the range of 700 to 1200 mm/yr (27.6 to 47.0 in/yr) depending on the LAI of the stand (2.5 and 3.5, respectively) (Cleverly and others, 2002; Coonrod & McDonnell, 2001; Dahm and others, 2002). Cottonwood stands, with the same range of LAI values, had annual ET rates with very similar values, varying between 1000 to 1200 mm/yr (39.4 to 47 in/yr) (Dahm and others, 2002). Mesquite stands on the San Pedro River in Arizona which grow at a greater distance from the river than cottonwoods and willows, have a lower LAI range (between 1 and 1.6), and have annual ET rates between 400 to 700 mm/yr (15.7 to 27.6 in/yr) (Appendix 2; Scott and others, 2000a, b, 2004).

3.4 Leaf-Level Measurements

Using stand-level characteristics as the most important predictor of canopy scale ET rates is backed up to a large degree by leaf-level ET measurements of the dominant riparian species. Under non water-stressed conditions, several studies have reported that the main riparian species on these rivers, regardless of whether they are obligate or facultative phreatophytes (for example mesquite, arrowweed, saltcedar, cottonwood, and willow) have similar rates of ET as a function of leaf area (Nagler and others, 2003; Nagler and others, 2004; Sala and others, 1996; Smith and others, 1998). Under water-stressed conditions, however, saltcedar maintains higher transpiration rates per unit leaf area than the native trees it typically replaces (Glenn & Nagler, 2005; Nagler and others, 2004; Sala and others, 1996; Smith and others, 1998).

3.5 Primary Conclusions from these Studies

1) Important parameters in predicting ET include stand density, LAI, distance from the riparian zone which are more important than plant functional type characteristics but may be related to plant functional types. These fundamental controls on ET provide great promise to being able to estimate ET using remote sensing methods (Nagler and others, 2005a, b).

2) Riparian ET rates measured by micrometereological methods are generally lower than earlier estimates due to more indirect water balance and crop-coefficient methods (Appendix 2: Scott and others, 2000a, b; Nagler and others, 2005a, b). Due to the patchy nature of vegetation and complex hydrology of riparian corridors, as long as a prevailing wind condition exists, direct measurements using micrometeorological techniques are more accurate and give more reasonable ecosystem-level ET estimates. Extrapolating leaf-level transpiration rates or tree-level sap flux rates to larger ecosystem scales can lead to biased estimates due to inherent problems associated with scaling.
3) It does not appear that ET rates along riparian corridors in the southwestern US are universally altered due to the increase of the invasive saltcedar (Glenn and Nagler, 2005).

3.6 Ongoing Studies in Texas

Much of the ongoing ET and sap flux work in Texas is concentrated in upland savanna ecosystems on the Edwards Plateau. Some of the common species in these ecosystems access groundwater through fractures in the limestone bedrock in these karst landscapes. Through a survey of deep roots in 15 caves on the Edwards Plateau, (Jackson and others, 1999) determined that the 10 Live oak (*Quercus fusiformis)* and chittamwood (*Bumelia lanuginosa)* trees found in these caves have roots that reached 17 to 22 m (55.8 to 72.2 ft) in depth and accessed deep groundwater. Roots from other common species including hackberry (*Celtis laevigata*), honey mesquite (*Prosopis glandulosa),* cedar elm (*Ulmus crassifolia)*, Ashe juniper (*Juniperus ashei)*, Shin oak (*Quercus sinuate)*, and American elm (*Ulmus americana)* were found at depths from 7 to 17 m (23.0 to 55.8 ft), and approximately 50 percent of the trees in these species had access to groundwater. By monitoring sap flow in the deep roots of Ashe juniper and Live oak, Jackson and others (1999) determined that during dry periods, use of this deep groundwater source increased.

There are currently four eddy covariance systems measuring ET continuously in four land covers on the Edwards Plateau that range from open pasture, mesquite-juniper savanna with 30 percent woody cover, Live oak-mesquite-juniper with 60 percent woody cover, and closed canopy Live oak-juniper woodland. Preliminary results suggest ET rates from Jan 1 to June 16, 2005 range from 312 to 351 mm (12.3 to 13.8 in) among the 4 land covers (Heilman, J. and K. McInnes, TAMU, and M. Litvak, UT, unpublished data). The small differences in ET despite the large changes in ecosystem structure suggest that woody species with access to groundwater do not significantly alter ET rates. These micrometeorological approaches could be used to monitor ET throughout Texas.

3.7 Rooting Depths of Phreatophytes in the US Southwest

General information on rooting depths of vegetation relative to extinction depths used in MODFLOW models are described in Section 4.

There are few reports in the literature that have directly measured rooting depths of riparian species in Texas. From the ongoing work in the southwestern US, it is clear that riparian species vary widely in their capacity to shift between seasonally varying water sources and rooting depths. Cottonwood (*Populus fremontii)* is an obligate phreatophyte that typically occurs in areas with depth to ground water less than 5 m (16.4 ft) (Busch and others, 1992; Busch and Smith, 1995; Stromberg and others, 1996) and has rooting depths which typically vary from 3 to 4 m (9.8 to 13.1 ft) (Kate Baird, pers. comm., 2005a). Black willow (*Salix gooddingii)* tends to have slightly shallower rooting depths (2-4 m, 6.6 – 13.1 ft, Kate Baird, pers. comm., 2005a), and compared to cottonwood (*P. fremontii)*, is less able to tolerate deep and fluctuating water tables (Horton and others, 2001). In addition, cottonwood (*P. fremontii)* is able to use a greater quantity of soil moisture from precipitation and unsaturated soils than black willow (*S. goodingii)* (Snyder and Williams, 2000; Busch and others, 1992; Horton and others, 2001). Both cottonwood (*P. fremontii)* and black willow (*S. goodingii)* employ mechanisms to prevent mortality during low water availability in including branch sacrifice and canopy dieback (Horton and others, 2001). Saltcedar (*Tamarix ramosissima)* is a deep-rooted facultative phreatophyte (6 to 9 m, 19.7 to 29.5 ft, Kate Baird, pers. comm., 2005a), that typically obtains water from unsaturated and saturated soil (Snyder and Williams, 2000; Horton and others, 2001). Physiologically, saltcedar appears to be more drought tolerant than either cottonwood (*P. fremontii)* or *black willow (S. goodingii)* and is much less sensitive to deep groundwater (Horton and others, 2001). Overall, cottonwood (*Populus)* and black willow (S*alix)* in the southwestern US typically maintain healthy mature trees when depth to groundwater stays less than 3 m (9.8 ft). Cottonwood and black willow can use stream base flows as a water source as well (Smith and others, 1991).

Mesquite rooting depths in riparian areas in the southwestern US have been reported to be as high as 10 m (32.8 ft) (Scott and others, 2004, Kate Baird, pers. comm., 2005a). Mesquite is typically able to supplement tap root uptake of groundwater with water uptake from lateral and surface roots, when surface water is available (Scott and others, 2004). Scott and others, (2004) demonstrated a tight linkage between an increase in mesquite activity in the spring from water use and carbon uptake associated with leaf out and a decrease in groundwater depth. The average mesquite tree in this study used an estimated 1.9 to 2.3 mm/day (0.07 to 0.09 in/day) of groundwater in 2001 and 2002.

4.0 Task 3. Assess How ET Processes and Rates Can Be Incorporated into Groundwater Availability Models

4.1 Significance of Groundwater ET to Water Resource Modeling and Groundwater Availability Models

Groundwater ET, like stream baseflow and other sources of natural discharge, is a potential source of water that can be captured by increased groundwater development (pumping) if water tables are lowered below plant rooting depths. Characterizing current or potential sources of groundwater capture is one of the most vital aspects of water availability modeling for future conditions. However, because groundwater ET is not directly observable, it is often difficult to characterize, especially on a regional scale.

When groundwater ET is mischaracterized or ignored in groundwater models, stream baseflow often acts as a surrogate sink in topographically low riparian areas. Thus, mischaracterization of groundwater ET will often lead to poor estimation of the parameters that govern groundwater and surface water interactions, such as streambed conductance. Such poor parameterization may cause the resulting model to incorrectly predict future baseflows or misrepresent a future source of groundwater capture.

Thus, for those models where groundwater ET should be a significant part of the overall water balance (this includes many of the current Texas GAMs), a significant effort should be made to conceptualize and implement groundwater ET correctly in order to improve the predictive capability of the resulting model. An added benefit is the possibility of developing a consistent approach for all of the GAMs, allowing a more direct comparison of the predicted results.

4.2 Review of ET Simulations in MODFLOW

4.2.1 Texas Groundwater Availability Models

Of 19 groundwater availability models (GAMs) in Texas, 10 used the evapotranspiration (ET) package. Evapotranspiration accounts for 2 to 96 percent of the outflow in these models, as can be seen in Table 4.1. In this review, we report the results from the steady-state water balance, unless otherwise noted. This wide range in the magnitude of ET in the water balance of these models may be an artifact of different approaches used to simulate ET or may be related to varying geologic, ecologic, and climatic conditions.

Table 4.1. Summary of groundwater ET in current GAMs

Aquifer		Sensitivity Analyses	ET Package	Percent outflow	Root depth or extinction depth (m)	Root depth or extinction depth (ft)
Major Aquifers						
Carrizo-Wilcox	Southern	no	yes	31	mean 1.8	mean 6
	Central	yes	yes	60	4.6	15
	Northern	no	yes	28	0 to 2.1	0 to 7
Edwards	Northern	--	no			
	Barton Springs	--	no			
	San Antonio	--	no			
Edwards Trinity Plateau	--	--	no			
Gulf Coast	Northern	--	no			
	Central	no	yes	3	1.5 to 9.1	5 to 30
	Southern	yes	yes	2	9.1	30
Hueco and Mesilla	Hueco Bolson		yes	41	4.6	15
	Mesilla Bolson		yes			
Pecos	--	--	no			
Ogallala	South	--	no			
	North	--	no			
Seymour	--	no	yes	31	median 1.8	median 6
Trinity	Northern	yes	yes	96	2.1 to 5.8	7 to 19
	Hill Country	--	no			
Minor Aquifers						
Blaine (Modeled with Seymour)	--	no	yes	31	0.3 to 2.1	1 to 7
Lipan	--	yes	yes	59	2.1 to 14.3	6.9 to 47
Queen City and Sparta (w/Carrizo-Wilcox)	Southern	no	yes	8	0.3 to 2.4	1 to 8
	Central	no	yes	32	0.3 to 2.4	1 to 8
	Northern	no	yes	48	0.3 to 2.4	1 to 8
West Texas Bolsons and Igneous	--	no	yes	15	3.0	10
Woodbine (w/Trinity)	--	yes	yes	96	2.1 to 5.8	7 to 19

The Queen City and Sparta (Kelley and others, 2004), Carrizo-Wilcox (Deeds and others, 2003; Fryar and others, 2003; Dutton and others, 2003), Seymour and Blaine (Ewing and others, 2004) GAMs reported ET values between 8 and 60 percent of groundwater discharge. These models used the Soil Water Assessment Tool (SWAT) software package to estimate parameters for the ET package. The extinction depth was obtained by extracting vegetation rooting depths from the SWAT results. These rooting depths were based on vegetation in the SWAT data tables and used depths that ranged between 0.3 to 4.6 m (1.0 and 11.2 ft). Maximum ET (ETmax) was estimated by taking the results for total possible daily ET and then subtracting the results for daily actual unsaturated zone ET. The difference between these two results was estimated to be the unsatisfied ET that could potentially tap groundwater.

GAMs for the Lipan (Beach and others, 2004a) and West Texas Bolsons (Beach and others, 2004b) aquifers indicated that 59 and 15 percent of the flow out of the model was due to ET. In these models, it was assumed that phreatophytic vegetation accounts for the largest amount of groundwater ET. The vegetation types reported to grow in the study area are crops, live oak, juniper, and mesquite. To estimate extinction depth, vegetation rooting depths were obtained from a study done by Canadell and others (1996). Applied rooting depths varied from 2.1 m (6.9 ft, crops) to 14.3 m (47.0 ft, mesquite). Rates used for ETmax were obtained using several different literature sources. ETmax ranged from 787 mm/yr (31.0 in/yr) for crops to 224 mm/yr (8.8 in/yr) for mesquite. Table 4.2 shows values used for ETmax and rooting depth.

Table 4.2. Values for ETmax and rooting depth used in the Lipan and West Texas Bolson GAMs.

Plant Type	Estimated Rate				Rooting (m)	Rooting (ft)
	Min (in/yr)	Min (mm/yr)	Max (in/yr)	Max (mm/yr)		
Crops[1]	31	787	31	787	2.1	7
Live oak[2]	30	762	30	762	4.0 to 12.5	13 to 41
Juniper[3]	23	584	25	635	3.9	13
Mesquite[4]	8.8	224	25	635	11.9 to 14.3	39 to 47

1. ET Rates from Borelli and others (1998).
2. ET Rates from Dolman (1988)
3. ET Rates from Dugas and others (1998)
4. ET Rates from Duell (1990); Tromble (1977); Ansley and others (1998)

The ET package applied to the GAMs for the Northern Trinity and Woodbine Trinity aquifers which were modeled together, showed 96 percent outflow due to ET (Harden and others, 2004). Extinction depth in the ET package was defined based on rooting depths obtained from Canadell and others (1996). However, with the exception of crops, rooting depths applied to the vegetation differed from those used in the Lipan and West Texas Bolsons GAMs. Rooting depths ranged from 2.1 to 5.8 m (6.9 ft to 19.0 ft). To calculate ETmax, scale factors ranging from 0.5 to 1.0 were assigned to different land use and vegetation types. These factors were then used to scale measured lake evaporation data.

The Central Gulf Coast (Chowdhury and others, 2004) GAM showed only 3 percent outflow through ET. It was assumed that mesquite was the dominant phreatophyte and the maximum rooting depth was 9.1 m (29.8 ft). This maximum rooting depth was then scaled by factors ranging from 0 to 1, depending on soil type. ETmax was calculated using a crop coefficient based on ranchland vegetation from Wight and Hanson (1990).

Evapotranspiration in the Southern Gulf Coast (Chowdhury and Mace, 2003) GAM accounted for 2 percent of the outflow. The ET package was used to model transpiration from mesquite. Rooting depth was set to 9.1 m (29.8 ft). ETmax was calculated by scaling precipitation by factors of 0.001, 0.0012, and 0.0015, depending on the estimated density of mesquite.

In the Hueco Bolson (Heywood and Yager 2002) GAM, 41 percent of the outflow was calculated to be due to ET. The extinction depth used in this model was 4.6 m (15.1 ft).

4.2.2 Other Models

Several USGS groundwater models were reviewed that used the ET package. As with the GAMs, the ET package was applied using different conceptual approaches and methodologies.

A simulation of groundwater flow in the basin-fill aquifer of the Tularosa Basin in south-central New Mexico (Huff, 2005) used the ET package. This model used literature sources for estimating a maximum ET rate of 1219 mm/yr (48.0 in/yr). The extinction depth in the model was set to 4.6 m (15.1 ft). ET represented 88 percent of groundwater discharge.

A groundwater model of the Cedar Valley in Utah (Brooks and Mason, 2005) used an initial rate of 0.3 m/yr (1.0 ft/yr) for ETmax that was later adjusted during calibration. The initial extinction depth was set to 9.1 m (29.9 ft), which had to be reduced to 5.8 m (19.0 ft) during calibration. The water budget indicated that 41 percent of the outflow was through ET.

A groundwater model of Santa Clara County, California (Hanson and others, 2004), applied the ET package only near streams and creeks. It was assumed that when the water table fell far below the surface there would be no ET. The model assumed a constant value for maximum ET of 1219 mm/yr (48.0 in/yr) to represent willow trees and an extinction depth of 1.5 m (4.9 ft). As a result, only 2 percent of the outflow water budget was composed of ET.

A 2004 model of the Cedar River Alluvial Aquifer in Iowa (Turco and Buchmiller, 2004) set a constant rooting depth of 1.5 m (4.9 ft) below the surface. The maximum ET rate of 1067 mm/yr (42.0 in/yr) was determined through calibration. ET was not reported in the outflow calculations.

A 2002 groundwater model of Palm Beach County, Florida (Renken and others, 2001) included the ET package. The model used a modified Blaney-Criddle algorithm to estimate maximum ET values. Extinction depths varied from 0.3 to 1.5 m (1.0 to 4.9 ft) based on rooting depths of different types of vegetation. Evapotranspiration had an outflow of 0.001 percent of the water budget.

A 1988 groundwater model of Black Mesa, Arizona (Brown and Eychaner, 1988), (which has since been improved and updated) used a constant maximum ET rate of 1549 mm/yr (61.0 in/yr). The rooting depth was set to 3 m (9.8 ft) below ground surface, with the assumption that vegetation with rooting depths greater than 3 m (9.8 ft) use much less water at these depths. Evapotranspiration accounted for 33 percent of model outflow.

4.3 Guidance for Application to GAMs

4.3.1 Conceptualizing Groundwater ET in Models

Much of the discussion in this section is based on the paper by Ross and others (2005) where they describe their approach to modeling ET in a fully coupled groundwater and surface water model. In the current study, we are considering the application of ET in a groundwater model only; however, by first looking at a rigorous approach we can develop a good understanding of the principles, and thus derive an application of a scaled-down version to MODFLOW.

Figure 4.1 shows four scenarios of increasing water table elevation with respect to the bottom of vegetation roots and ground surface. This figure illustrates two zones above the water table. Just above the water table is the near saturation capillary fringe. The capillary zone includes the capillary fringe and is the region where soils are not saturated, but are above irreducible saturation. In the capillary zone, roots can be strongly hydraulically coupled with the water table so that plant transpiration affects water table decline. The height of the capillary zone might be approximately 1 m (3.3 ft) for a uniform sandy soil, but could increase to as much as 4.5 m (14.8 ft) for some clays. The capillary fringe is typically 1/3 to 1/4 the height of the capillary zone.

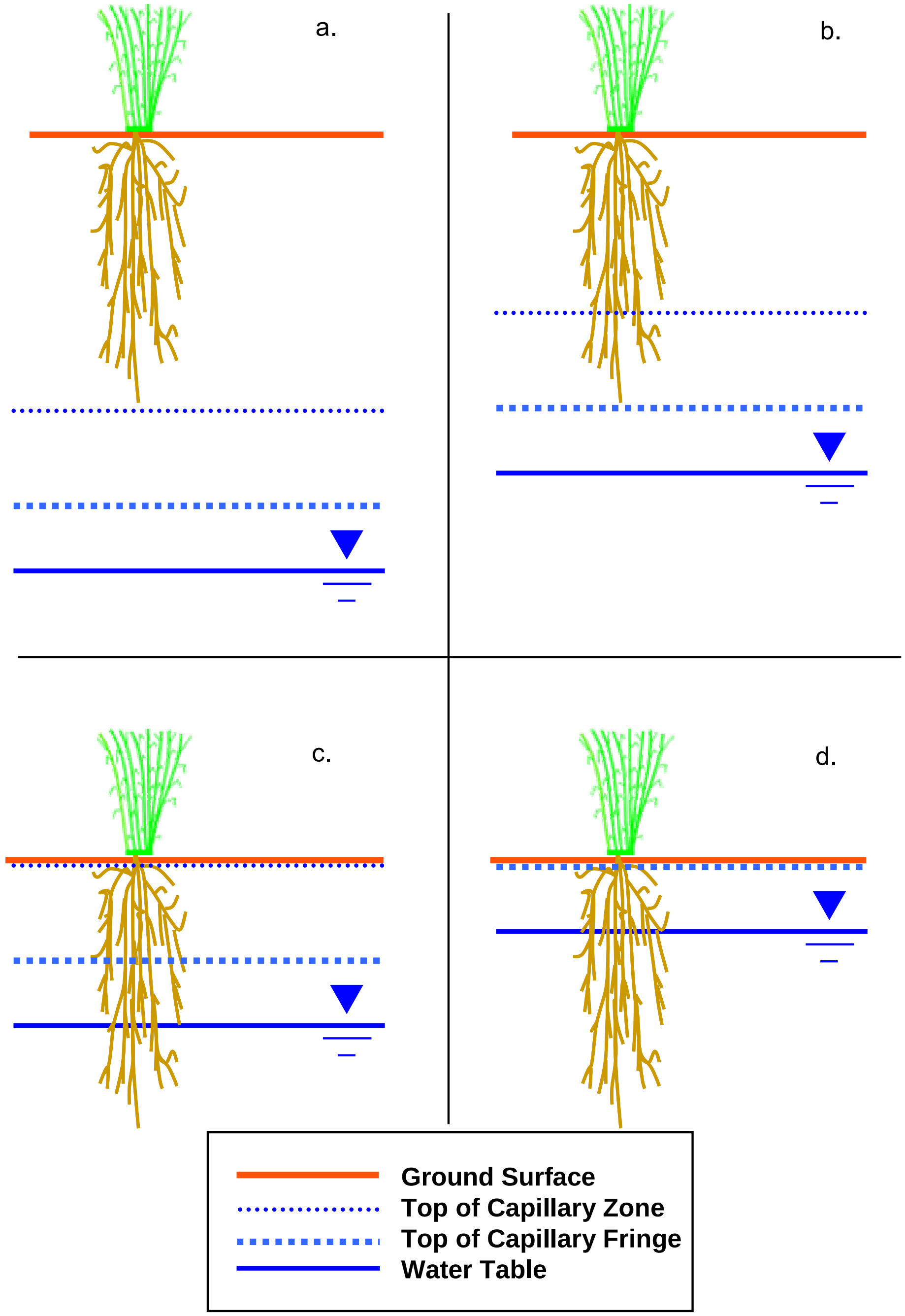

Figure 4.1. Illustration of scenarios for groundwater ET conceptualization.

In Figure 4.1a, the capillary zone is below the plant root zone, so the plant will extract all of its subsurface water from unsaturated zone storage. In Figure 4.1b, the plant roots are in the capillary zone, so there is potential for groundwater ET, although there is likely to be additional contribution from unsaturated zone storage. Here, the unhindered vegetative ET rate, ETVmax, can be estimated by

$$ETV_{max} = PET * K_c \tag{14}$$

where K_c is the crop coefficient. In this scenario, ET will contain contributions from unsaturated zone storage and from groundwater, assuming negligible surficial contributions. In a fully coupled model, a subsurface moisture balance would allow estimation of how ET is likely to partition between unsaturated zone storage and groundwater. This is not possible in a standalone groundwater model.

In Figure 4.1c, the top of the capillary zone has reached ground surface. At this point, direct evaporation of groundwater from the ground surface can potentially occur. We would expect that actual ET would be somewhere between ETVmax and PET. In Figure 4.1d, the capillary fringe has reached ground surface, so some direct evaporation from the groundwater may occur, and ET should be approximately equal to PET. Note that ET might actually exceed PET (as defined in section 2.1), if direct evaporation occurs at the rate of pan evaporation, However, we assume the presence of vegetation attenuates the direct evaporation of groundwater from the soil. If the soil is bare, and direct evaporation is assured, then ET at the soil surface may be closer to 1.5 times PET (FAO, 1997).

In the next two sections we will discuss how we can simplify this conceptualization and apply it to a standalone MODFLOW-based groundwater model.

4.3.2 MODFLOW ET Packages and Parameters

The approach of the original ET package for MODFLOW, EVT1, is summarized in Figure 4.2. The user-specified ETmax flux rate is extracted from the groundwater when the water table is above a user-specified ET surface. If the water table falls below the ET surface, but stays above the extinction depth, the groundwater ET rate decreases linearly with depth from the ET surface. If the water table falls below the extinction depth, then the groundwater ET rate is zero. So the user must specify three parameters: ETmax, the ET surface elevation, and the extinction depth.

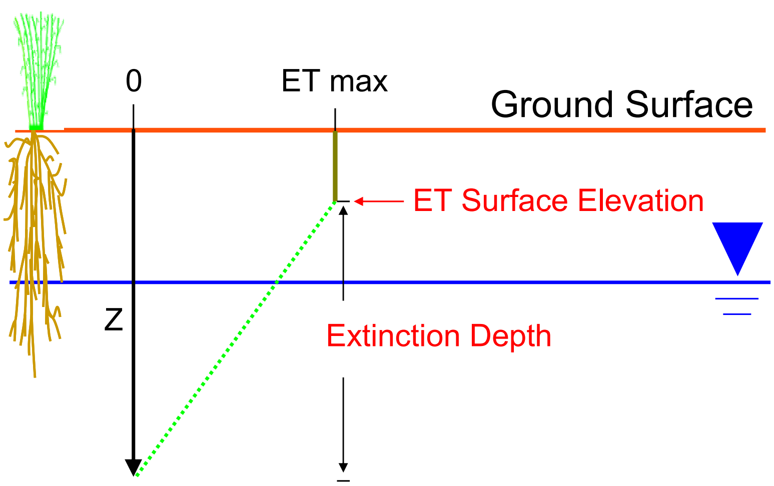

Figure 4.2. Parameters in the EVT1 MODFLOW package.

The approach of the updated ET package, ETS1, is similar to the original ET package, except that the single linear decrease in ET rate from the ET surface elevation to the extinction depth is replaced by a series of linear segments that are specified by the user. This concept is shown in Figure 4.3. If only one segment is specified, the functionality of the ETS1 package reverts to that of the older EVT1 package.

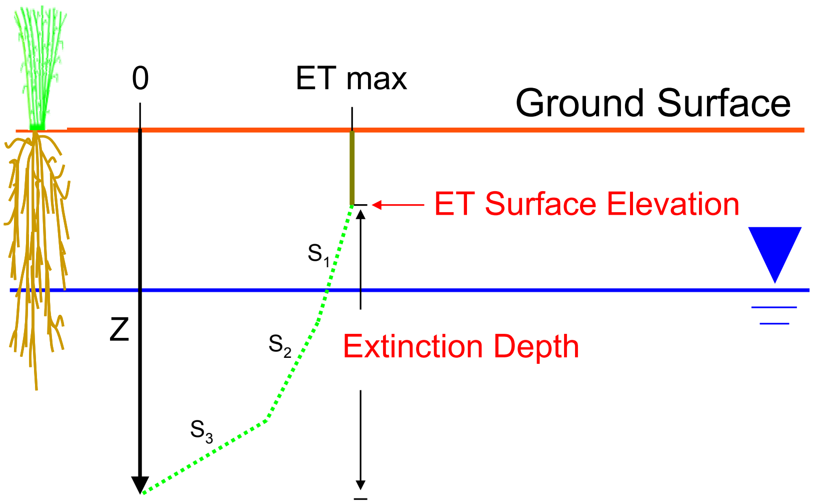

Figure 4.3. Parameters in the ETS1 MODFLOW package.

4.3.3 Recommended Approach to using ET in MODFLOW

Basic Approach

This section details what we would recommend as the most conceptually sound approach to applying ET in MODFLOW. However, in the application of ET in MODFLOW, the modeler must first consider the availability and quality of data that will be used for parameterization. If relevant data in the area of interest are poorly known, then the value of attempting to estimate all of the necessary parameters (detailed in Section 4.3.4) must be weighed against the possible similar accuracy of a more rudimentary approach. The modeler must also consider the potential value in establishing a solid framework for future model updates, even in the absence of complete data.

Figure 4.4 shows how groundwater ET could be implemented in the ETS1 MODFLOW package using a simplified approach to that discussed in Section 4.3.1. The extinction depth is set at the combined thickness of the capillary zone and the height of the rooting zone. This means if top of the capillary zone reaches the bottom of the rooting zone, groundwater ET flux will begin. As the water table elevation increases, groundwater ET flux increases linearly. This is conceptually emulating an increase in the fraction of ET that is taken from the groundwater rather than unsaturated zone storage, as a larger percentage of the plant roots are in the capillary zone.

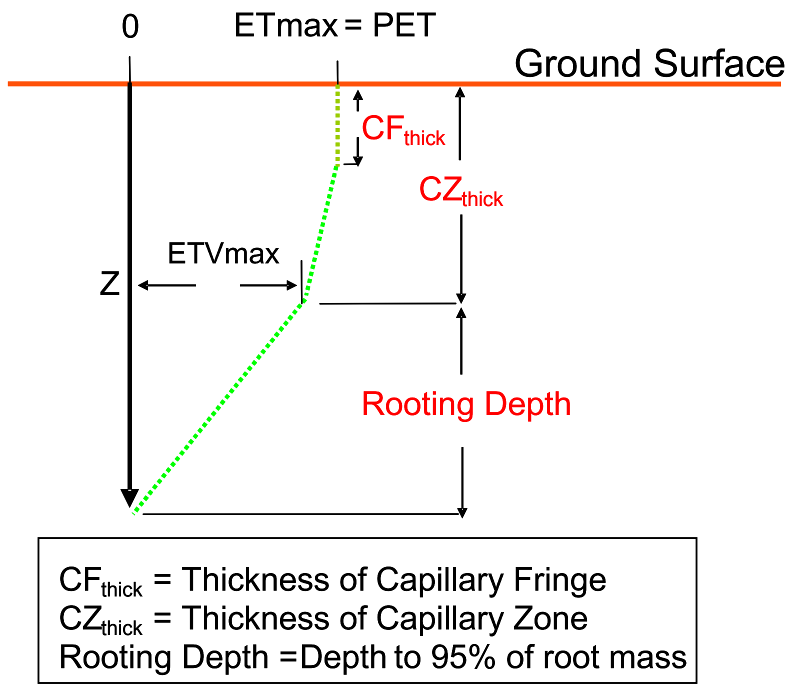

Figure 4.4. Suggested approach to parameterizing groundwater ET in MODFLOW.

When the top of the capillary zone reaches ground surface, then we assume that groundwater ET flux is equal to the vegetative ET rate, as all of the plant roots have access to the groundwater. The ET flux then increases linearly to PET as the capillary fringe nears ground surface. Thus, the ET surface is set at a depth of the estimated thickness of the capillary fringe. ETmax is set to PET when the top of the capillary fringe reaches ground surface. Note that as proposed in Baird and Maddock (2005) and Baird and others (2005), near-surface water tables may reduce actual plant transpiration (for non-phreatophytes) due to anoxia. Our assumption is that ET from shallow-rooted vegetation and direct evaporation are dominant processes at this level.

A possible exception to the linear decrease in groundwater ET flux with depth would be when the vegetative type is an obligate phreatophyte. If the vegetation exclusively draws its water from the groundwater, then the approach might be more like that shown in Figure 4.5, with a fixed rate down to the rooting depth. However, as described in earlier sections, even obligate phreatophytes can be opportunistic about unsaturated zone moisture. So the approach in Figure 4.4 is more general but could be modified in the presence of good site-specific vegetation information.

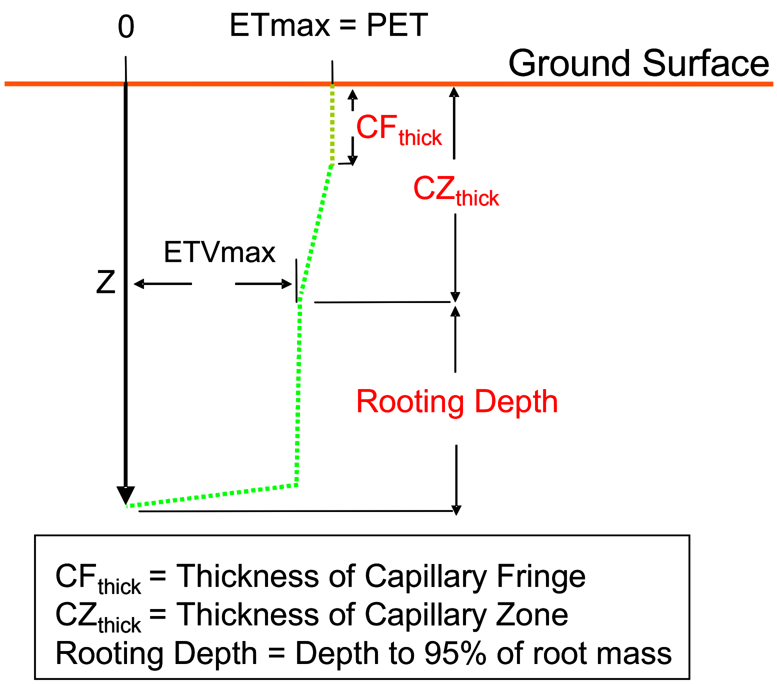

Figure 4.5. Possible approach to parameterizing groundwater ET in MODFLOW for obligate phreatophytes.

Considerations

The efficacy of the approach outlined above is dependent on the modeler having good access to supporting data, including PET, vegetation distributions in the model area, crop coefficients for identified plant types and knowledge of vegetation densities/LAI, soil textures for estimating capillary zones, and rooting depths for identified plant types in the area soils. In some cases, some of these parameters will be unavailable and difficult to accurately estimate. Under these conditions, the modeler should consider whether expending the resources to try to gather the remaining, obtainable data will result in a more defensible application of groundwater ET. However; because the Texas GAMs are intended to be "living", that is, periodically updated and improved, models, the modeler should to make an effort to provide a solid foundation for future studies, by implementing the best framework, perhaps at the initial expense of parsimony.

4.3.4 Estimating the Necessary Parameters

Potential Evapotranspiration

Typical approaches to approximating PET have been detailed previously in Task 1c. The average annual Texas PET coverage shown in Figure 2.6 can be used as a baseline for estimating annual rates.

Vegetation Distributions

Information about the location, type, and density of vegetation can sometimes be found from local sources, namely county reports or specific studies in the area. Other options can include

GIS based estimates, such as the GAP study (Parker and others, 2003). The Texas GAP coverage is included with this report and is available for download from the USGS website. The coverage is for all of Texas on a 90 m (295.3 ft) resolution and divides the vegetation types into about 45 classes. Figure 4.6 shows a map of the GAP vegetation classes for Polk County. An alternative coverage with more general classifications and a lower resolution is the 1984 Vegetation of Texas coverage from Texas Parks and Wildlife Department (TPWD). This coverage is also included with this report (Appendix 1), and is available from the TPWD website.

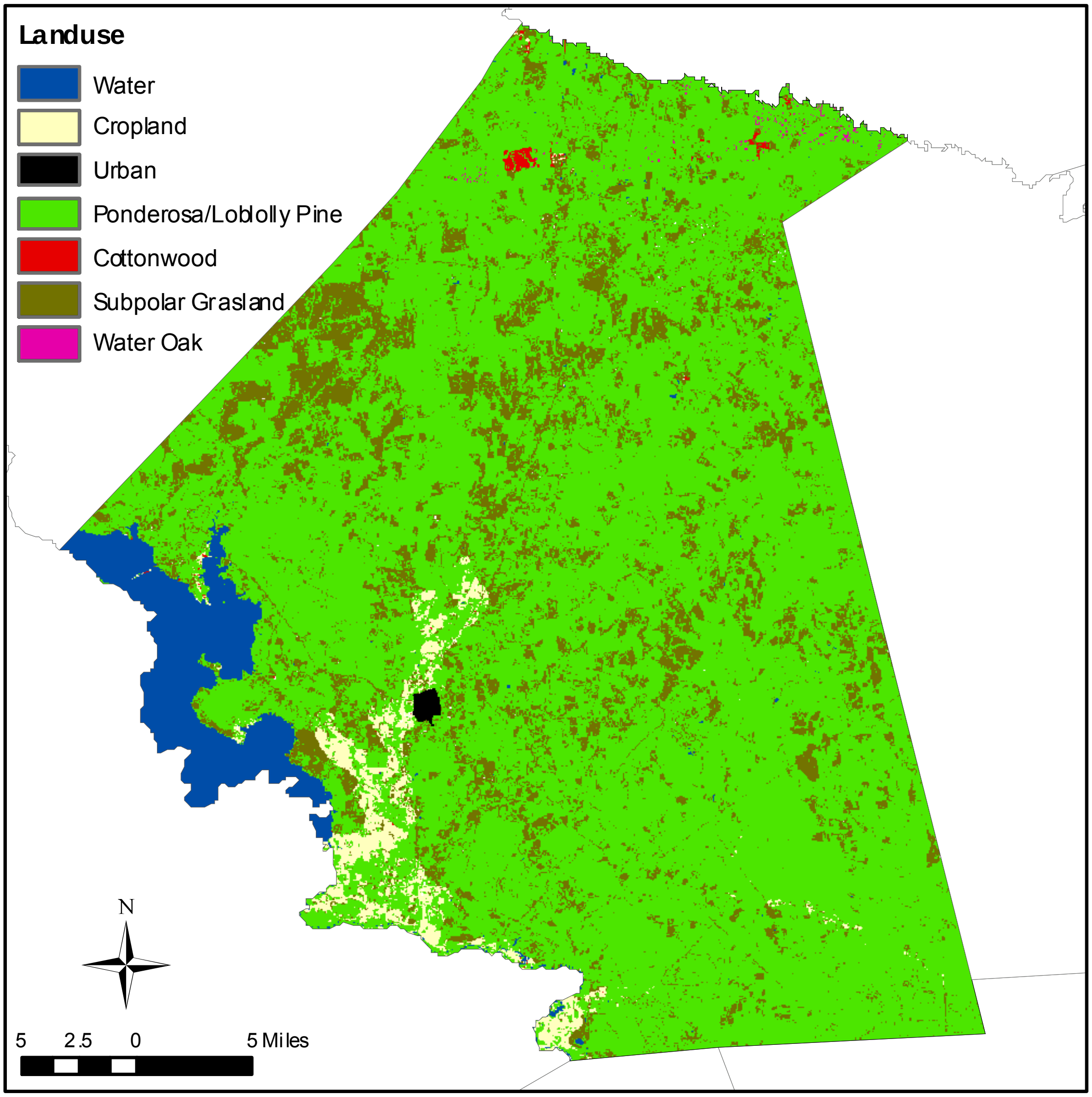

Figure 4.6. GAP vegetation classification in Polk County.

In the absence of more local information about vegetation, these coverages can provide the modeler with an estimate of the density of particular vegetation classes in the study area.

Soil Types

Understanding the soil types in the study area is important for two reasons. First, the soil texture is important in estimating the height of the capillary fringe and capillary zone. Secondly, the soil type can have an effect on the rooting depth, even among similar plant types. Information about soils can be taken from the STATSGO (USDA, 1994) or the newer SSURGO (USDA, 1995) datasets compiled by the Natural Resource Conservation Service and available for download from their website.

The height of the capillary fringe and the capillary zone can be estimated by various methods based on the textural class of the soil. One common method to estimate the height of the capillary fringe is (Fetter, 1993):

$$h_c = \frac{0.15}{r} \tag{15}$$

where h_c is the height in cm and r is the mean pore radius, also in cm. The mean pore radius can be estimated from the mean particle diameter, d, by

$$r = 0.2\, d \tag{16}$$

Table 4.3 shows some mean particle diameters for 12 Soil Conservation Service (SCS) soil textural classes (EPA, 2003). These mean particle diameters can be used with equations (15) and (16) to estimate the height of the capillary fringe.

Table 4.3. Mean particle diameters for 12 SCS textural classifications.

Textural Class	**Mean Grain Diameter (cm)**	**Mean Grain Diameter (in)**
Sand	0.044	0.1118
Loamy sand	0.040	0.1016
Sandy loam	0.030	0.0762
Sandy clay loam	0.029	0.0737
Sandy clay	0.025	0.0635
Loam	0.020	0.0508
Clay loam	0.016	0.0406
Silt loam	0.011	0.0279
Clay	0.009	0.0234
Silty clay loam	0.006	0.0142
Silt	0.005	0.0117
Silty clay	0.004	0.0099

The height of the capillary zone compared to the capillary fringe is largely dependent on the gradation of the soil. Hazen (1930) offers an approximation based on the effective grain size in cm, D_{10} (where 10 percent of the soil by weight is finer):

$$h_c = \frac{C(1-\phi)}{D_{10}\phi} \tag{17}$$

where C is a constant in the range of 0.1 to 0.5 cm^2 (0.04 to 0.20 in^2) and ϕ is the porosity. In general, the height of the capillary zone will be about 3 to 4 times the height of the capillary fringe in sands.

Vegetation Coefficients

Vegetation coefficients (Kc) are used to scale potential evapotranspiration to provide a vegetation ET rate, as described in equation (14). In this section, we use the term "vegetation coefficient" instead of crop coefficient first because we are dealing predominantly with non-crop plants and to be consistent with the primary references we used in deriving the coefficients. Vegetation coefficients are available in the literature, although they are typically calculated for crops. Here, we provide an example of calculating annual vegetation coefficients based on several available studies. It is important to note that using vegetation coefficients and PET as given in equation (14) results in total ET, the combination of groundwater ET and ET from unsaturated zone storage. As explained in section 4.3.3, we attempt to account for this by linearly decreasing groundwater ET with water table depth.

The yearly average Kc values were determined using available vegetation coefficient curves from New Mexico. Vegetation coefficient curves were found for saltcedar, cottonwood, mesquite, ranchland with warm season grasses, ranchland with creosote, pine, and pecan which are displayed in Figure 4.7. The curves were obtained from the New Mexico Climate Center and from the AWARDS system (Agricultural Water Decisions Support) developed by the Bureau of Reclamation. The curves were developed by performing polynomial regressions of Kc values, which are taken from field data or the literature, at different times of the year. Figure 4.8 is an example of a regression of Kc values for a one type of vegetation. The sources of the data used to create the Kc curves are displayed in Table 4.4.

Table 4.4. Sources for vegetation coefficient values used in the polynomial regressions.

Vegetation	Source
Mesquite[1]	Levitt, D. G. , J. R. Simpson and J. L. Tipon, 1995. *Water use of two landscape tree species in Tucson Arizona.* J Amer. Soc Hort. Sci. 120(3) 409 to 416.
Pecans[1]	Miyamoto, 1983. *Consumptive Water Use of Irrigated Pecans*. J. Amer. Soc. Hort Sci. 108(5):676 to 681
Pine[1]	White RW, Fisher JT. 1985. Seasonal evapotranspiration, growth, and water use efficiency by plantation grown *pinus eldarica*. Derived from field and weighting lysimeter studies. Technical Report 193. New Mexico Water Resources Research Institute. 1 - 51.
Ranchland[1]	Wight, J.R. and Hanson, C.L. 1990. *Journal of Range Management.* 43(6) 482 to 485.
Saltcedar[1,2]	King and Bawazir, 2000. Riparian evapotranspiration of the middle Rio Grande. (http://tamarisk.nmsu.edu/)
Cottonwood[2]	Bawazir, Salim. NMSU. Extensive field studies in 1999 at the Bosque Del Apache National Wildlife Refuge.

[1] New Mexico Climate Center (http://weather.nmsu.edu/)

[2]AWARDS/ET toolbox (http://www.usbr.gov/pmts/rivers/awards/ettoolbox.pdf)

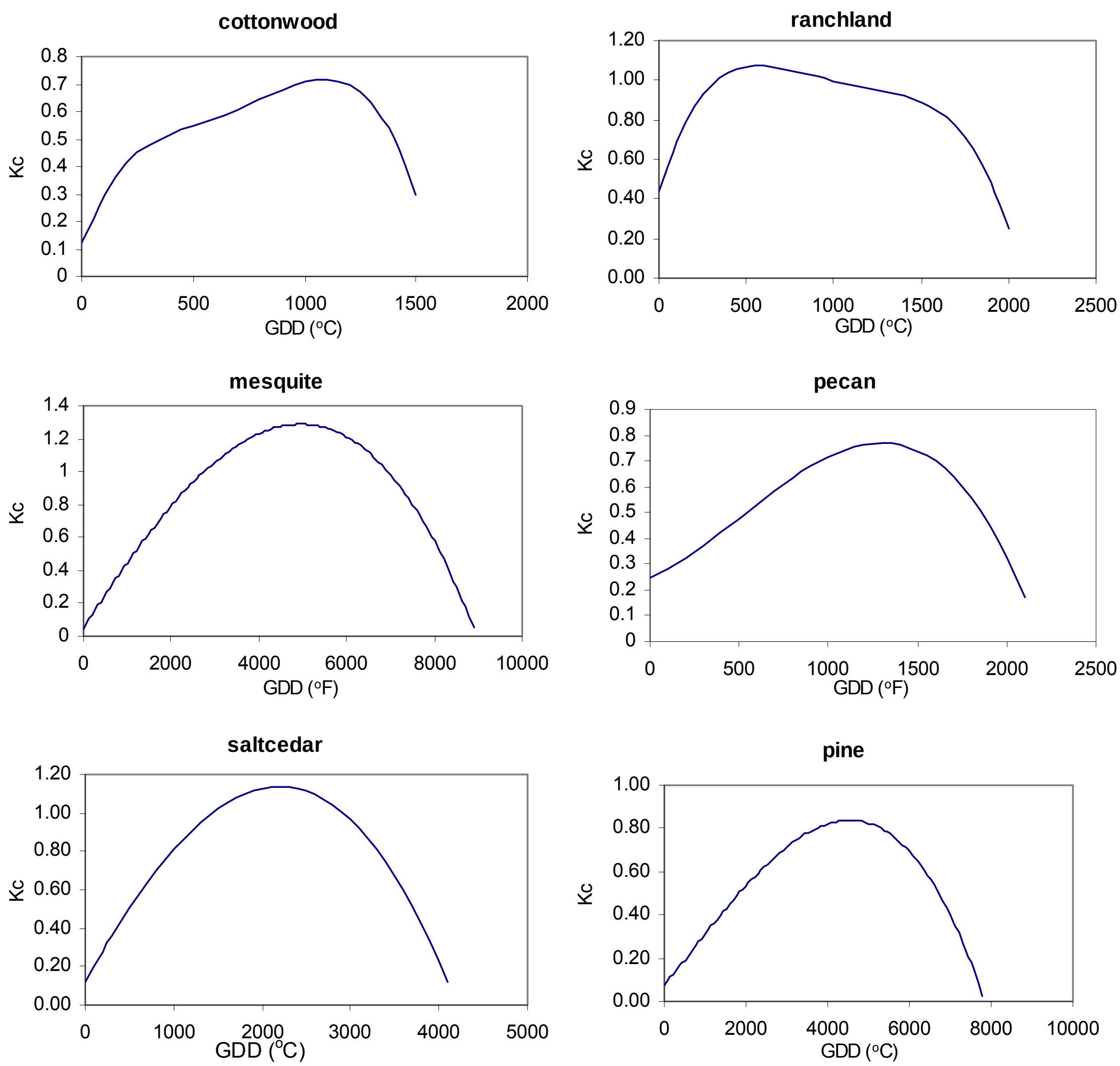

Figure 4.7. Relationship between crop coefficients and growing degree days.

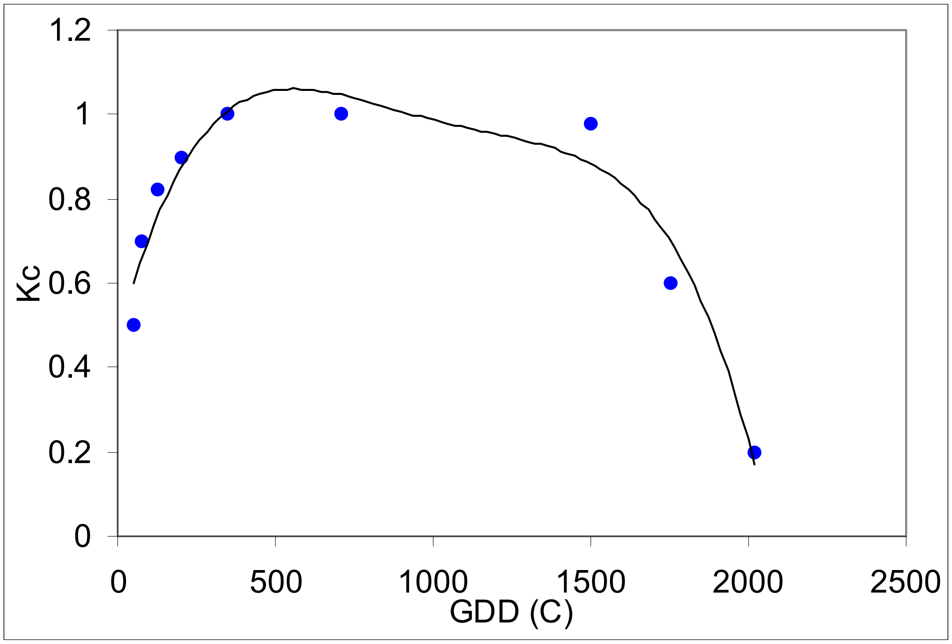

Figure 4.8. Example of polynomial fit to vegetation coefficient data.

The curves for vegetation are based on cumulative growing degree days (GDDs). A growing degree day is computed as:

$$GDD = (T_{daily\_\max} - T_{daily\_\min})/2 - T_{base} \quad (18)$$

where the base temperature, T_{base} may vary among different types of vegetation. When a temperature falls below a minimum or exceeds a maximum cutoff temperature then the GDD is zero. A growing season starts when the average monthly temperature rises above the minimum cutoff temperature. During the no-growth season, the GDD are set to zero. In many regions, this is from the middle of November to the beginning of April. Once the growing season begins, a temperature may rise above a maximum cutoff temperature defined for a crop, in which case the GDD is zero.

The growing season for New Mexico is not the same as the growing season in parts of Texas, thus the curves have to be scaled. Scale factors (f) are obtained by dividing the maximum cumulative growing days (GDD_C) for a particular crop in New Mexico by the maximum cumulative growing days for that crop in a region of Texas. The vegetation coefficients are then calculated using the following polynomial (fit through field data):

$$K_c = C_1(GDD_C \cdot f)^4 + C_2(GDD_C \cdot f)^3 + C_3(GDD_C \cdot f)^2 + C_4(GDD_C \cdot f)^2 + C_5 \cdot GDD_C \cdot f + C_6 \quad (19)$$

where K_c is the crop coefficient and C_x are coefficients given in Table 4.5.

Table 4.5. Polynomial constants for vegetation coefficient curve.

	C1	C2	C3	C4	C5	C6
wetlands						
saltcedar	0	0	-1.69E-11	-1.38E-07	8.5E-04	1.16E-01
cottonwood	3.38E-16	2.79E-12	5.85E-09	-5.06E-06	2.25E-03	1.20E-01
ranchland: warm grasses	0	-7.74E-13	3.21E-09	-4.86E-06	2.98E-03	4.39E-01
ranchland: creosote	0	0	-2.66E-12	-6.21E0-8	4.97E-04	1.55E-01
mesquite	0	0	-3.22E-12	-1.89E-08	4.24E-04	4.25E-02
pine	0	0	-5.02E-12	8.48E-09	2.33E-04	7.40E-02
pecan	0	0	-2.97E-10	4.61E-07	3.05E-04	2.46E-01

For months with a GDD_C above zero for a particular crop, monthly crop coefficients were calculated using equation (19). During the months where the crop coefficient curves did not apply, a crop coefficient of 0.20 was assumed. The exception to this was creosote where a coefficient of 0.25 was assumed for months where the average daylight is less than 11 hours. The crop coefficients for all months were then averaged to obtain an annual crop coefficient. These annual coefficients are shown in Table 4.6, calculated with historical average monthly temperatures from several locations in Texas.

Table 4.6. Calculated annual vegetation coefficients at several locations in Texas

	Del Rio	Austin	El Paso	Amarillo
wetlands	0.77	0.77	0.77	0.77
saltcedar	0.66	0.66	0.54	0.52
cottonwood	0.40	0.37	0.36	0.34
ranchland: warm grasses	0.74	0.70	0.62	0.53
ranchland: creosote	0.58	0.57	0.56	0.54
mesquite	0.72	0.54	0.53	0.44
pine	0.53	0.53	0.42	0.37
pecan	0.41	0.41	0.37	0.34

We see from Table 4.6 that the coefficients typically range from 0.4 to 0.7, with a median of about 0.5. So in the absence of specific information about vegetation type, annual vegetation ET may be assumed to be approximately 0.5 * PET.

As detailed in section 3.3, in some cases the type of vegetation may be less important than the stand density or LAI. So even after these average vegetation coefficients are calculated, estimates of the relative variation of LAI, based on remote sensing data, may help in assessing the spatial variance in the vegetation ET rate.

Rooting Depths

Vegetation rooting depths must be estimated from values found in the literature. Because rooting depths not only vary among plant types, but also vary among different soil types for the same plant, they can be difficult to estimate. Ideally, a rooting depth value can be found in the literature for a similar plant under similar soil and climate conditions.

Table 4.7 gives some examples of rooting depths from Canadell and others (1996) for species that occur in Texas. This reference has many types of plants, but few actual measurements in Texas. However, there may be analogous measurements available for some Texas vegetation and soil types. Table 4.8 gives example rooting depths from Jackson and others (1999), which was a study on the Edwards Plateau of central Texas. Note that this is a very specific soil type with "shallow, calcareous soils overlying fractured Cretaceous limestone." Table 4.9 gives some measured rooting depths from Schenk and Jackson (2002), which is basically a large database of rooting depths compiled from various literature sources. Table 4.9 shows those measurements that were made in Texas. In this database, only the vegetation classes are given, without particular species names.

Table 4.7. Example rooting depths from Canadell and others (1996).

Vegetation	**Root depth (m)**	**Root depth (ft)**
Crops	2.1	7
Loblolly Pine	2.1 to 4.0	7 to 13
Bur Oak	4.3	14
Mesquite	2.1 to 14.9	7 to 49

Table 4.8. Example rooting depths from Jackson and others (1999) from the Edwards Plateau in Texas.

Vegetation	**Root depth (m)**	**Root depth (ft)**
Sugarberry	5.8	19
Ashe juniper	7.9	26
Live Oak	18.3	60
White Shin Oak	7.0	23
Cedar Elm	8.8	29
American Elm	7.0	23

Table 4.9. Example rooting depths from Schenk and Jackson (2002) in Texas.

Vegetation	**$95^{percentile}$ Root depth (m)**	**$95^{percentile}$ Root depth (ft)**
Open Shrubland	2.4 to 6.1	8 to 20
Wooded grassland	1.2 to 2.4	4 to 8
Grassland	0.6 to 0.9	2 to 3

For some perspective on the rooting depths given in these tables, Figure 4.9 shows the estimated depth to water in major outcrops in Texas (Calhoun and others, 2002). In eastern Texas, we see that water table depths are typically less than 6 m (19.7 ft) from land surface, so many types of vegetation would have access to groundwater. As we move west, the water table is less than 6 m (19.7 ft) from land surface only in various riparian or other topographically low areas. With this information, the modeler can estimate which types of vegetation will likely have an impact in the study area, therefore reducing the amount of data that must be gathered.

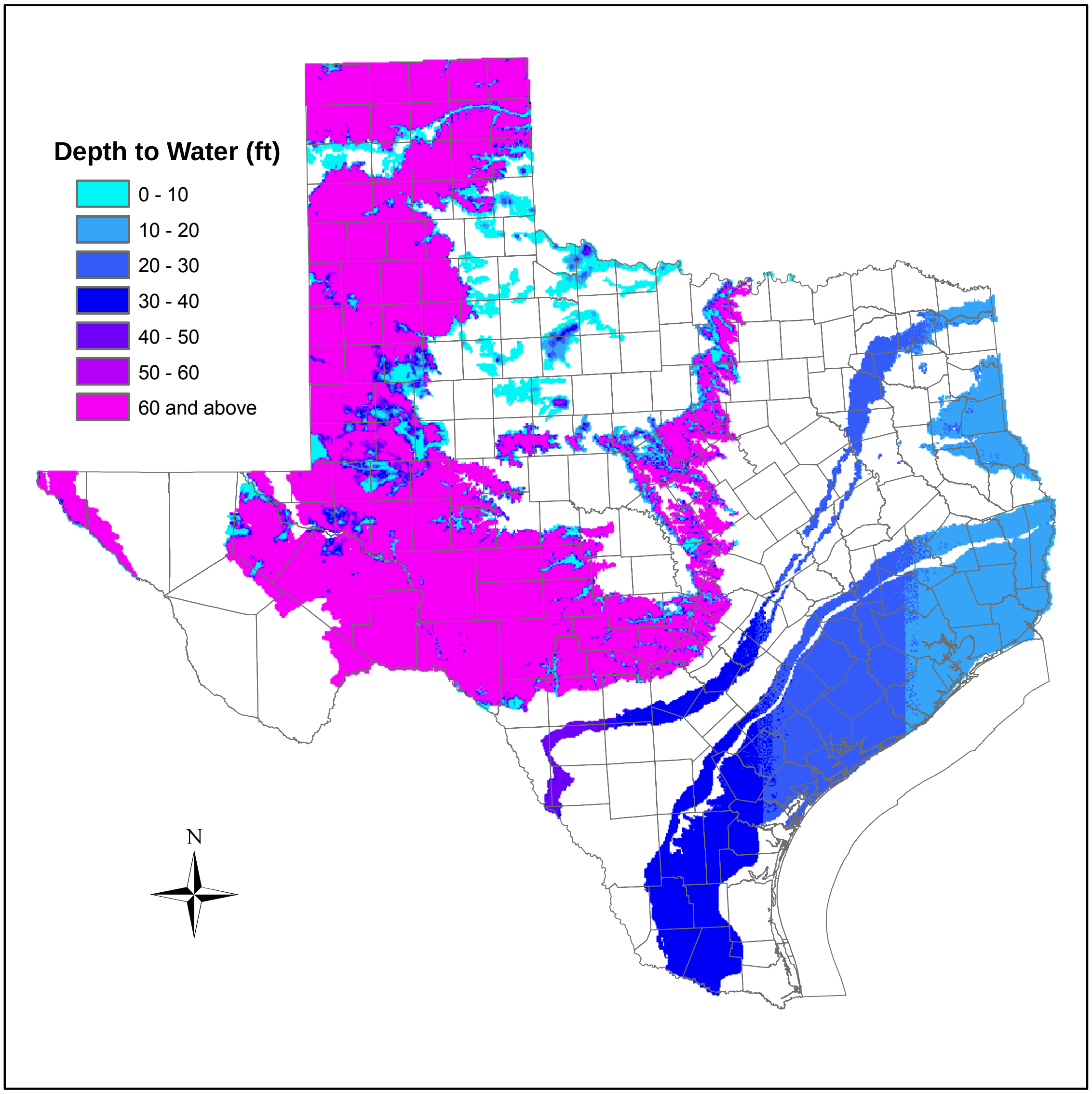

Figure 4.9. Estimated depth to water in major aquifer outcrops in Texas (Calhoun and others, 2002).

4.4 Sample Calculation of ETVmax

As part of the current work, we made a large-scale calculation of long term average ETVmax for all of Texas, using the GAP vegetation map and some of the example vegetation coefficient values derived previous (Table 4.6). As stated previously, for any specific region, local (or smaller scale) information about vegetation is required for a defensible estimation of ET, so the values we have generated should be used only as a starting point, or as a “filler” where information is unknown.

To calculate this coverage, we used an average annual temperature map of Texas to determine which of the values in Table 4.6 would be most appropriate for a given region. We then assigned Kc values based on similar GAP vegetation types to those shown in Table 4.6. For those GAP vegetation types that were dissimilar to those types shown in Table 4.6, a constant Kc value of 0.5 was used. These Kc values were then multiplied by the long term PET estimate given in Figure 2.6, resulting in the values shown in Figure 4.10. Because the variation in Kc with temperature and vegetation type is relatively small compared to the variation in PET, the trends in Figure 4.10 are similar to those in Figure 2.6.

4.5 Limitations of the Proposed Approach

The most glaring conceptual limitation of applying the ET package in a groundwater model is the lack of an unsaturated zone water balance. Without the unsaturated zone water balance, we cannot accurately estimate the proportion of total ET that is groundwater ET. We know how the relationship should trend with water table elevation, but cannot make direct estimates without this water balance.

The data requirements are significant for rigorous application of the method, where PET, vegetation coverage, vegetation coefficients, rooting depths, and soil types are all required. Vegetation coefficients are unavailable for many types of vegetation in Texas. Rooting depths are available for many types of vegetation, but are sensitive to soil types. So not only must the analyst find rooting depths for certain vegetation, but must also consider whether the soil types are similar between the measured values and the study area.

Because of these data requirements, there is significant likelihood that data will be partial or incomplete. However, as stated earlier, although making estimates where data is incomplete and following the overall methodology may not immediately improve the accuracy of the model over a more rudimentary approach, establishing this framework will make the model easier to update when future data becomes available.

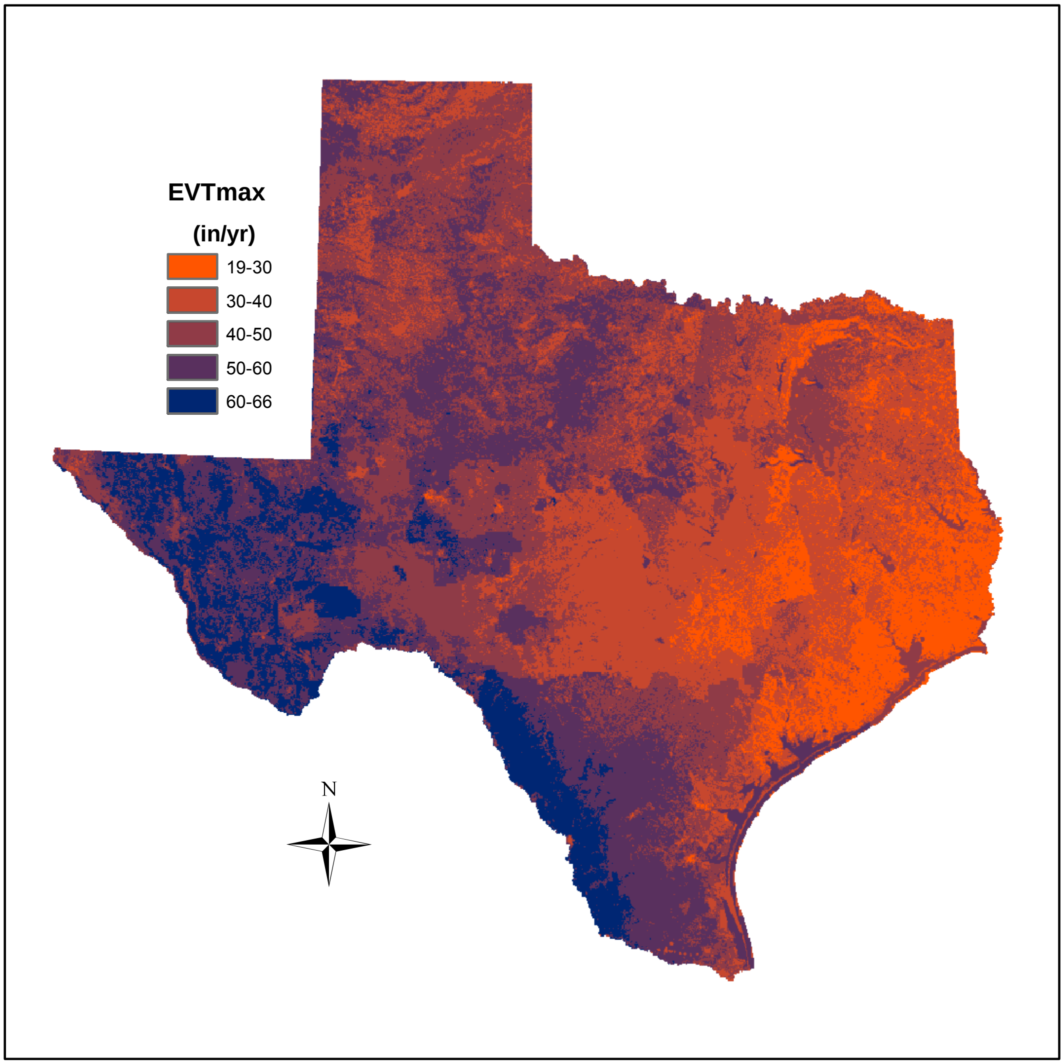

Figure 4.10. Estimated average annual ETVmax for Texas.

5.0 Conclusions and Recommendations

Accurate estimation of groundwater evapotranspiration (ET) is important for reliable assessment of groundwater resources. The purpose of this study was to

1) compile existing information on ET rates and processes, focusing primarily on groundwater ET from databases and literature,
2) evaluate relationships between vegetation types in different settings and ET rates, and
3) translate information collated in this study on groundwater ET rates and processes into the Groundwater Availability Modeling (GAM) program.

ET rates were compiled from the literature. A variety of techniques were used to estimate ET including water balance, lysimeters, micrometeorological approaches such as Bowen Ratio and Eddy Covariance, and water table fluctuations. ET rates in the literature ranged from 46 to 1839 mm/yr (1.8 to 72.4 in/yr). There is no systematic variation in ET rates among different vegetation types of riparian, trees, shrubs, and grasses. Within riparian zones, ET rates were generally higher in obligate phreatophytes such as cottonwood and willow than in facultative phreatophytes such as mesquite and saltcedar, which is considered to reflect a more fundamental control of leaf area and plant density. Detailed information on ET is available from a limited number of sites including the riparian zones adjacent to the San Pedro River in Arizona and the Rio Grande in New Mexico. At the San Pedro River site, ET was partitioned into groundwater ET and indicates that even in riparian zones where vegetation has access to groundwater, groundwater ET rates generally range from 30 to 50 percent of PET. ET rates from previous GAM models ranged from 2 to 96 percent of groundwater discharge.

We recommend the following approach to simulate ET in GAMs:

1) setting an extinction depth based on combined depth of root zone and thickness of capillary fringe (based on soil type),
2) increasing ET linearly from zero for most vegetation types at the extinction depth to the vegetation ET rate over a span equivalent to the thickness of the root zone, and
3) increasing ET approximately linearly over a span equivalent to the thickness of the capillary zone.

ET at the surface is set at the PET rate. A map of long-term average annual PET is available for Texas. Information on crop coefficients for riparian vegetation to reduce PET to actual ET is provided. Data requirements for this approach for modeling ET include PET, distribution of riparian vegetation or wetland vegetation in areas of shallow water tables, vegetation coefficients for identified plant types, soil textures for estimating thickness of capillary fringe and capillary zone, and rooting depths for specified plant types in area soils. Application of this approach to simulating ET in future GAMs should result in more reliable ET discharge rates and more comparable ET rates among GAMs. This consistent approach may result in improved predictions of groundwater capture resulting from increased groundwater development and lowering of water tables below root extinction depths.

This reconnaissance study highlights the lack of riparian ET measurements in Texas, which contrasts with much more advanced monitoring programs in New Mexico, Arizona, and Oklahoma. To advance quantitative understanding of riparian ET in Texas, the following program should be adopted:

1. Map riparian vegetation at an appropriate scale using remote sensing or appropriate procedure
2. Monitor riparian ET using a variety of approaches including micrometeorological approaches, water table fluctuations, sap flux measurements, and modeling.
3. Evaluate the use of satellite based estimates of ET and compare with ground-based measurements.

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Appendix 1

Assess the Status of Knowledge of the Mapped Distribution and Types of Riparian Vegetation

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Sections

A1.1 Sources of Existing Map Products showing the geographic distribution of riparian vegetation in the State of Texas

A review of existing map products showing global, national and statewide vegetation distribution indicates the lack of a map that focuses exclusively on the geographic distribution of riparian vegetation within the State of Texas. General land cover and vegetation maps do exist. These vary in currency, level of detail, and appropriateness of mapped categories for the purpose of inferring the location and composition of riparian corridors.

One widely cited map is The Vegetation Types of Texas (McMahan and others, 1984), shown in Figure 1. The map was compiled at the Texas Parks and Wildlife Department (TPWD) in the late 1970s to early 1980s. McMahan and colleagues used Landsat Multi-Spectral Scanner satellite imagery acquired between 1972 and 1976 to classify vegetation associations in the eastern two-thirds of the state. Ground survey data collected by the Bureau of Economic Geology and additional Landsat data dating from 1979 and 1980 were used to map the remainder of the State. Remarks on the general distribution of each vegetation type and commonly associated plants were published in a companion report. TPWD later created a digital version of the map shown in Figure 1. The attributed region polygons are also available in a format suitable for use in a Geographic Information System (GIS). The Vegetation Types of Texas was compiled at a map scale of 1:250,000. As a consequence, riparian vegetation is mapped separately where resolution constraints permit. In many cases, riparian corridors were too narrow to include in the final product. The map authors note that vegetation distribution has been greatly influenced by human activity, becoming more heterogeneous and less characteristic of natural conditions.

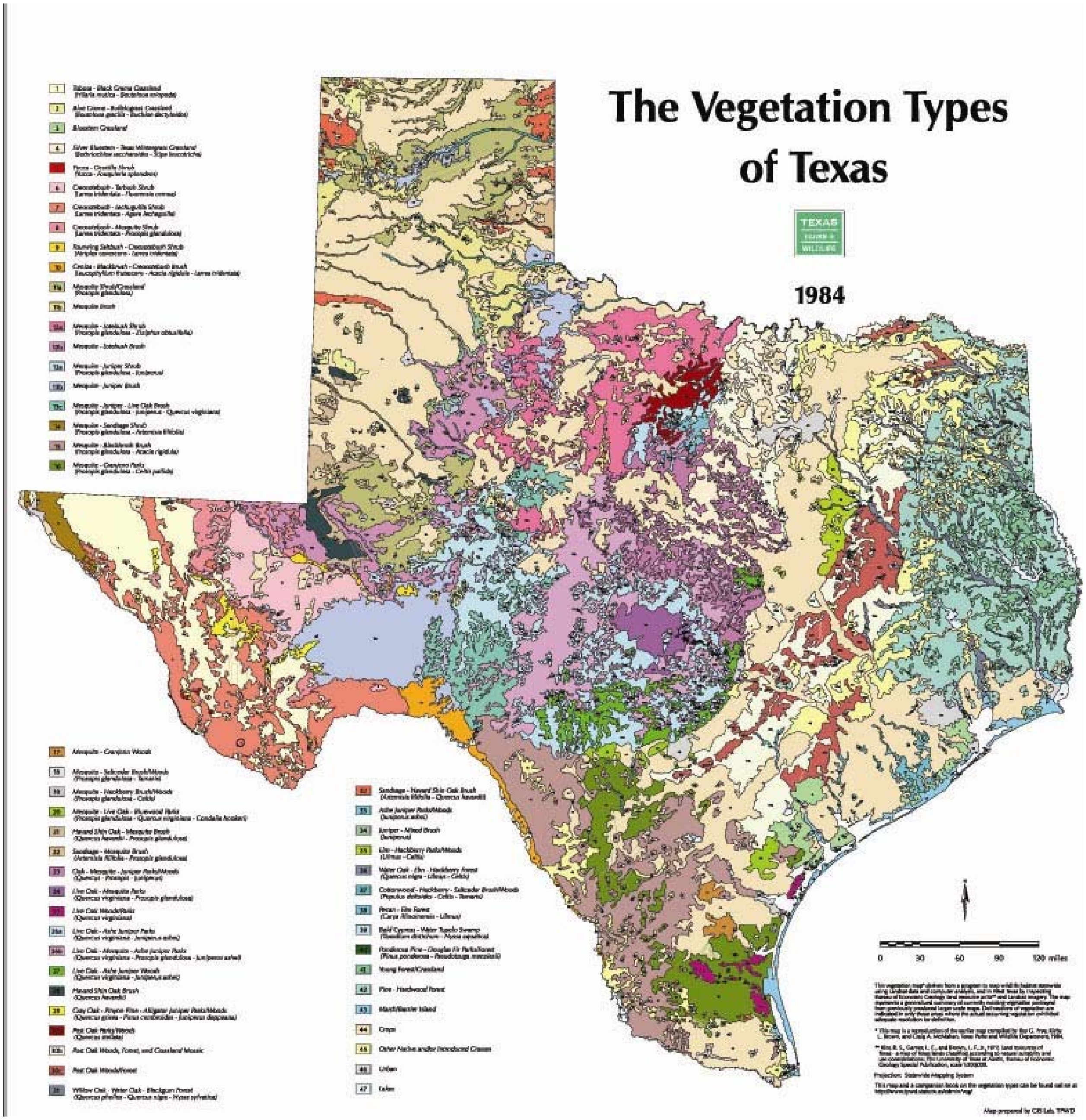

Figure 1. The Vegetation Types of Texas, after McMahan and others (1984). Map produced by TPWD.

No other statewide vegetation mapping has been attempted in the years since the publication of The Vegetation Types of Texas. However, members of the Texas Geographic Information Council collaborated to provide guidance for any future mapping efforts. The Texas Land Classification System (TGIC, 1999) provides a detailed description of general vegetation classes recommended for use in any future statewide mapping effort. The classification scheme includes a riparian forest class in a nested hierarchy under the categories of vegetated wetland, woody wetland, and forested wetland. Riparian forest is further subdivided into seasonally and temporarily flooded categories. Some organizations have adopted the classification system for small projects. The Texas Parks and Wildlife Department has funded detailed vegetation mapping for limited areas within the State, prior to and following the publication of the Texas Land Classification System. Published mapped areas include the proposed Cibolo and Goliad reservoir sites (Cypher and Frye, 1993), the Cypress Creek watershed (Liu and others, 1996b), the potential future Waters Bluff Reservoir site (Liu and others, 1996a), and three proposed reservoir sites in Northeast Texas (Liu and others, 1997). Unpublished work has been conducted at Lost River, Cow Bayou, and the Middle Neches River in East Texas. All sites include riparian vegetation.

A recent publication resulting from the collaboration of several offices of the Environmental Protection Agency (EPA), the Texas Commission of Environmental Quality, and the US Department of Agriculture-Natural Resources Conservation Service (NRCS) contains information pertinent for riparian vegetation mapping in the State. Ecoregions of Texas (Griffith and others, 2004) is a large format color poster of a map compiled at the scale of 1:2,500,000. The poster includes descriptive text and photographs. A page size version of the map, adapted from materials published on the EPA website, is shown in Figure 2. The map delineates twelve Level III and 56 Level IV EPA ecoregions in Texas, shown in Table 1. Table 2 lists riparian vegetation community composition as indicated for Level IV ecoregions. Not all ecoregion descriptions include explicit references to riparian vegetation. Consequently, it cannot be assumed that all or even most riparian species are mentioned. The species mentioned are predominantly trees. Associated shrubs, grasses and forbs are not identified. It is also important to note that the primary goal of the ecoregion map is to describe natural areas based on geology, physiography, soils, vegetation, climate and other discriminating factors. Although mention is made of the human footprint on the landscape, the conversion of the natural landscape for agriculture and human settlement is not emphasized. The vegetation in many riparian areas of present-day Texas may no longer correspond to the riparian vegetation types listed in Table 2.

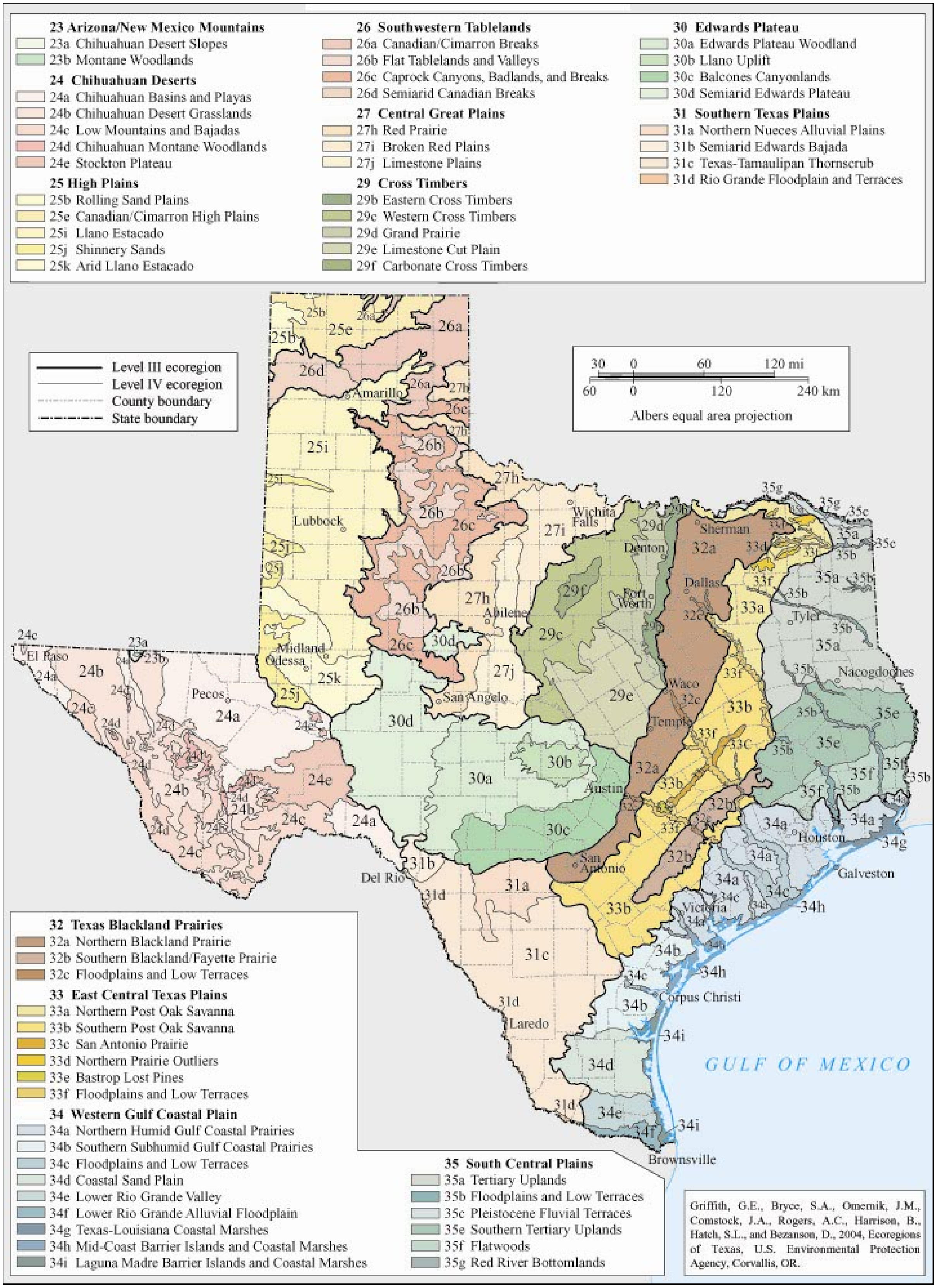

Figure 2. Level III and Level IV EPA Ecoregions of Texas (Griffith *et al.*, 2004)

Table 1. Level III (in bold) and Level IV EPA ecoregions found in Texas (Griffith and others, 2004). Level IV ecoregions that include explicit descriptions of riparian vegetation communities are italicized. Note that gaps in the numbering system exist; the ecoregions are part of a national taxonomy. Many nationally identified ecoregions are not found in Texas.

23. Arizona/New Mexico Mountains
- 23a Chihuahuan Desert Slopes
- 23b *Montane Woodlands*

24. Chihuahuan Deserts
- 24a *Chihuahuan Basins and Playas*
- 24b Chihuahuan Desert Grasslands
- 24c *Low Mountains and Bajadas*
- 24d Chihuahuan Montane Woodlands
- 24e Stockton Plateau

25. High Plains
- 25b Rolling Sand Plains
- 25e Canadian/Cimarron High Plains
- 25i Llano Estacado
- 25j Shinnery Sands
- 25k Arid Llano Estacado

26. Southwestern Tablelands
- 26a Canadian/Cimarron Breaks
- 26b *Flat Tablelands and Valleys*
- 26c *Caprock Canyons, Badlands, and Breaks*
- 26d *Semiarid Canadian Breaks*

27. Central Great Plains
- 27h Red Prairie
- 27i *Broken Red Plains*
- 27j *Limestone Plains*

29. Cross Timbers
- 29b Eastern Cross Timbers
- 29c Western Cross Timbers
- 29d *Grand Prairie*
- 29e Limestone Cut Plain
- 29f Carbonate Cross Timbers

30. Edwards Plateau
- 30a Edwards Plateau Woodland
- 30b Llano Uplift
- 30c *Balcones Canyonlands*
- 30d *Semiarid Edwards Plateau*

31. Southern Texas Plains
- 31a *Northern Nueces Alluvial Plains*
- 31b Semiarid Edwards Bajada
- 31c Texas-Tamaulipan Thornscrub
- 31d *Rio Grande Floodplain and Terraces*

32. Texas Blackland Prairies
- 32a *Northern Blackland Prairie*
- 32b Southern Blackland/Fayette Prairie
- 32c *Floodplains and Low Terraces*

33. East Central Texas Plains (Post Oak Savanna)
- 33a Northern Post Oak Savanna
- 33b Southern Post Oak Savanna
- 33c San Antonio Prairie
- 33d Northern Prairie Outliers
- 33e Bastrop Lost Pines
- 33f *Floodplains and Low Terraces*

34. Western Gulf Coastal Plain
- 34a Northern Humid Gulf Coastal Prairies
- 34b Southern Subhumid Gulf Coastal Prairies
- 34c *Floodplains and Low Terraces*
- 34d Coastal Sand Plain
- 34e Lower Rio Grande Valley
- 34f *Lower Rio Grande Alluvial Floodplain*
- 34g Texas-Louisiana Coastal Marshes
- 34h Mid-Coast Barrier Islands and Coastal Marshes
- 34i Laguna Madre Barrier Islands and Coastal Marshes

35. South Central Plains (Pineywoods)
- 35a Tertiary Uplands
- 35b *Floodplains and Low Terraces*
- 35c Pleistocene Fluvial Terraces
- 35e Southern Tertiary Uplands
- 35f Flatwoods
- 35g *Red River Bottomland*

Table 2. Riparian Vegetation Types of Texas as listed by Level IV EPA Region from Griffith and others (2004).

Level III Ecoregion	Level IV Ecoregion	Riparian Vegetation Types
Arizona/New Mexico Mountains	Montane Woodlands (Guadalupe Mountains)	velvet ash, chinkapin oak, Texas madrone, bigtooth maple, maidenhair fern, and sawgrass
Chihuahuan Deserts	Chihuahuan Basins and Playas	saltcedar, common reed (non-native)
Chihuahuan Deserts	Low Mountains and Bajadas	gray oak, velvet ash, little walnut
Southwestern Tablelands	Flat Tablelands and Valleys	saltcedar (non-native)
Southwestern Tablelands	Caprock Canyons, Badlands, and Breaks	cottonwood, willow, hackberry, big bluestem grasses (native), elm, saltcedar (non-native)
Southwestern Tablelands	Semiarid Canadian Breaks	cottonwood, willow, hackberry (native), saltcedar (non-native)
Central Great Plains	Broken Red Plains	cottonwood, hackberry, cedar elm, pecan, little walnut
Central Great Plains	Limestone Plains	hackberry, cottonwood, elms, willows
Cross Timbers	Grand Prairie	elm, pecan, hackberry
Edwards Plateau	Balcones Canyonlands	bald cypress, American sycamore, black willow
Edwards Plateau	Semiarid Edwards Plateau	live oak in floodplains only
Southern Texas Plains	Northern Nueces Alluvial Plains	hackberry, plateau live oak, pecan, cedar elm (floodplain), black willow, eastern cottonwood (river banks)
Southern Texas Plains	Rio Grande Floodplain and Terraces	sugar hackberry, cedar elm, Mexican ash, black willow, black mimosa, common and giant reed, cattails, bulrushes, sedges, cotton, grain sorghum, cool-season vegetables
Texas Blackland Prairies	Northern Blackland Prairie	bur oak, Shumard oak, sugar hackberry, elm, ash, eastern cottonwood, pecan (historically), now widely converted to cropland, pasture, non native vegetation, urban sprawl
Texas Blackland Prairies	Floodplains and Low Terraces	bur oak, Shumard oak, sugar hackberry, elm, ash, eastern cottonwood, pecan (historically), now widely converted to cropland/pasture
East Central Texas Plains	Floodplains and Low Terraces	hackberry, eastern cottonwood (west); water oak, post oak, elms, green ash, pecan, willow oak (east); more forest in north, more cropland/pasture in south
Western Gulf Coastal Plain	Floodplains and Low Terraces	pecan, water oak, southern live oak, elm, bald cypress, widespread conversion to cropland/pasture
Western Gulf Coastal Plain	Lower Rio Grande Alluvial Floodplain	Texas ebony, Texas palmetto, sugar hackberry-cedar elm (small parcels)
South Central Plains	Floodplains and Low Terraces	water oak, willow oak, sweetgum, blackgum, elm, red maple, southern red oak, swamp chestnut oak, loblolly pine, baldcypress, water tupelo
South Central Plains	Red River Bottomlands	water oak, sweetgum, willow oak, southern red oak, eastern redcedar, blackgum, blackjack oak, overcup oak, river birch, red maple, green ash, American elm (historically), now widely converted to cropland/pasture

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Other maps investigated during the review process were compiled to show the distribution of land cover and land use. The mapped categories include broad vegetation classes but do not focus on riparian vegetation. The most recent available products are the 1992 National Land Cover Dataset (NLCD) and the MODerate-resolution Imaging Spectroradiometer (MODIS) Land Cover Classification. A new National Land Cover Dataset representing conditions in 2001 is in production at the USGS. Three of the five map regions encompassing Texas are slated for release in late 2005; the other regions are not yet in production and may be delayed for more than a year. The MODIS Land Cover product is available for 2001 and 2002. It is not known when additional updates will be published.

The 1992 NLCD, derived from imagery collected with the Landsat 5 Thematic Mapper instrument, characterizes 21 land cover classes, including three forested upland classes, one shrubland class, one herbaceous upland class, five planted or cultivated classes, and two wetlands classes. The wetlands classes, based on definitions adopted by the National Wetlands Inventory (NWI) consist of woody wetlands, periodically saturated areas with 25 to 100 percent forest or shrubland canopy cover, and emergent herbaceous wetlands, periodically saturated areas with 75 to 100 percent perennial herbaceous vegetation (Cowardin and others, 1979). The 2001 NLCD classification is similar, with the same general definitions for upland forest, shrubland, and herbaceous classes. The cultivated classes are reduced to two. Each wetlands class has been subdivided into four additional classes for all coastal mapping regions. The additional eight class subdivisions are also based on the NWI classification system. Two Texas mapping regions will include the additional classes. Source data for the 2001 NLCD consist of triplicate dates of Landsat 7 Enhanced Thematic Mapper-Plus data ranging in dates from 1999 to 2002, supplemented with Thematic Mapper data as needed. Both datasets use a 30 meter ground cell mapping resolution. The NLCD products, used in conjunction with other GIS data layers such as the National Hydrography Dataset, may serve as useful starting points for future Texas-based riparian vegetation mapping projects. However, the land cover classes are too generalized and the products themselves too dated for immediate assessment of current riparian conditions. More information about both NLCD programs is available at http://www.mrlc.gov .

The MODIS Land Cover Classification uses the International Geosphere-Biosphere Programme (IGBP) global vegetation classification scheme mapped to a one-kilometer ground cell resolution (Friedl and others, 2002). The scheme includes eleven natural vegetation cover types – five forest classes, two shrubland classes, two savanna classes, one grasslands class, and one permanent wetlands class. In addition, one class is designated as a mosaic of cropland and natural vegetation. Three to four other related classification schemes are included in the product. The MODIS Land Cover Classification shows promise, in part because of its use of seasonal time series data and supervised decision trees for class definition. With daily data collections, the product can be refined and regenerated more frequently and rapidly than the NLCD. However, the product has serious limitations for the assessment of riparian vegetation in Texas. The scope of the product is to map global vegetation trends; therefore, the dataset's suitability for smaller regional applications is questionable. The classification schema does not explicitly represent the riparian environment and the product has not been validated for use in Texas. Most importantly, the one kilometer mapping unit cannot capture the variation within the narrow riparian corridors of West and Central Texas. More information about the MODIS Land Cover Classification products is available at http://modis-land.gsfc.nasa.gov/landcover.htm and http://geography.bu.edu/landcover .

Two national biological programs that hold great promise for vegetation mapping have yet to yield results for Texas. Both programs are sponsored by the US Geological Survey (USGS). The Gap Analysis Program is concerned with the inventory of native species and natural land areas within the United States and the preservation of biodiversity (USGS, 2005a). One of the program's five primary objectives was to map the nation's land cover. The distribution of vegetation based on this study is shown in Figure 3. The National Biological Information Infrastructure (NBII) is a related program (USGS, 2005c). The intent of the NBII is to serve as an information clearinghouse rather than to guide a national project. The program highlights biodiversity and invasive species as current biological issues. Vegetation mapping is critical to the understanding of both topics. Riparian vegetation would be an essential component of any mapping effort, but few products are available at present.

In recent years, more mapping resources have been focused on the issue of invasive species. Some generalized maps of species distributions are available. An example is the US distribution of the Giant and Common Salvinia, aquatic invasive species (USGS, 2005b). Attempts have been made to map occurrences of saltcedar in the US Southwest. However, detailed mapping is limited, mapping methods are inconsistent, temporal content may vary, and few species are represented. An attempt to incorporate single species map products into a comprehensive statewide map seems inadvisable at present.

A1.2 Information about Types of Riparian Vegetation in the State of Texas and their Geographic Distribution.

The Texas Parks and Wildlife Department has conducted many vegetation assessments within Texas with a focus on the condition of riparian vegetation and other wetlands. The companion report to the map of the Vegetation Types of Texas includes brief descriptions of species associated with the vegetation communities whose geographic distribution is presented in the map. The map and report are frequently cited in TPWD publications. In subsequent work based on the Vegetation Types of Texas, Frye (1987) quantified the geographic distribution of bottomland hardwoods in Texas at 5,973,000 acres, excluding 95,000 acres of swampland. An estimated 1,169,000 acres of forested wetlands were located along the Trinity, Neches, Sabine, Sulphur, and Angelina rivers and the Cypress Bayou. Another 3,062,000 acres lined river tributaries and riparian drainages east of the Navasota River. The remaining 1,742,000 acres of riparian forest was found in other Texas rivers, creeks, and riparian drainages. Subsequent studies conducted at TPWD, Texas A&M University, and the US Forest Service have measured changes in the bottomland hardwood population. In 1990, TPWD and the US Fish and Wildlife Department published an assessment of the impacts of new reservoir construction on wildlife habitat, also based on earlier vegetation mapping projects. In an undated Texas Parks and Wildlife Department publication, Wagner reviews riparian habitats of Texas with brief characterizations of vegetation and general indications of the quantity of riparian vegetation. The habitats are organised by natural areas (Gould and others, 1960). Table 3 summarizes Wagner's

Table 3: Vegetation of riparian habitat by natural area from Wagner (Undated TPWD Report).

Natural Area	Representative Riparian Species	Other comments
Rolling Plains	cottonwood, willow, hackberry, soapberry or locust, associated with persimmon, bumelia, and mesquite	Riparian habitat accounts for 2 to 5% of wildlife habitat in the High Plains and Rolling Plains
High Plains	unwooded, entrenched draws, frequently dominated by invasive saltcedar	See above
Central Texas/Edwards Plateau	bald cypress and sycamore; pecan and hackberry; hackberry and elm	netleaf hackberry/little walnut; plateau live oak/netleaf hackberry; and sycamore/willow communities predominate in smaller creeks of western Plateau
Trans-Pecos	deciduous riparian woodlands contain ash, cottonwood, willow, walnut, and hackberry communities; shrub or	Riparian habitat in Rio Grande and Pecos River drainages accounts for

	scrubland has understory of mesquite/acaci, and sumac, and overstory of cottonwoods, willows or ash	<5% of wildlife habitat; great vegetation diversity
South Texas	mesquite, retama, granjeno, anacua (Rio Grande), live oak, cedar elm, hackberry, and whitebrush	Riparian habitat found along Nueces River and Rio Grande and associate tributaries
Pineywoods and Post Oak Savanna	Lower floodplains: willow oak, green ash and overcup oak; upper flood plains: water oak, cherrybark oak and sweetgum; swamps: bald cypress and water tupelo	No additional comments

report findings. Land use activities that impact the quality of riparian wildlife habitat include grazing, farming and timber production. Signs of negative impacts include bank destabilization, erosion, topsoil loss caused by removal of perennial native vegetation, and tree harvesting along drainage banks. Recommended mitigation practices are improved grazing strategies, the establishment of wide riparian zones in areas of cultivation, and the implementation of sound streamside management in silvaculture zones. Any future inventory of riparian vegetation conditions should assess both negative and positive impacts. The Texas Wetlands Conservation Plan (TPWD, 1997) and the recently published Land and Water Resources Conservation and Recreation Plan (TPWD, 2005) are also based on vegetation assessments conducted at the agency.

Griffith and others (2004) provide a rich bibliography of sources related to the distribution of natural vegetation in Texas, as does Bezanson (2000). It may be possible to tease out information related to riparian vegetation with a thorough review of cited references. Bezanson (2000) identified 120 natural vegetation communities in Texas. Figure 4 shows Bezanson's compilation of the natural areas of Texas as delineated by Gould and others (1960) with revisions based on other sources. Vegetation communities are organized by natural areas. Of the 120 vegetation communities, at least 37 contain riparian elements (Table 4), not including other wetland environments, such as playas, bogs, coastal marshes. Bezanson presents an exhaustive list of woody and herbaceous species associated with the named plant communities. Table 5 is a compilation of his findings for each identified community, with geographical notes where available. For each natural area of Texas, Bezanson presents lists of protected areas and the percent of each vegetation community represented in each area. Although no maps of the vegetation communities are included, it would be possible to infer the distribution of riparian species within the protected areas. The publication includes an extensive bibliography of regional and local surveys, reports and research. Although Bezanson's work represents an excellent reference about the distribution of riparian species in Texas, his focus is on conservation areas and native species and does not constitute a quantitative assessment of conditions in disturbed areas.

In the arid west, some invasive riparian vegetation is subject to removal. Phreatophytes such as saltcedar are considered to be pest species that transform native habitat, establish monocultures, increase stream salinity, and reduce water flows (TAES, 2003). Saltcedar has been removed along the Pecos River in West Texas, and studies of the effects of the vegetation removal are ongoing (Clayton and others, 2000; Hart and others, 2005). Other brush control projects in Texas focus on upland vegetation, primarily Ashe juniper and mesquite, and do not directly

Table 4: Riparian vegetation communities by region as described in Bezanson (2000).

Natural Area of Texas	Vegetation Type #	General Description
East Texas Pineywoods	9	Forested acid seeps/wet creeksides
	10b	American beech mesic slope forests
	12	Forested depressional wetlands (baygalls)
	14	Swamp chestnut oak-oak floodplain forests
	15a	Floodplain hardwood forests
	15b	Frequently inundated floodplain forests
	16	Sloughs/seasonally flooded floodplain forests
	17	Bald cypress-tupelo inundated forests
	18	Freshwater shrub swamps
	19	River banks
Post Oak Savannas	25	Water oak floodplain forests
	26	Sugarberry-elm floodplain forests
Blackland Prairies	32	Bur oak-Shumard oak mesic (or floodplain) forests
Gulf Coast Prairies and Marshes	37	Live oak-water oak floodplain forests
South Texas Plains	61a	Wetland brush
	63a	Texas ebony floodplain forests
	63b	Texas palmetto floodplain forest
	64	Sugarberry-elm floodplain forests (South Texas Plains)
	65	Sugarberry-elm floodplain forests (Lower Rio Grande Valley)
Edwards Plateau	72	Deciduous mesic canyon forests
	73	Limestone bluffs and seeps
	75	Spring-fed streams (Edwards Plateau)
	76a	Pecan-elm floodplain woodlands (Edwards Plateau)
	77	Streambeds
	78	Bald cypress riparian woodlands
	79	Netleaf hackberry-plateau live oak floodplain woodlands
Prairies and Cross Timbers	76b	Pecan-elm floodplain woodlands (Cross Timbers)
Rolling Plains	87	Mesquite floodplain brush
	88	Cottonwood-willow riparian woodlands
West Texas	95	Saline or alkaline wetlands
	101	Mesquite thickets
	102	Cottonwood-willow riparian woodlands
	103	Arroyo scrub
	108	Riparian shrublands
	110	Spring-fed streams/cienegas
	114	Canyon riparian woodlands
	117	Deciduous canyon forest

Table 5: Examples of riparian plant communities in Texas as compiled by Bezanson (2000).

East Texas Pineywoods

9. Forested acid seeps/wet creeksides

Woody species: *blackgum, sweetbay, titi, red maple, red bay, hollies, evergreen bayberry, Elliott's blueberry, sweetgum, azaleas, poison sumac, other evergreen shrubs; occasional pines and southern magnolia; possomhaw viburnum, smooth alder, Elliott's blueberry, southern wax-myrtle to north and west*
Other species: *ferns, beaksedges, sphagnum, club mosses*

10b. American beech mesic slope forests
Dominant species: *American beech*
Associated species: *white oak, maple, other hardwoods*
Geographical note: *limited distribution; found in sandy, calcareous slopes, ravines, and creeksides from Sabine County to Jasper, Newton, and Tyler counties; western extent of some southeastern forbs (not described)*

12. Forested depressional wetlands (baygalls)
Dominant overstory species: *swamp gum, laurel oak*
Common associated species: *red maple, sweetbay, gallberry holly, Carolina ash, titi, mayhaw, bald cypress, Virginia sweetspire, southern wax myrtle, greenbriar, sedges, cinnamon fern, sphagnum, rare orchids, saprophytic forbs*
Aquatic species: *Carolina water hyssop, waterlily*
Geographical note: *floodplain margins of Jasper, Hardin, Newton, and Tyler counties*

14. Swamp chestnut oak-oak floodplain forests
Woody and other species: *Loblolly pine, swamp chestnut oak, cherrybark oak, sweetgum, blackgum, willow oak, southern red oak, green ash, laurel oak, red maple, American elm, deciduous holly, hornbeams, Sebastian bush, partridgeberry*

15a. Floodplain hardwood forests
Common dominant species: *water oak, sweetgum, willow oak, American hornbeam, elm, hophornbeam, blackgum, southern red oak, loblolly pine, river birch, deciduous holly, poison ivy, muscadine grape, Virginia creeper, rattan vine, crossvine, greenbriar, violet, St. John's wort, Sebastian bush, longleaf spikegrass, ferns, mosses; occasional giant cane stands*
Co-dominant species in Southern East Texas: *laurel oak, swamp chestnut oak, southern magnolia*

15b. Frequently inundated hardwood forests
Overstory species: *Willow oak, overcup oak, bottomland post oak, elms, green ash, sweetgum*
Understory species: *Dwarf palmetto*

16. Sloughs/seasonally flooded floodplain forests
Common dominant species: *water hickory, planer tree, overcup oak, sweetgum, swamp privet, green ash, Carolina ash, red maple, mayhaw, buttonbush, lizard's tail, sedges, cutgrass, water willow, smartweed*

17. Bald cypress-tupelo inundated forests
Dominant species: *bald cypress, water tupelo*
Common associated species: *red maple, Carolina ash, buttonbush, water hickory, planer tree, sweetgum, swamp privet, common persimmon*
Other species: *Spanish moss, water millefoil, water pennyworts, water willows, false nettle, cypress swamp sedge, lizard's tail, water primroses, other floating leaf aquatic plants*

18. Freshwater shrub swamps
Dominant species: *buttonbush*

Common associated species: *green ash, smartweeds, water willows, sedges, water primroses, grasses, lizard's tail, black willow, smooth alder, river birch*

19. River banks
Common species: *Black willow, sycamore, eastern cottonwood, green ash*
Non-native species: *giant reed, planted grasses*

Post Oak Savannas

25. Water oak floodplain forests
Dominant species: *water oak*
Associated overstory species: *American elm, green ash, sugarberry and other woody floodplain species*
Understory species: *grapevine, poison ivy, rattan vine, switchcane, sedges, Virginia wildrye, other grasses*

26. Sugarberry-elm floodplain forests
Overstory species: *cedar elm, sugarberry, green ash, American elm, box elder, pecan, western soapberry, eastern cottonwood, sycamore, occasional bald cypress*
Understory species: *Virginia creeper, rattan vine, poison ivy, peppervine; in undisturbed areas, longleaf spikegrass, sedges, switchgrass, Virginia wildrye, coralberry, white avens, ruellia, Turks cap; in disturbed areas, giant ragweed and other weedy forbs*
Geographical note: *also common in Blackland Prairies, Cross Timbers, Coastal Prairies, northern South Texas, eastern Edwards Plateau, and Rolling Plains*

Blackland Prairies

32. Bur oak-Shumard oak mesic (or floodplain) forests
Dominant species: *bur oak, shumard oak, elm, pecan, green ash, sugarberry, eastern cottonwood*
Associated species: *yaupon, roughleaf dogwood, elderberry, bois d'arc, Virginia wildrye, sedges, rattan vine, Virginia creeper, peppervine, autumn bluegrass, low ruellia, frostweed, and other floodplain forbs*

Gulf Coast Prairies and Marshes

37. Live oak-water oak floodplain forests
Dominant species: *live oak, in swamps, green ash, black willow, swamp privet, sedges, smartweed*
Co-dominant species: *pecan, water oak, bald cypress on larger streams*
Associated species: *sugarberry, elm, dwarf palmetto, gum bumelia, bois d'arc, holly, grapevine, rattan vine, Virginia creeper, poison ivy, basketgrass, longleaf spikegrass, Cherokee sedge*

South Texas Plains

61a. Wetland brush
Dominant species: *huisache, mesquite, retama*
Associated species: *seep-willow, baccharis, rattlebush, bermudagrass, Guineagrass, silver bluestem, knotroot bristlegrass, buffalograss, Texas virgin's bower, western ragweed, spiny aster, blueweed sunflower, flatsedges, dwarf spikesedge, cattail, bulrush; black mimosa, amantillo, black willow, hairy panicum, common reed, giant reed in the Lower Rio Grande Valley*
Note: *found in disturbed wet areas such as depressions, streamcourses, resaca banks*

63a. Texas ebony floodplain forests
Overstory species: *Texas ebony, anacua, tepeguaje, coma, tenaza, mesquite, sugarberry*

Mid- and understory species: *snake-eyes, lotebush, brasil, granjeno, colima, Barbados cherry, chapotillo, crucillo, tropical heartseed, snailseed, pigeonberry, serjania vine, sparse ground cover*
Geographical note: *found in alluvial bottomland of Lower Rio Grande Valley in Hidalgo and Cameron counties on natural levees adjoining resacas and river channels; rarely found due to human intervention*

63b. Texas palmetto floodplain forest
Dominant species: *Texas palmetto and sometimes tepeguaje*
Associated species: *sugarberry, tepeguaje, Texas ebony, anacua, tenaza, colima, snake-eyes, lotebush, mesquite, granjeno*
Geographical note: *found in lower delta of the Rio Grande on floodplain ridges; exceedingly rare because of widespread clearing in early twentieth century*

64. Sugarberry-elm floodplain forests (South Texas Plains)
Dominant species: *hackberries, live oak, cedar elm, huisache, pecan, Mexican ash, boxelder, mesquite, western soapberry, granjeno, black willow, eastern cottonwood*
Understory species: *peppervine, grapevine, creek oats, Virginia wildrye, Texas wintergrass, bristlegrass, pigeonberry*
Geographical note: *found along Frio and Nueces rivers*

65. Sugarberry-elm floodplain forests (Lower Rio Grande Valley)
Dominant species: *sugarberry, cedar elm, Mexican ash*
Understory species: *tepeguaje, anacua, Barbados cherry, granjeno, brasil, Texas persimmon, coma, snailseed, serjania vine, pigeonberry, Texas virgin's bower, violet ruellia*
Geographical note: *found along lower Rio Grande; possibly in decline due to flood control and diversion*

Edwards Plateau

72. Deciduous mesic canyon forests
Overstory species: *slippery elm, chinquapin oak, other hardwoods in sheltered stream canyons in southern plateau; bigtooth maple, chinquapin and other oak species in riparian stringers in Bandera and neighboring counties and Bell County*
Note: *limited distribution*

73. Limestone bluffs and seeps
Woody species: *Texas persimmon, Mexican buckeye*
Other species: *wand butterfly bush, cedar sage, shrubby boneset, sunflower goldeneye, Lindheimer rock daisy, lip fern, cliffbrake fern, mock orange and other endemic species, southern maidenhair, southern shield fern*
Note: *occurrences in exposed limestone streambeds and canyon bluffs*

75. Spring-fed streams (Edwards Plateau)
Herbaceous species: *sedges, switchgrass, big muhly, bushy bluestem, other graminoids on stream banks*

76a. Pecan-elm floodplain woodlands (Edwards Plateau)
Dominant species: *pecan, American elm, sugarberry, plateau live oak in floodplain; eastern cottonwood, sycamore, black willow along river banks*
Groundcover species: *Virginia wildrye and other grasses, caric sedges, Turk's cap, frostweed*
Geographical note: *examples occur along Guadalupe, Colorado, and South Llano rivers and other sites*

77. Streambeds
Dominant species: *sycamore, ash, willow, walnut, Roosevelt weed, buttonbush, switchgrass, busy bluestem, spike sedge, rushes*

Geographical note: *also found in frequently flooded or scoured limestone streambeds, washes and stream terraces in the Cross Timbers, adjacent areas of the Blackland Prairie and South Texas; species occurrence also along semi-perennial streams in the Rolling Plains and South Texas*

78. Bald cypress riparian woodlands
Dominant species: *bald cypress along frequently flooded perennial streams*
Associated species: *deciduous floodplain forests, oak-juniper woodlands on adjacent terraces*
Geographical note: *widespread on Guadalupe, Frio, Medina, Blanco, and Colorado rivers*

79. Netleaf hackberry-plateau live oak floodplain woodlands
Dominant overstory species: *netleaf hackberry, plateau live oak, pecan, little walnut, ash*
Understory species: *Texas persimmon, Texas mountain laurel, Mexican buckeye*
Associated species: *juniper and oak, mesquite, acacias in adjacent woodlands*
Geographical note: *found in western Edwards Plateau and South Texas west to Pecos River*

Prairies and Cross Timbers

76b. Pecan-elm floodplain woodlands (Cross Timbers)
Dominant species: *bur oak, elm, pecan, hackberry, western soapberry in floodplain in Cross Timbers; mesquite, little walnut, netleaf hackberry, brush species in Rolling Plains along Colorado River; eastern cottonwood, sycamore, black willow along river banks*
Groundcover species: *switchgrass, Torrey rush, western ragweed, smartweed species, warty spurge, plains coreopsis*

Rolling Plains

87. Mesquite floodplain brush
Woody species: *mesquite, western soapberry, netleaf hackberry*
Understory species: *skunkbush, littleleaf sumac, tasajillo, lotebush, saltbush species*
Geographical note: *found in small bottomlands and drainages in southern Rolling Plains; widespread saltcedar encroachment with resulting dominance*

88. Cottonwood-willow riparian woodlands
Woody species: *plains cottonwood, black willow, hackberry, sandbar willow, seep willow, western soapberry along streams and springs*
Groundcover species: *switchgrass, Indian grass, grama species, bluestem species, dropseed species, barnyardgrass, western wheatgrass, vine mesquite, non-native grasses in bottomlands*
Geographical note: *widespread saltcedar encroachment with resulting dominance; similar cottonwood and willow woodlands found along creeks, seeps and wet playas found in High Plains*

West Texas

95. Saline or alkaline wetlands
Associated species: *salt grass, sacaton, seepweed, prairie cordgrass in moist saline soils along stream drainages; Olney bulrush, sedge species, bordered sea lavender, puzzle sunflower(rare), clasping flaveria (rare) along perennial desert springs and creeks*
Geographical note: *limited occurrences in Panhandle and Trans-Pecos*

101. Mesquite thickets
Dominant species: *mesquite, acacia species, fourwing saltbush; saltcedar gaining dominance*
Associated species: *lotebush, creosotebush, knifeleaf condalia, weedy grasses and forbs; alkali sacaton in more saline conditions*

Geographical note: *found in low saline soils near streams, arroyos, and basins in floodplains of the Rio Grande and the Pecos River*

102. Cottonwood-willow riparian woodlands
Dominant species: *Arizona cottonwood, Rio Grande cottonwood, Gooding willow, willow species*
Associated species: *ash, mesquite, acacia, seep willow, desert willow, arrowweed, spiny aster, little walnut, Mexican buckeye, whitebrush*
Geographical note: *limited distribution in Trans-Pecos; non-native bermudagrass, giant reed, tree tobacco and other species encroaching along Rio Grande*

103. Arroyo scrub
Associated species: *desert willow, Apache plume, seep willow, Roosevelt weed, splitleaf brickellia, acacia, mesquite, althorn, catclaw mimosa, dalea, granjeno, burrobush, mariola, little walnut, stool, guayacan, spiny greasebush, netleaf hackberry in Trans-Pecos; whitebrush, desert willow, splitleaf brickellia in southwest Edwards Plateau drainages*
Geographical note: *found in and along arroyos, washes, sheet drainages*

108. Riparian shrublands
Woody species: *little walnut, desert willow, netleaf hackberry in intermittent streams; apache plume, splitleaf brickelia, seep willow, willow species, granjeno, acacia species, mesquite, ash species, whitebrush, agarito, scrub oak, Mexican buckeye, Texas persimmon, lotebush in dryer conditions*
Geographical note: *widespread in drainages of Trans-Pecos and western Edwards Plateau*

110. Spring-fed streams/cienegas
Associated species: *spikesedge, sawgrass, caric sedge, Torrey rush, western umbrella sedge, brookweed, water bentgrass in cienegas; prairie wedgegrass and other grasses on stream banks*
Note: *increasingly rare*

114. Canyon riparian woodlands
Associated species: *velvet ash, netleaf hackberry, oak species, little walnut, Mexican buckeye, granjeno, agarito, sumac, acacia, esperanza, scarlet bouvardia in canyon bottoms; occasional bigtooth maple; Apache plume, splitleaf brickelia, seep willow in streambeds*
Geographical note: *local occurrences in Big Bend National park and Big Bend Ranch State Park*

117. Deciduous canyon forest
Associated species: *gray oak, Gambel oak, Emory oak, alligator juniper, evergreen sumac, Texas madrone, beargrass, Arizona grape, other grass, sedge and forb species; occasional occurrence of bigtooth maple, chinquapin oak, western hophornbeam in Trans-Pecos*
Geographical note: *limited distribution in Davis, Chisos, Glass, Vieja, and Diable mountains impact vegetation in the riparian zone although the scope of such projects is to increase water flows.*

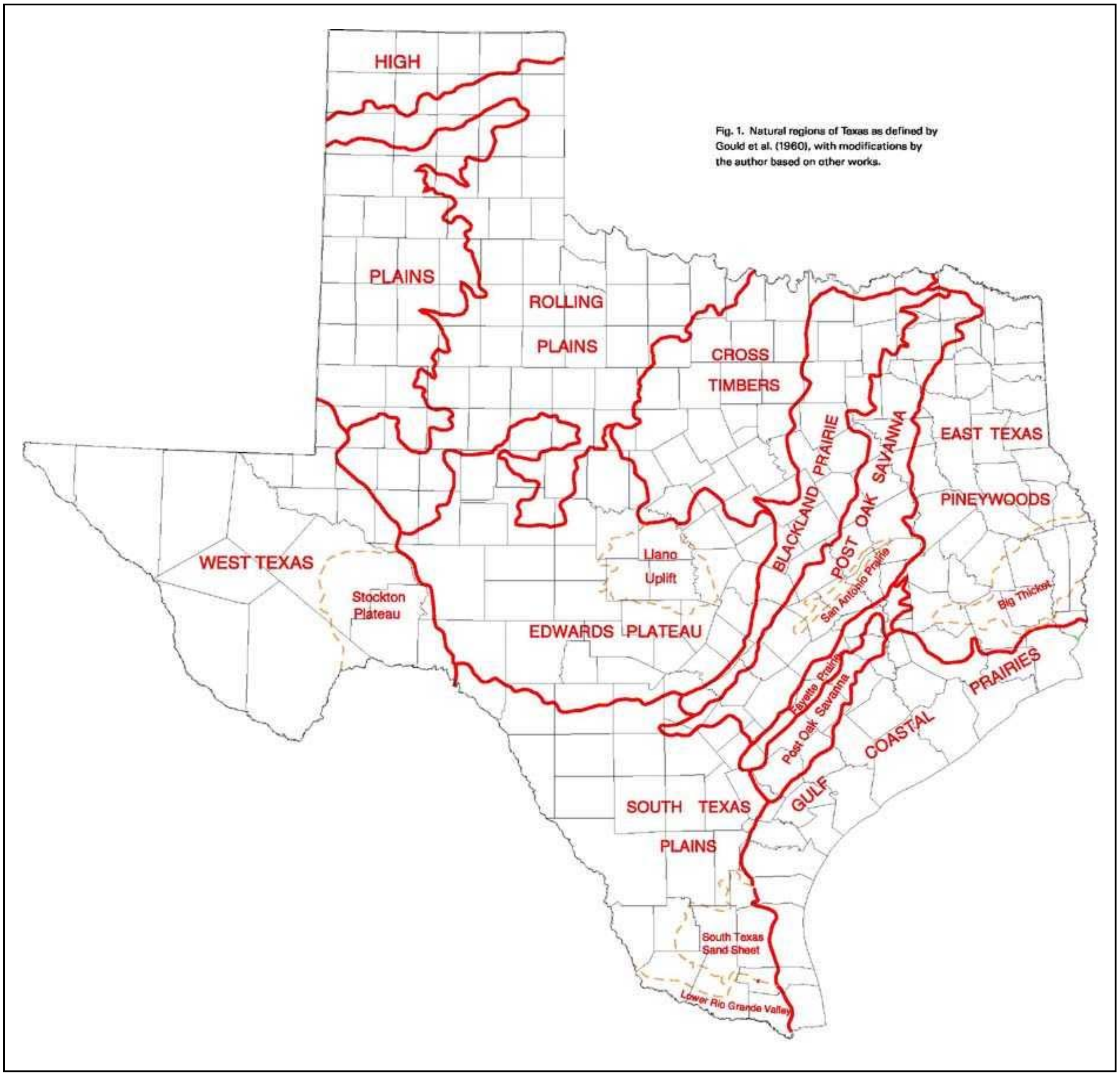

Figure 4. Natural Areas of Texas (Gould and others, 1960) with modifications by Bezanson from Bezanson (2000).

It is beyond the scope of the report to conduct a thorough review of all published studies and resources relating to riparian vegetation in Texas, but a brief mention of some regionalized studies may offer a glimpse of the effort required to compile a comprehensive overview. Watts (1998) mentions the paucity of studies and surveys of riparian vegetation or habitat along the Rio Grande from Elephant Butte to Fort Quitman, although extensive work has been done downstream in Big Bend National Park. Lonard and others (2000) report on riparian zone vegetation in two small sites along the Rio Grande in Starr and Cameron counties, and also lament the lack of previous research. Perhaps more representative of the research that may need to be investigated are the publication by Negrete and others (2002) reporting on vascular species of the Texas Gulf Coast, county reports of flora conducted by governmental agencies and universities (Neill, 2000; Singhurst and others, 2003), and botanical compendiums (Hatch and others, 1990). The level of information about riparian vegetation will vary significantly from source to source. Online resources about the vegetation species of Texas may be a helpful resource. Texas A&M University and the US Department of Agriculture host plant databases. Some sites include maps of geographic distribution by region or county. Others may have more limited geographical information. Such guides are generally organized by botanical taxonomy and do not group species by community or landscape feature, although the USDA Plants Database features a search by state and wetlands indicator status.

A1.3 Data Sources Appropriate for Improved Mapping of Riparian Vegetation in the State of Texas.

A number of new satellite and aerial sensors suitable for vegetation mapping have become available since the last state-wide mapping effort undertaken by TPWD in the late 1970s. In addition, the federal and state government have invested in the development of the National Spatial Data Infrastructure. Some of the resulting GIS data layers would significantly enhance riparian vegetation mapping. A list of available resources follows. A brief discussion of the data type, spatial and temporal resolution, availability and appropriate use is included.

Multispectral Remote Sensing Resources:

Multispectral sensors measure reflected light in the visible and shortwave portions of the electromagnetic spectrum. Satellite sensors image the earth from orbit. Most collect data from a pre-ordained path, but others are pointable and may be programmed to image a location from an off-nadir angle. Operational sensors collect data at predetermined times and places and usually guarantee repeat coverage of any given target area. Mission-specific and experimental sensors generally operate less frequently and may not provide complete coverage of a region. Generally, US government programs provide public domain data and data products at reasonable costs. Other government programs, notably the European, French, Indian and Canadian programs, view products as a commodity and may also restrict data use through licensing. Commercial for-profit operations generally collect data as specified by paying customers, and may not provide complete coverage of a region of interest, although most provide archive data at reduced costs.

Moderate-Resolution Imaging Spectroradiometer (MODIS)

Two MODIS sensors are in operation at present on board NASA's Terra and Aqua satellites. MODIS images the earth in wide swaths; two daytime passes over mid-latitude locations are common, one in mid-morning and another in the early afternoon. Good nadir acquisitions occur less frequently. MODIS collects data in the visible red and the near infrared channels, frequencies used to construct vegetation indices, at the approximate ground cell size of 250 m. Another five multispectral channels, ranging from the visible blue to the shortwave infrared, are collected at the ground cell size of 500 m. An additional 29 channels collect data designed for oceanographic and atmospheric applications at a resolution of 1000 m. MODIS data reside in the public domain and are distributed electronically by NASA and USGS at no cost. The University of Texas Center for Space Research (CSR) acquires the MODIS direct broadcast in near real time, and maintains a large archive for Texas, dating from the summer of 2000. MODIS data are too coarse spatially to effectively map riparian corridors in great detail. However, they provide a low-cost means to map environmental changes over time, and may prove useful for regional ecological mapping. It would be beneficial to attempt a Texas-centric land cover classification with MODIS time series data in conjunction with other geospatial data resources for comparison with the maps of Texas vegetation and ecoregions. More information about the MODIS sensor can be obtained from the NASA MODIS site at http://modis.gsfc.nasa.gov.

The Landsat Program

The Landsat Project, sponsored by the US government program and currently managed by the USGS, launched the first Landsat satellite in 1972. At present, two Landsat satellite sensors are in orbit and imaging the earth on an operational basis. Data collected by the Landsat instruments are a primary resource for regional vegetation mapping.

Landsat Thematic Mapper (TM)

Since July 1982, the Landsat 5 TM sensor has collected data along a 183-kilometer (115 mile) swath on a 16-day repeat cycle. The TM data sensor images the earth in seven multispectral bands. Six multispectral bands (1 to 5 and 7) are collected at 30 meter resolution, and one thermal infrared band (6) is collected at 120 meter resolution. CSR maintains a fairly extensive archive of Texas TM data. More information about Landsat 5 is available at: http://edc.usgs.gov/guides/landsat_tm.html.

Landsat Enhanced Thematic Mapper-Plus (ETM+)

The Landsat 7 ETM+ satellite was launched in April 1999 and collects data on a 16-day repeat cycle. The 183-kilometer (115 mile) swath width data are collected in eight bands. Six multispectral bands (1 to 5 and 7) are acquired at 30 meter resolution, one panchromatic band (8) at 10 meter resolution, and one thermal infrared band (6 and 9, the band is split based on gain differences) at 60 meter resolution. On May 31, 2003, Landsat 7 experienced a failure of the Scan Line Corrector (SLC), a device that accounts for the forward motion of the satellite. Although the satellite remains operational, the mechanical failure has restricted the acquisition of high quality data to an approximately 22-kilometer wide strip in the middle of the swath. CSR maintains a multi-date SLC-on archive of ETM+ data for all of Texas. Although a replacement for the ailing Landsat 7 has yet to be determined and Landsat 5 is not guaranteed to continue long-term data collection, it may be feasible to conduct a regional assessment of riparian vegetation in Texas using data from the CSR archive. The spatial resolution of the data will impede reliable identification of vegetation types in some parts of Texas, as is noted in the results of previous studies in the methodology section. For more information about SLC-off Landsat 7 data, including a sample image, see http://landsat.usgs.gov/slc_enhancements/slc_off_background.php. General information about Landsat 7 is available at: http://landsat.usgs.gov/.

Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)

ASTER is an experimental sensor developed in Japan. It resides on the same NASA Terra satellite as MODIS. ASTER data are publicly available. The sensor collects 14 bands of data with a swath width of 60 km (37 mi). The visible and near infrared bands (1 to 3) are collected at 15 meter resolution, the shortwave infrared bands (4 to 9) are collected at 30 meter resolution, and the thermal infrared bands (10 to 14) are collected at 90 meter resolution. A visible blue band is not collected. Because this sensor is experimental, data are not acquired on a regular repeat cycle. Much of Texas has been imaged, but no attempt has been made to collect cloud-free imagery for the entire State. CSR maintains an archive of ASTER data collected over Texas. The 15-meter ASTER data are of high quality, and should be exploited for mapping vegetation. However, it would be difficult to conduct more than a limited project because of the lack of seasonal repeat coverage. For more information about ASTER data, visit: http://asterweb.jpl.nasa.gov.

Satellite Pour l'Observation de la Terre (SPOT) 5

The French satellite SPOT 5 became operational in 2002 and follows in the same orbit as its predecessors: SPOT 1, SPOT 2, and SPOT 4. SPOT 5 is a mission-specific pointable satellite sensor with a swath width of 60 km (37 mi). SPOT 5 passes over the same area every 26 days but does not collect data on a continual basis. One panchromatic band is collected at 2.5 meter resolution, two visible bands (red and green) and one infrared band are collected at 10 meter resolution, and one shortwave infrared band is collected at 20 meter resolution. SPOT 5 data are distributed through the commercial vendor SpotImage. SPOT 5 data may be cost prohibitive for a statewide mapping project. Licensing restrictions impede data sharing. However, the pushbroom technology developed for the SPOT program yields data of a very high quality. Currently, the Texas Forest Service is working with SPOT 5 data to characterize fuel loads in East Texas. More SPOT 5 information is available at http://spot5.cnes.fr/gb/index2.htm.

SPOT Vegetation

The French SPOT VEGETATION instrument was first launched onboard the SPOT 4 satellite in 1998. At present, SPOT 5 carries an advanced version of the sensor called VEGETATION 2 that acquires data with a 2250-kilometer-wide swath. This sensor collects three spectral bands, two visible and one shortwave infrared, all at 1-kilometer resolution. These bands can be used for constructing vegetation indices. Additionally, VEGETATION 2 collects another band at 1-kilometer resolution in the visible range to correct atmospheric effects in the other three bands. Some SPOT VEGETATION products are freely available, although most require registration with the commercial vendor, SpotImage. SPOT Vegetation products, like those of MODIS, are likely too coarse for delineation of riparian features. However, they may be useful resources for vegetation mapping planning. More information about SPOT VEGETATION can be found at http://spot-vegetation.com/.

Indian Remote Sensing Satellite IRS-P6 (RESOURCESAT-1)

For the past two decades, the Indian national space agency has sponsored research into Landsat-style multispectral remote sensing satellites. Launched in 2003, the IRS-P6 RESOURCESAT-1 carries an Advanced Wide Field Sensor (AWiFS) that collects imagery in four spectral bands with a ground resolution of 56 m along a 740-kilometer swath. Three bands are collected in the visible and near infrared, while a fourth band records shortwave infrared radiation. The imagery from RESOURCESAT-1 may be particularly well-suited for studies of riparian vegetation because the wide image swath ensures a frequent repeat cycle of coverage, with the same surface location imaged every 4 to 5 days. The increased frequency of observations raises the chances that important phenological changes can be traced under relatively cloud-free conditions. RESOURCESAT-1 products are available through Antrix Corporation Ltd., the commercial distribution arm for IRS, which releases imagery of North America through their channel partner, Space Imaging (http://www.spaceimaging.com). For more information on RESOURCESAT-1 see: http://www.isro.org/pslve5/index.html.

Indian Remote Sensing Satellite IRS-P5 (CARTOSAT-1)

The IRS-P5 CARTOSAT-1, launched in the spring of 2005, is the first Indian Remote Sensing Satellite to collect high-resolution imagery comparable to that acquired by commercial high resolution satellites. Two panchromatic cameras collect imagery with a 2.5 meter ground resolution along a 30-kilometer swath. The dual panchromatic imaging system permits collection of stereographic imagery that can be used to extract surface elevation data from image pairs. CARTOSAT-1 may prove to be a source of economical, high-quality digital surface models for riparian environments. For more information on CARTOSAT-1 see: http://www.isro.org/Cartosat/Page3.htm.

High Resolution Satellite Sensors

Several high resolution satellite sensors collect multispectral data. Increased competition has lowered pricing, although not significantly. Licensing restrictions for governmental agencies have loosened in recent years to allow for mandated data sharing among cooperating organizations. Although current available sensors collect data in a limited number of multispectral channels, the increased bit depth afforded by the technology prevents data loss in areas of very high or low reflectance. It may be many years before it is feasible to conduct a statewide mapping project using high resolution satellite data as the sole image resource.

IKONOS

IKONOS is a high resolution commercial satellite put into orbit by Space Imaging in September 1999. This sensor acquires one band of panchromatic data at 1 meter resolution and four bands of spectral data at 4 meter resolution. The revisit time is every three days within a fairly wide collection angle window. Nadir repeat collections are infrequent. A typical IKONOS product covers a twelve by 12-kilometer extent. The data are costly and protected by copyright. Archival data can be obtained at a slightly reduced price but complete regional coverage most likely does not exist. IKONOS is a programmable, pointable sensor; consequently many images are collected at relatively high angles from nadir. A variety of IKONOS data products are available for purchase through Space Imaging and approved resellers. More information is available at: http://www.spaceimaging.com/products/ikonos/.

QuickBird

QuickBird is a high resolution pointable commercial satellite operated by DigitalGlobe. One panchromatic band is available at a resolution range of 61 to 72 cm (2 to 2.4 ft) and four spectral bands are available at a resolution range of 2.44 to 2.88 m (8 to 9.4 feet). An image footprint covers a square bounded by 16.5 km (10.3 mi) on all sides. The repeat cycle of QuickBird is approximately seven days for imagery 0 to 15 degrees off-nadir and four days for imagery 0 to 25 degrees off-nadir. Data can be ordered from archive or a collection can be specified. Imagery is available for purchase through DigitalGlobe. For more information on

QuickBird products, go to http://www.digitalglobe.com/product/product_docs.shtml and view the QuickBird Imagery Products FAQ.

Leica Geosystems ADS40 Aerial Sensor System

A by-product of research by the German space agency, Deutschen Zentrum für Luft- und Raumfahrt, the advanced ADS40 sensor produced by Leica Geosystems is the first digital aerial camera system capable of acquiring high-resolution (1-meter) imagery for large-scale projects, such as the 2004 statewide data collected for Texas by the National Aerial Agriculture Program. The ADS40 is comprised of a series of visible and near infrared line scanners that collect visible color imagery with one set of three detectors, false color infrared imagery with a second set and panchromatic imagery with two other detectors. For 1-meter image collection, the ADS40 is flown in pressurized aircraft at 27,000 feet to collect image data line-by-line across a 10.2 to kilometer swath. The digital data products generated by the ADS40 are captured in much greater radiometric depth than analog film photographs, allowing features to be discerned within shadows that would otherwise be opaque. Digital data collection with high radiometric fidelity permits the ADS40 data to be used with image classification techniques that were formerly restricted to applications with more costly satellite imagery. Future aerial sensors in the ADS40 category will be five-band common aperture systems in which three visible bands, plus a near infrared band and a shortwave infrared band, will be collected simultaneously. With the ADS40, multispectral, high-resolution imagery can be economically collected for the entire state of Texas, allowing much more frequent production of map-corrected orthoimagery of the state for use in change detection studies. Rapidly changing riparian environments could be documented in greater detail and accuracy than ever before. The ADS40 instrument was used in 2004 to image Texas with one-meter color infrared data for the USDA Farm Service Agency's (FSA) National Agricultural Imagery Program (NAIP).

Other Remote Sensing Resources:

Aerial LiDAR Systems

Aerial LiDAR detection of vegetation canopy height can be accomplished by calculating the elevation difference between the first- and last-return records of a laser pulse in which the first laser return indicates the top of the canopy and the last return represents the closest measurement to the ground surface. Different kinds of riparian vegetation, particularly gallery forests, exhibit a distinctive height profile across a floodplain that can be distinguished by LiDAR elevation data. Recent advances in LiDAR collection technology can capture many discrete reflections from each incident laser pulse in a process known as waveform digitization. The waveform data may be used to infer structural characteristics between different canopy types, such as needle-leafed versus broad-leafed trees. The return beam intensity recorded by some LiDAR instruments can also be used to discriminate different tree crown types and densities. The Bureau of Economic Geology and CSR co-own a LiDAR sensor that has been recently equipped with a wave form digitizer.

Aerial Interferometric Synthetic Aperture Radar (IFSAR) Systems

The latest generation of aerial radar terrain mapping systems incorporates P-Band radar frequencies that are capable of penetrating vegetation canopy and X-Band frequencies that are strongly reflected by the top of the canopy. As with aerial LiDAR data, the elevation differences between the P-Band and X-Band data can be used to profile changes in canopy height within riparian environments. Some systems, such as EarthData's GeoSAR sensor, also collect data from a profiling laser altimeter to provide more accurate calibration of the IFSAR data.

Hyperspectral Resources

Hyperspectral instruments are passive optical sensors that collect data in the visible and infrared electromagnetic spectrum. The most significant distinction between multispectral and hyperspectral imaging sensors is that the latter divide the electromagnetic spectrum, typically within the range from 400 to 2500 nm, into very thin slices, usually no wider than 10 nm, resulting in more than 200 channels of data. The basic premise is that the increased spectral resolution will mimic spectral signatures generated by scientific spectrometers, enabling better differentiation among the features imaged. Most hyperspectral instruments are flown on airplanes. The ground cell resolution varies from 2 to 20 m. Some of the more commonly used sensors for scientific research are the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS), the Compact Airborne Spectrographic Imager (CASI), the Hyperspectral Mapper (HyMap), and the Hyperspectral Digital Imagery Collection Experiment (HYDICE). NASA launched an experimental mission named EO-1 in 2000 that included a satellite hyperspectral sensor named Hyperion. Hyperion collects data along a very narrow track (7.5 m wide) in 220 10 nm channels. The ground cell resolution is 30 m. Once hyperspectral technology matures, it may become one of the best resources for operational vegetation mapping. At present, however, acquisition costs are high, band-to-band registration is challenging, and data arrays are overwhelming for current computer algorithms and processors.

Airborne Videography

Airborne videography systems have been touted as a rapid, low-cost means of data collection, particularly for linear mapping projects. Industry has adopted the technology for pipeline, road, and power line monitoring. In the past, the utility of videography was limited by the challenges of image rectification. At present, GPS technology can be incorporated into the data acquisition process to facilitate registration (Everitt and others, 2004). James H. Everitt, a range scientist at the USDA Kika De La Garza Agricultural Research Center in Weslaco, Texas, has conducted extensive work on the use of airborne videography for natural resources management. Airborne videography may be a useful resource for riparian corridor mapping, although its use for a statewide assessment project has not been attempted to date.

Other Geospatial Data Resources

Shuttle Radar Topography Mission (SRTM) and National Elevation Dataset (NED) Elevation Difference Data

The NASA SRTM collected elevation data for most of the global land surface during an 11-day mission in February 2002. The C-Band frequency used by the synthetic aperture radar of the SRTM cannot penetrate vegetation. Thus, the elevations derived from SRTM data produce a digital surface model that includes features of the ground surface, manmade structures, and the top of the vegetation canopy. The National Elevation Dataset is a seamless digital elevation model constructed from the information represented in the form of elevation contours and surveyed spot elevations on 1:24,000 scale U.S. Geological Survey topographic maps. The NED reflects the ground surface without structures and vegetation at the time of field surveying and aerial photography used to compile the topographic map. Subtracting the NED ground surface from the SRTM surface yields an elevation difference dataset that contains information about the relative heights of vegetation canopy across a landscape. Although uncertainties in the SRTM data limit the absolute measurement of tree crown heights within forest stands, different height classes of vegetation can be differentiated. For instance, within riparian environments, areas of dense, mature deciduous woodland can be separated from stands of younger trees and other vegetation.

National Elevation Dataset (NED)

The NED described in the previous paragraph profiles elevation at 30 meter intervals. The NED product has been completed for the entire continental US. A higher resolution dataset is in production at the USGS. A ten-meter product will be generated as funding and partnership opportunities allow. A significant portion of Texas has been completed to date. A status map sponsored by the NRCS is available at http://data4.ftw.nrcs.usda.gov/website. There may be a lag between NED 10-meter production and status map update. The higher resolution NED can be used to better model the riparian environment as the 30-meter product may omit critical information about floodplain structure. It can be used to enhance multispectral image classifications. All NED datasets reside in the public domain and are available through the USGS and other governmental agencies. Information about the NED is available from http://ned.usgs.gov.

National Hydrography Dataset (NHD)

The NHD is an important tool for modeling surface water features at relatively high spatial resolutions. The product is an enhanced version of the standard USGS Digital Line Graph hydrography data set. The NHD combines point, line, and polygon geographic features representing rivers, streams, lakes, wells and other standard hydrography classes with network information and the EPA Reach File Version 3 dataset. For Texas, the NHD is available at the 1:100,000 and 1:24:000 mapping resolutions. The larger scale data set was corrected to match the mid-1990s Digital Orthophoto Quarter Quadrangle framework dataset. Although there may be discrepancies between the NHD and actual riparian conditions, the dataset would be an asset for any local, regional or statewide riparian vegetation mapping effort. Additional information about the NHD is available from http://nhd.usgs.gov.

National Wetland Inventory (NWI) Digital Data and Hard Copy Maps

The NWI, a three-decade US Fish and Wildlife Service (USFWS) program, was undertaken to provide information about the status of wetland, riparian, deepwater and other aquatic habitat resources within the United States. A standard hierarchical classification system that subdivides wetland features into marine, estuarine, riverine, lacustrine, and palustrine systems is used for all products (Cowardin and others, 1979). NWI maps are compiled from high altitude color infrared photography collected through several national programs. The compilation methodology relies primarily on photo-interpretation techniques, not ground surveys. Compilation usually occurs once, as the program is funded piecemeal through partnerships and other similar mechanisms. Wetlands are one of the most rapidly transformed features on the landscape. Consequently, NWI map currency is problematic. Also, not all wetland features are mapped. Wetlands in agricultural production are omitted, as well as some prominent riparian features. A separate USFWS program is responsible for the mapping of riparian areas, but has not been implemented in Texas (USFWS, 1998). A recent NWI status map for Region 2 indicates that all of Texas has been mapped. Most of the state is available in 1:24,000 scale hard copy maps. The extent of NWI digital data for the State is limited to the Gulf Coast. From the 104^{th} to 106^{th} meridians and in some South Texas locations adjacent to the Gulf Coast, only small scale maps are available. Digital data photography for the NWI in Texas dates primarily from the 1990s, with limited areas dating from the 1980s. The currency of NWI hard copy maps for Texas is not indicated. The NWI is not a reliable source for the comprehensive identification of riparian features in the State, but it could provide a useful starting point, in conjunction with other data resources. One serious limitation is the dearth of digital data for Texas. Additional information about the NWI is available from http://wetlands.fws.gov.

A1.4 Methodologies Appropriate for Improved Mapping of Riparian Vegetation in the State of Texas.

Numerous publications describe vegetation mapping that rely on remote sensing resources, however, fewer are concerned with the identification of specific species or vegetation alliances. The sources cited herein primarily differentiate among a single riparian class and other general vegetation cover types.

Sohn and Qi (2005) mapped biotic communities in southeastern Arizona using a single Landsat ETM+ scene acquired in 2000. Their classification schema included a riparian gallery, a vegetation community of willows and cottonwoods found in narrow perennial and intermittent stream channels. However, the riparian class demonstrated a very low producer's accuracy in relation to other desert biotic communities. The authors attributed the poor classification performance to the narrowness of the riparian corridor, typically only one or two trees deep along either side of the channel. Dowling and Accad (2003) estimated vegetation height classes within the riparian zone of an Australian river using LiDAR data and an automated classification regime but report that manual interpretation was necessary in order to calculate canopy cover and to determine species composition. Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) data have been investigated as a resource for improved riparian and wetlands vegetation mapping. Neuenschwander and others (1998) report on the successful discrimination of spectrally similar wetlands species in Florida. Almeida and de Souza Filho (2004) mapped riparian forests, grasslands and crops in Brazil. Neither AVIRIS study focused exclusively on distinguishing among different riparian vegetation communities. Everitt and others (2004) identified giant reed along the Rio Grande in three Texas locations. The project methodology included videography capture, color infrared photographs and spectra measurements of giant reed, common reed, honey mesquite, sunflower, bermudagrass and other herbaceous species. Aerial videography integrated with GPS was deemed to be a cost–effective way to image a long riparian corridor. Scanned color infrared photography, ground reflectance measurements and an unsupervised classification process were used for a riparian study in South Texas (Everitt and others, 2002). Soil, water and several dominant vegetation types were identified. Another South Texas study identified dominant overstory, understory, and ground cover species in the riparian zone of the Rio Grande using ground transects and large scale color infrared photography (Lonard and others, 2000).

Congalton and others (2002) also investigated the use of color infrared photography for riparian vegetation mapping in a project that compared classification results generated from Landsat TM data with those based on higher spatial resolution photography. The study found large discrepancies between the classification results, with class agreement ranging from 25 to

36 percent. The methodology for the classification of the color infrared photography featured a combination of photointerpretation and GIS analysis. A vector representation of hydrography was co-registered with scanned color infrared photography, and a buffer was generated around the stream centerline. A dynamic segmentation technique utilized more commonly in transportation applications was used to quickly divide features in the buffer area into several pre-determined vegetation types. An unspecified unsupervised-supervised hybrid classification was applied to the TM data. Seven general riparian vegetation types were identified in both classifications. The authors suggest that high resolution satellite imagery may be useful for riparian mapping and that coarser spatial resolution TM and ETM+ data are not suitable for mapping the inherently linear features of the riparian environment or for defining structural components. In an earlier publication, Muller (1997) comes to a similar conclusion. He submits that a ground cell spatial resolution of no greater than 10 m is required for riparian vegetation applications.

Muller also emphasizes the need to select a suitable classification scheme that can be implemented using available geospatial resources and algorithms. The riparian environment is inherently a dynamic one, particular in Texas where land use conversion and frequent flash flooding contribute to rapid changes to floodplain vegetation. Such conditions lead to heterogeneous vegetation distributions that may not conform to desired ecological associations, as noted by the map authors of the Vegetation Types of Texas. A workshop designed by the US Army Corps of Engineers (1994) includes a discussion of possible classification schemes for riparian areas, distinct from other accepted schemes for wetlands and other hydrographical features. Proposed national and regional schemes, several of which have been adapted for use in the arid Southwest, should be reviewed prior to the commencement of a major mapping project. USFWS (1998) has developed a system based on photointerpretation techniques for the western United States, including most of Texas, that complements the existing NWI system. The classification scheme divides riparian systems into lotic and lentic subsystems that are further subdivided into forested or scrub-schrub deciduous, evergreen, or mixed subclasses or an emergent class. Dominant species are indicated. Many are found in Texas, although some species associations may be more appropriate for the State than others.

Based on the findings of the map product and literature review conducted for the current project, and ongoing research at CSR, a general approach to mapping riparian vegetation in Texas is proposed. The primary constituents of the program would be data resources that are currently available:

- ADS40 color infrared imagery collected under the auspices of the NAIP program, augmented where available with concurrent visible color imagery acquired from the vendor for other governmental programs,
- SRTM-NED difference data,
- digital NHD, NED and NWI data, at appropriate mapping resolutions, and
- additional geospatial resources, such as the Level IV Ecoregions of Texas, supplemented by field data where available.

The NAIP imagery would provide the necessary framework for class identification. The elevation difference data would be used to enhance classification and interpretation procedures. NHD data, supplemented by 10-meter NED and available NWI digital data, could be used to reduce the number of image tiles required for the project, by identifying the quarter quads that potentially contain riparian features. Buffers of appropriate extent would be generated from the NHD data, further reducing the area requiring review.

Figures 5 and 6 demonstrate how the interpretation of high resolution NAIP imagery can be enhanced with information derived from SRTM-NED difference data. Figure 5 shows the Nueces River as it traverses San Patricio and Nueces counties. Figure 6 covers the same map extent at a coarser resolution but provides information about canopy structure that is not immediately evident in the NAIP product.

A successful program would also require extensive field verification data and a practical classification scheme. Ideally, more than one complete NAIP acquisition for Texas would be used, and climatic conditions prior to acquisition would be recorded. Since the NAIP will be collected at frequent intervals, annually if current FSA plans are maintained, such a goal may be attainable. One of the shortcomings of the NWI mapping program was the reliance on single date aerial imagery and photointerpretation by people who were not familiar with conditions in the field. Although the computer automation of the classification process is desirable, a semi-automated methodology that incorporates image processing and GIS techniques may yield more accurate results.

Figure 5. Example of one-meter color infrared AD40 imagery collected in 2004 for the USDA National Agricultural Imagery Program. Note the contrast in vegetation appearance near the banks of the Nueces River with areas in the surrounding agricultural fields and scrubland. The imagery is not shown at full resolution.

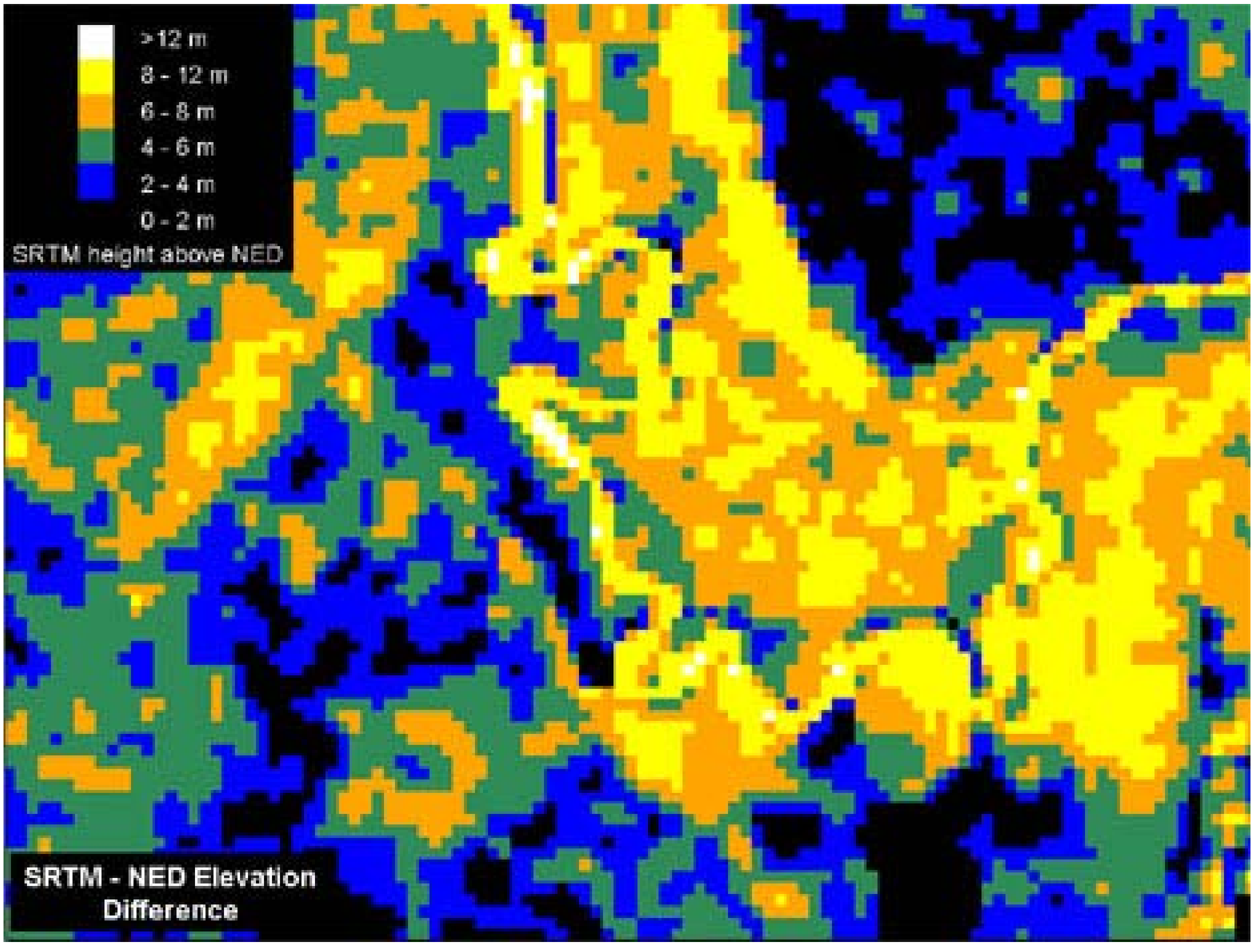

Figure 6. An illustration of relative canopy heights as calculated form the difference between Shuttle Radar Topography Mission elevation data and National Elevation Dataset bare earth elevation data for the same extent depicted in Figure 4. Heights model conditions present in early 2000.

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Online Resources

A Checklist of the Vascular Plants of Texas, Texas A&M University

http://www.csdl.tamu.edu/FLORA/taes/tracy/regecoNF.html

Biology of the Rio Grande Border Region: A Bibliography

http://www.cerc.cr.usgs.gov/pubs/riogrande/woody.HTM

Texas Endemics: Distribution of all endemics, Texas A&M University

http://www.csdl.tamu.edu/FLORA/cgi/endemics_map_page2?all=yes

(Note: click on link to All Endemics to get to a list of plants, which in turn leads to maps of species distribution)

Texas Native Trees, Texas A&M University

http://aggie-horticulture.tamu.edu/ornamentals/natives/tamuhort.html

USDA Plants Database, Natural Resources Conservation Service
http://plants.usda.gov/index.html

Appendix 2

Evapotranspiration Database

ET Rate (mm/yr)	Year(s)	Notes	Location	Technique Used	Vegetation Type	*Precip (mm/yr)	Reference
Crops							
690	1998	ET	Gediz River Basin, Turkey, near Menemen	Hargreaves 1985 equation	Cotton (irrigated)	535	Allen, 2000
770	1998	PET	Gediz River Basin, Turkey, near Menemen	Eto (Penman-Monteith)	Cotton (irrigated)	535	Allen, 2000
790	1998	PET	Gediz River Basin, Turkey, near Menemen	Eto (Hargreaves)	Grapes (irrigated)	535	Allen, 2000
880	1998	PET	Gediz River Basin, Turkey, near Menemen	Eto (Penman-Monteith)	Grapes (irrigated)	535	Allen, 2000
1020	1998	PET	Gediz River Basin, Turkey, near Menemen	Eto (Hargreaves)	Peach orchards (irrigated)	535	Allen, 2000
1160	1998	PET	Gediz River Basin, Turkey, near Menemen	Eto (Penman-Monteith)	Peach orchards (irrigated)	535	Allen, 2000
730	1998	PET	Menemen, Turkey, cotton field	Eto (Hargreaves)	Cotton (irrigated)	535	Allen, 2000
800	1998	PET	Menemen, Turkey, cotton field	Eto (Penman-Monteith)	Cotton (irrigated)	535	Allen, 2000
885	1998	PET	Menemen, Turkey, cotton field	Eto (Blaney-Criddle)	Cotton (irrigated)	535	Beyazgul et al., 2000
816	1998	PET	Menemen, Turkey, cotton field	Eto (Penman modified)	Cotton (irrigated)	535	Beyazgul et al., 2000
794	1998	PET	Menemen, Turkey, cotton field	Eto (Radiation)	Cotton (irrigated)	535	Beyazgul et al., 2000
697	1998	PET	Menemen, Turkey, cotton field	Eto (Penman-Monteith)	Cotton (irrigated)	535	Beyazgul et al., 2000
736	1998	PET	Menemen, Turkey, cotton field	Eto (Hargreaves)	Cotton (irrigated)	535	Beyazgul et al., 2000
715	1998	PET	Menemen, Turkey, cotton field	Eto (Pan)	Cotton (irrigated)	535	Beyazgul et al., 2000
554	1985 to 1989	ET	Tyne Basin, England	Model (physically based)	Arable	752	Dunn & Mackay, 1995
*1040	1976 to 1980	ET	Safford, AZ, Field H @ Univ. of AZ	Soil salinity relation to ET	Cotton (irrigated)	NP	Matthias et al., 1986
*1060	1976 to 1980	PET	Safford, AZ, Field H @ Univ. of AZ	Eto (Blaney-Criddle)	Cotton (irrigated)	NP	Matthias et al., 1986
*2150	1976 to 1980	ET	Safford, AZ, Field H @ Univ. of AZ	Pan	Cotton (irrigated)	NP	Matthias et al., 1986
600	1970	ET	near Treynor, IA, research watersheds	Lysimeter	Corn	NP	Saxton et al., 1974
544	1944 to 1955	ET	Coshocton, OH	Lysimeter	Corn (irrigated)	NP	van Bavel, 1961
1750	1980 to 1982	PET	Pecos River floodplain, NM	Jensen-Haise equation	Alfalfa	NP	Weeks et al., 1987
1825	1990 to 1993	ET	Murray Basin, NSW, Australia, Griffith Laboratory	Penman–Monteith	Alfalfa (irrigated)	90	Zhang et al., 1999
3650	1990 to 1993	PET	Murray Basin, NSW, Australia, Griffith Laboratory	Penman–Monteith	Alfalfa (irrigated)	90	Zhang et al., 1999
Riparian							
1300	1998	PET	Gediz River Basin, Turkey, near Menemen	Eto (Hargreaves)	Trees (riverine)	535	Allen, 2000

ET Rate (mm/yr)	Year(s)	Notes	Location	Technique Used	Vegetation Type	*Precip (mm/yr)	Reference
Riparian							
1470	1998	PET	Gediz River Basin, Turkey, near Menemen	Eto (Penman-Monteith)	Trees (riverine)	535	Allen, 2000
408	1988 to 1990	ET	Pasco County, FL	Eddy covariance	Cypress	1378	Bidlake et al., 1996
970	1988 to 1990	ET	Pasco County, FL	Eddy covariance Bowen ratio	Cypress	1378	Bidlake et al., 1996
1540	1988 to 1990	ET	Pasco County, FL	Eddy covariance energy balance residual	Cypress	1378	Bidlake et al., 1996
720	1988 to 1990	ET	Sarasota County, FL	Eddy covariance	Marsh mix	1378	Bidlake et al., 1996
990	1988 to 1990	ET	Sarasota County, FL	Eddy covariance Bowen ratio	Marsh mix	1378	Bidlake et al., 1996
1180	1988 to 1990	ET	Sarasota County, FL	Eddy covariance (residual)	Marsh mix	1378	Bidlake et al., 1996
1030	2000	ET	Middle Rio Grande, NM, Belen	Eddy covariance	Cottonwood (flooded)	194	Cleverly pers. com., 2005b
1522	2000	PET	Middle Rio Grande, NM, Belen	Eddy covariance	Cottonwood (flooded)	194	Cleverly, 2005a
1080	2001	ET	Middle Rio Grande, NM, Belen	Eddy covariance	Cottonwood (flooded)	117	Cleverly pers. com., 2005b
1588	2001	PET	Middle Rio Grande, NM, Belen	Eddy covariance	Cottonwood (flooded)	117	Cleverly, 2005a
960	2002	ET	Middle Rio Grande, NM, Belen	Eddy covariance	Cottonwood (flooded)	200	Cleverly pers. com., 2005b
1273	2002	PET	Middle Rio Grande, NM, Belen	Eddy covariance	Cottonwood (flooded)	200	Cleverly, 2005a
1270	2003	ET	Middle Rio Grande, NM, Belen	Eddy covariance	Cottonwood (flooded)	168	Cleverly pers. com., 2005b
1634	2003	PET	Middle Rio Grande, NM, Belen	Eddy covariance	Cottonwood (flooded)	168	Cleverly, 2005a
1340	2000	ET	Middle Rio Grande, NM, Albuquerque	Eddy covariance	Cottonwood (unflooded)	157	Cleverly pers. com., 2005b
1555	2000	PET	Middle Rio Grande, NM, Albuquerque	Eddy covariance	Cottonwood (unflooded)	157	Cleverly, 2005a
1260	2001	ET	Middle Rio Grande, NM, Albuquerque	Eddy covariance	Cottonwood (unflooded)	111	Cleverly pers. com., 2005b
1521	2001	PET	Middle Rio Grande, NM, Albuquerque	Eddy covariance	Cottonwood (unflooded)	111	Cleverly, 2005a
1280	2002	ET	Middle Rio Grande, NM, Albuquerque	Eddy covariance	Cottonwood (unflooded)	76	Cleverly pers. com., 2005b
1283	2002	PET	Middle Rio Grande, NM, Albuquerque	Eddy covariance	Cottonwood (unflooded)	76	Cleverly, 2005a
1250	2003	ET	Middle Rio Grande, NM, Albuquerque	Eddy covariance	Cottonwood (unflooded)	72	Cleverly pers. com., 2005b
1321	2003	PET	Middle Rio Grande, NM, Albuquerque	Eddy covariance	Cottonwood (unflooded)	72	Cleverly, 2005a
1150	2004	ET	Middle Rio Grande, NM, Albuquerque	Eddy covariance	Cottonwood (unflooded)	61	Cleverly pers. com., 2005b
855	2004	PET	Middle Rio Grande, NM, La Joya	Eddy covariance	Cottonwood (unflooded)	61	Cleverly, 2005a

ET Rate (mm/yr)	Year(s)	Notes	Location	Technique Used	Vegetation Type	*Precip (mm/yr)	Reference
Riparian							
1080	2003	ET	Middle Rio Grande, NM, La Joya	Eddy covariance	Russian Olive (flooded)	102	Cleverly pers. com., 2005b
1362	2003	PET	Middle Rio Grande, NM, La Joya	Eddy covariance	Russian Olive (flooded)	102	Cleverly, 2005a
1150	2004	ET	Middle Rio Grande, NM, La Joya	Eddy covariance	Russian Olive (flooded)	149	Cleverly pers. com., 2005b
1262	2004	PET	Middle Rio Grande, NM, La Joya	Eddy covariance	Russian Olive (flooded)	149	Cleverly, 2005a
*1220	1999	ET	Middle Rio Grande, NM, Bosque del Appache	Eddy covariance	Saltcedar (flooded)	NP	Cleverly pers. com., 2005b
1190	2000	ET	Middle Rio Grande, NM, Bosque del Appache	Eddy covariance	Saltcedar (flooded)	200	Cleverly pers. com., 2005b
1034	2000	PET	Middle Rio Grande, NM, Bosque del Appache	Eddy covariance	Saltcedar (flooded)	200	Cleverly, 2005a
1160	2001	ET	Middle Rio Grande, NM, Bosque del Appache	Eddy covariance	Saltcedar (flooded)	105	Cleverly pers. com., 2005b
1675	2001	PET	Middle Rio Grande, NM, Bosque del Appache	Eddy covariance	Saltcedar (flooded)	105	Cleverly, 2005a
880	2002	ET	Middle Rio Grande, NM, Bosque del Appache	Eddy covariance	Saltcedar (flooded)	135	Cleverly pers. com., 2005b
1009	2002	PET	Middle Rio Grande, NM, Bosque del Appache	Eddy covariance	Saltcedar (flooded)	135	Cleverly, 2005a
1020	2003	ET	Middle Rio Grande, NM, Bosque del Appache	Eddy covariance	Saltcedar (flooded)	108	Cleverly pers. com., 2005b
1836	2003	PET	Middle Rio Grande, NM, Bosque del Appache	Eddy covariance	Saltcedar (flooded)	108	Cleverly, 2005a
1150	2004	ET	Middle Rio Grande, NM, Bosque del Appache	Eddy covariance	Saltcedar (flooded)	148	Cleverly pers. com., 2005b
1234	2004	PET	Middle Rio Grande, NM, Bosque del Appache	Eddy covariance	Saltcedar (flooded)	148	Cleverly, 2005a
*740	1999	ET	Middle Rio Grande, NM, Sevilleta	Eddy covariance	Saltcedar (unflooded)	NP	Cleverly pers. com., 2005b
870	2000	ET	Middle Rio Grande, NM, Sevilleta	Eddy covariance	Saltcedar (unflooded)	167	Cleverly pers. com., 2005b
809	2000	PET	Middle Rio Grande, NM, Sevilleta	Eddy covariance	Saltcedar (unflooded)	167	Cleverly, 2005a
840	2001	ET	Middle Rio Grande, NM, Sevilleta	Eddy covariance	Saltcedar (unflooded)	114	Cleverly pers. com., 2005b
1706	2001	PET	Middle Rio Grande, NM, Sevilleta	Eddy covariance	Saltcedar (unflooded)	114	Cleverly, 2005a
720	2002	ET	Middle Rio Grande, NM, Sevilleta	Eddy covariance	Saltcedar (unflooded)	159	Cleverly pers. com., 2005b
1446	2002	PET	Middle Rio Grande, NM, Sevilleta	Eddy covariance	Saltcedar (unflooded)	159	Cleverly, 2005a
700	2003	ET	Middle Rio Grande, NM, Sevilleta	Eddy covariance	Saltcedar (unflooded)	102	Cleverly pers. com., 2005b
1834	2003	PET	Middle Rio Grande, NM, Sevilleta	Eddy covariance	Saltcedar (unflooded)	102	Cleverly, 2005a

ET Rate (mm/yr)	Year(s)	Notes	Location	Technique Used	Vegetation Type	*Precip (mm/yr)	Reference
Riparian							
810	2004	ET	Middle Rio Grande, NM, Sevilleta	Eddy covariance	Saltcedar (unflooded)	182	Cleverly pers. com., 2005b
1740	2004	PET	Middle Rio Grande, NM, Sevilleta	Eddy covariance	Saltcedar (unflooded)	182	Cleverly, 2005a
1090	1963 to 1971	GW ET	Graham County, AZ, Gila River flood plain	Water budget	Saltcedar & mesquite (average)	305	Culler et al., 1982
1420	1963 to 1971	ET	Graham County, AZ, Gila River flood plain	Water budget	Saltcedar & mesquite (dense)	305	Culler et al., 1982
980	2000	ET	Belen, NM	Eddy covariance	Cottonwood	260	Dahm et al., 2002
1230	2000	ET	South Valley, NM	Eddy covariance	Cottonwood	290	Dahm et al., 2002
1220	1999	GW ET	Bosque del Appache, NM	Eddy covariance	Saltcedar	200	Dahm et al., 2002
1110	2000	GW ET	Bosque del Appache, NM	Eddy covariance	Saltcedar	200	Dahm et al., 2002
740	1999	GW ET	Sevilleta, NM	Eddy covariance	Saltcedar	230	Dahm et al., 2002
760	2000	GW ET	Sevilleta, NM	Eddy covariance	Saltcedar	230	Dahm et al., 2002
750 to 1450	1996	ET	Virgin River, NV	Bowen ratio	Saltcedar	100	Devitt et al., 1998
800 to 855	1984	ET	Owens Valley, CA, site A, 1984	Eddy covariance (residual)	Sacaton & thistle	160	Duell, 1990
802 to 838	1984	ET	Owens Valley, CA, site J, 1984	Eddy covariance (residual)	Saltbush, sacaton, & rabbitbrush	80	Duell, 1990
596 to 616	1984	ET	Owens Valley, CA, site E, 1984	Eddy covariance (residual)	Rabbitbrush, sacaton, & mormon tea	120	Duell, 1990
301 to 316	1984	ET	Owens Valley, CA, site F, 1984	Bowen ratio	Saltgrass & greasewood	120	Duell, 1990
378 to 442	1984	ET	Owens Valley, CA, site C, 1984	Bowen ratio	Saltgrass & rabbitbrush	160	Duell, 1990
841 to 975	1984	ET	Owens Valley, CA, site L, 1984	Bowen ratio	Saltgrass, sacaton, & rush	80	Duell, 1990
580 to 672	1984	ET	Owens Valley, CA, site G, 1984	Eddy covariance (residual)	Saltgrass, sacaton, & rabbitbrush	120	Duell, 1990
266	1987 to 1988	GW ET	near Perth, Western Australia	Ventilated chamber	Wetland vegetation	747	Farrington et al., 1990
1118	1943 to 1944	GW ET	Safford Valley, AZ, Gila River	Water table flux	Baccharis	171	Gatewood et al., 1950
1003	1943 to 1944	GW ET	Safford Valley, AZ, Gila River	Water table flux	Cottonwood	171	Gatewood et al., 1950
826	1943 to 1944	GW ET	Safford Valley, AZ, Gila River	Water table flux	Mesquite	171	Gatewood et al., 1950
1839	1943 to 1944	GW ET	Safford Valley, AZ, Gila River	Water table flux	Saltcedar	171	Gatewood et al., 1950

ET Rate (mm/yr)	Year(s)	Notes	Location	Technique Used	Vegetation Type	*Precip (mm/yr)	Reference
Riparian							
*1637	1980 to 1981	ET	Colorado River floodplain, CA, near Blythe	Bowen ratio	Saltcedar	79	Gay & Hartman., 1982
280 to 450	1931 to 1971	ET	San Carlos Reservoir, AZ	Pan evaporation	Saltcedar	352	Kipple, 1977
183	NP	GW ET	Ash Meadows, NV	Bowen ratio	Saltgrass	94	Laczniak et al., 1999
747	1994	GW ET	Ash Meadows, NV, Rogers Spring 1	Bowen ratio	Saltgrass	28	Nichols et al., 1997
768	1994	GW ET	Ash Meadows, NV, Rogers Spring 2	Bowen ratio	Saltgrass & wiregrass	28	Nichols et al., 1997
*375	1997	ET	San Pedro River, AZ, Lewis Springs site	Bowen ratio	Mesquite	247	Scott et al., 2000
*330	1997	ET	San Pedro River, AZ, Lewis Springs site	Bowen ratio	Mesquite	247	Scott et al., 2005
157	1997	GW ET	San Pedro River, AZ, Lewis Springs site	Precip. excess	Mesquite	247	Scott et al., 2005
*272	1997	ET	San Pedro River, AZ, Lewis Springs site	Bowen ratio	Sacaton grassland	247	Scott et al., 2000
*1151	2001	PET	San Pedro River, AZ, Charleston site	Penman Monteith	Mesquite	358	Scott et al., 2004
*744	2001	ET	San Pedro River, AZ, Charleston site	Eddy covariance	Mesquite	358	Scott et al., 2004
*488	2001	GW ET	San Pedro River, AZ, Charleston site	Precip. excess	Mesquite	358	Scott et al., 2004
*1175	2002	PET	San Pedro River, AZ, Charleston site	Penman Monteith	Mesquite	358	Scott et al., 2004
*645	2002	ET	San Pedro River, AZ, Charleston site	Eddy covariance	Mesquite	358	Scott et al., 2004
*394	2002	GW ET	San Pedro River, AZ, Charleston site	Precip. excess	Mesquite	358	Scott et al., 2004
*676	2003	ET	San Pedro River, AZ, Charleston site	Eddy covariance	Mesquite	358	Scott et al., 2004
*510	2003	GW ET	San Pedro River, AZ, Charleston site	Precip. excess	Mesquite	358	Scott et al., 2005
*966	2003	GW ET	San Pedro River, AZ, Lewis Springs site	Sap flux	Cottonwood-Willow (Perennial)	NP	Scott et al., 2005
*410	2003	GW ET	San Pedro River, AZ, Boquillas site	Sap flux	Cottonwood-Willow (Intermittent)	NP	Scott et al., 2005
531 to 754	1966, 1968 & 1969	ET	Arkansas River floodplain, CO, Lamar site	Model (groundwater)	Cottonwood & saltcedar	269	Weeks & Sorey, 1973
183 to 259	1966, 1968 & 1969	GW ET	Arkansas River floodplain, CO, Lamar site	Model (groundwater)	Cottonwood & saltcedar	269	Weeks & Sorey, 1973
668 to 737	1666 & 1968	ET	Arkansas River floodplain, CO, Las Animas	Model (groundwater)	Cottonwood & saltcedar	173	Weeks & Sorey, 1973
434 to 465	1666 & 1968	GW ET	Arkansas River floodplain, CO, Las Animas	Model (groundwater)	Cottonwood & saltcedar	173	Weeks & Sorey, 1973
94	1968	GW ET	Arkansas River floodplain, CO, Holly site	Water table flux	Saltgrass	277	Weeks & Sorey, 1973
600	1980 to 1982	ET	Pecos River floodplain, NM	Eddy covariance	Saltcedar	NP	Weeks et al., 1987
770 to 1070	1980 to 1982	ET	Pecos River floodplain, NM	Eddy covariance (residual)	Saltcedar	NP	Weeks et al., 1987
400	1980 to 1982	ET	Pecos River floodplain, NM	Eddy covariance	Weeds & sacaton	NP	Weeks et al., 1987

ET Rate (mm/yr)	Year(s)	Notes	Location	Technique Used	Vegetation Type	*Precip (mm/yr)	Reference
Riparian							
570 to 670	1980 to 1982	ET	Pecos River floodplain, NM	Eddy covariance (residual)	Weeds & sacaton	NP	Weeks et al., 1987
Trees							
820	1988 to 1990	ET	Sarasota County, FL	Eddy covariance	Palmetto & myrtle	1378	Bidlake et al., 1996
1010	1988 to 1990	ET	Sarasota County, FL	Eddy covariance Bowen ratio	Palmetto & myrtle	1378	Bidlake et al., 1996
1180	1988 to 1990	ET	Sarasota County, FL	Eddy covariance (residual)	Palmetto & myrtle	1378	Bidlake et al., 1996
815	1988 to 1990	ET	Sarasota County, FL	Eddy covariance	Pine, palmetto, & myrtle	1378	Bidlake et al., 1996
780	1988 to 1990	ET	Sarasota County, FL	Eddy covariance Bowen ratio	Pine, palmetto, & myrtle	1378	Bidlake et al., 1996
1060	1988 to 1990	ET	Sarasota County, FL	Eddy covariance (residual)	Pine, palmetto, & myrtle	1378	Bidlake et al., 1996
495	1991 to 1995	ET	Uvalde County, TX, Seco Creek watershed	Bowen ratio	Juniper	723	Dugas et al., 1998
633	1985 to 1989	ET	Tyne Basin, England	Penman-Monteith & Rutter	Deciduous	752	Dunn & Mackay, 1995
766	1985 to 1989	ET	Tyne Basin, England	Penman-Monteith & Rutter	Evergreen	752	Dunn & Mackay, 1995
1300	1992 to 2001	ET	Toronto, Canada, Oak Ridges moraine	Energy & water balances (EALCO)	Forest	900	Simic et al., 2004
Shrubs							
488	1963 to 1971	ET	Graham County, AZ, Gila River floodplain	Water budget	Understory (average)	305	Culler et al., 1982
360 to 660	1963 to 1971	ET	Graham County, AZ, Gila River floodplain	Water budget	Understory (increasing density)	305	Culler et al., 1982
411	1985 to 1989	ET	Tyne Basin, England	Model (physically based)	Bracken	752	Dunn & Mackay, 1995
473	1985 to 1989	ET	Tyne Basin, England	Model (physically based)	Heather	752	Dunn & Mackay, 1995
338 to 376	1990 & 1993	ET	Reynolds Creek Experimental Watershed, ID	Model (SHAW)	Sagebrush/grasses	448	Flerchinger et al., 1996
537	1990 & 1993	ET	Reynolds Creek Experimental Watershed, ID	Model (SHAW)	Sagebrush/snowberry	553	Flerchinger et al., 1996
638	1986 to 1987	GW ET	Great Salt Lake, UT, Ranch site	Bowen ratio	Grass & shrubs	126	Malek et al., 1990
1565	1986 to 1987	PET	Great Salt Lake, UT, Ranch site	Bowen ratio	Grass & shrubs	126	Malek et al., 1990

ET Rate (mm/yr)	Year(s)	Notes	Location	Technique Used	Vegetation Type	*Precip (mm/yr)	Reference
Shrubs							
1095 to 1825	1989 to 1993	GW ET	Cottonwood Lake wetlands, ND	Water table flux	Canada thistle	NP	Rosenberry & Winter, 1997
259	NP	ET	near Tucson, AZ, Sonoran desert site	Lysimeter	Creosote bush	234	Sammis et al., 1979
242	NP	ET	near Tucson, AZ, Sonoran desert site	Water budget	Creosote bush	234	Sammis et al., 1979
100 to 1000	NP	ET	Owens Valley, CA	Remote sensing	Saltbush scrub, sagebrush, & meadow	100 to 1000	Smith et al, 1990
Grasses							
870	1998	ET	Gediz River Basin, Turkey, near Menemen	Eto (Hargreaves)	Pasture	535	Allen, 2000
940	1998	ET	Gediz River Basin, Turkey, near Menemen	Eto (Penman-Monteith)	Pasture	535	Allen, 2000
787	1985 to 1989	ET	Tyne Basin, England	Model (physically based)	Grass	752	Dunn & Mackay, 1995
648	1982 to 1984	ET	Sheffield site, IL	Bowen ratio	Brome grass, clover, alfalfa	938	Healy et al., 1989
626	1982 to 1984	ET	Sheffield site, IL	Aerodynamic profile	Brome grass, clover, alfalfa	938	Healy et al., 1989
655	1982 to 1984	ET	Sheffield site, IL	Water budget	Brome grass, clover, alfalfa	938	Healy et al., 1989
876	1982 to 1984	PET	Sheffield, IL, waste disposal site	Penman	Brome grass, clover, alfalfa	938	Healy et al., 1989
615	1970	ET	near Treynor, IA, research watersheds	Lysimeter	Brome grass	NP	Saxton et al., 1974
787	2000 to 2002	ET	near Floral City, FL, Ferris Farms	Eddy covariance	Pasture	1360	Sumner & Jacobs, 2005
475	1944 to 1955	ET	Coshocton, OH	Lysimeter	Brome grass, clover, alfalfa	NP	van Bavel, 1961
566	1944 to 1955	ET	Coshocton, OH	Lysimeter	Meadow	NP	van Bavel, 1961
876	1950 to 1953	ET	Seabrook, NJ	Lysimeter	Grass & clover	NP	van Bavel, 1961
Soils							
630	1963 to 1971	E	Graham County, AZ, Gila River floodplain	Water budget	Bare soil & some plants	305	Culler et al., 1982
231	1985 to 1989	E	Tyne Basin, England	Modeling (physically based)	Bare soil	752	Dunn & Mackay, 1995
229	1986 to 1987	E	Pilot Valley, UT, Playa site	Bowen ratio	Salt-covered soil	127	Malek et al., 1990
1543	1986 to 1987	PET	Pilot Valley, UT, Playa site	Bowen ratio	Salt-covered soil	127	Malek et al., 1990

ET Rate (mm/yr)	Year(s)	Notes	Location	Technique Used	Vegetation Type	*Precip (mm/yr)	Reference
Soils							
46	1985	E	Railroad Valley, NV, Duckwater area	Bowen ratio	Playa/bare soil	NP	Nichols, 2000
46	1985	E	Railroad Valley, NV, Lockes area	Bowen ratio	Playa/bare soil	NP	Nichols, 2000
46	1985	E	Upper Fish Lake Valley, NV	Bowen ratio	Playa/bare soil	NP	Nichols, 2000
229	NP	E	near Tucson, AZ, Sonoran desert site	Lysimeter	Bare soil	234	Sammis et al., 1979
Open Water							
2621	NP	E	Ash Meadows, NV	Bowen ratio	Open water	94	Laczniak et al., 1999
*1156	2003	PET	San Pedro River, AZ, Lewis Springs site	Pan evaporation	Open water	NP	Scott et al., 2005

GW = groundwater
NP = not published in the text
*ET rates reflect the growing season rate rather than the true annual rate
Note: Some values are estimated from information given in the text or other references at the same location

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Appendix 3

Responses to review comments for “Evapotranspiration Estimates with Emphasis on Groundwater Evapotranspiration in Texas” draft report for TWDB Contract No. 2004-483-535

<u>Sections</u>

We have reviewed the draft report and found it to be interesting and informative. However, the electronic GIS database of ET throughout Texas has not been submitted. According to the original application

Subtask 1e:”Information on ET rates will be compiled in a GIS database.”

Also,

Task 3 “As an end product, the GAM developer will be provided with a relational database which will provide groundwater ET rates that can be used in the GAM program.”

Response: A database of ET rates was compiled from the literature as described in subtask 1a in the proposal and a GIS coverage of the locations of these ET studies is provided on CD . There is almost no information on ET in the literature for Texas; therefore, a simplified distribution of ET was developed based on PET and crop coefficients (Section 4.4 of Report).

We have reviewed the deliverables and report and our comments are listed below.

I. The following comments are related to specific project deliverables listed in the SOQ.

Subtask 1e in the SOQ lists project deliverables:

“1. provide ET estimates to be used directly by TWDB staff”
Usable ET estimates should be in the form of spatial electronic data (GIS) showing the distribution of ET at best available scales. Methodologies for doing this are well described in the report, and a GIS coverage of PET and is provided, but the usable product was not delivered.

Response: The database of ET rates for different vegetation types compiled from the literature can be used to guide GAM modelers in developing best estimates of ET rates for areas being simulated under the GAM program. A statewide coverage of EVTmax was developed based on PET and vegetation coefficients (Section 4.4 of Report).

“Unnumbered. Project information will be compiled into a GIS database”
Although pieces of GIS data are included with the report, a comprehensive GIS database was not delivered. An acceptable GIS database would include spatial data on vegetation, climate, and measured ET rates related to tabular data of ET estimates (PET and groundwater ET) using the methodologies described in the report. Spatial relationships would also be developed among ET estimates, soil textures, rooting depths, and parameters usable in the MODFLOW ET package.

The report and electronic data do provide many of the pieces of a GIS database, although in an unrelated state. There is a state-wide map (raster) of ETo and the implication that ETo is equal to PET. Section 4 and related electronic data provide vegetation coefficients (Kc). PET and Kc can be used to estimate actual ET. A GIS of vegetation distribution is included (GAP study), and we are told where to go to get soil type spatial data (STATSGO). Rooting depth data are provided in Excel and Access tables.

Response: A GIS database of EVTmax was provided based on PET and crop coefficients for Texas (Section 4.4 of Report).

In summary
1. Please include data from the following tables and figures in electronic format:
(see contract section VIII B)

- ET GIS database with metadata.

Response: A GIS distribution of EVTmax calculated from PET and crop coefficients (Section 4.4 of Report). A database of ET rates is provided in the report as described in subtask 1a of the proposal and the location of these studies is included in a GIS coverage.

- Appendix 2 database of ET rates (database or spreadsheet format).

Response: Appendix 2 database of ET rates (database or spreadsheet format).

<u>II. Report comments.</u>

Front Matter

2. Please seal final report with appropriate geoscientist(s) seal(s) as required by Texas state law.

Abstract

3. Executive Summary missing. Please either add executive summary or revise and rename "Abstract" to comply with contract Section VIII. Reports, subsection B requirements.

Response: Executive Summary is included in revised report

4. Page 1, line 1: Please spell out evapotranspiration (ET) the first time it is used.

Response: done

5. Page 1, line 11: Please add "the" to (the) San Pedro River and (the) Rio Grande.

Response: done

1.0 Introduction

6. Page 2, paragraph 2, line 5: Please use standard citation (Editor, Year) for Merriam Webster Dictionary and include it in the references.

Response: done

7. Page 2, paragraph 2, line 7: on first use of Groundwater Availability Models please follow with the acronym (GAMs). Then it is ok to use the acronym from there on.

Response: done

1.1 Water Resources

8. Page 2, equation 1: last term change in storage, gw should be a superscript to be consistent with other terms. Please update.

Response: corrected

9. Page 2, equation 2: next to last term superscript on flux (Q) should be gw not tw. Please update.

Response: corrected

2.1 Techniques for Estimating Evapotranspiration

10. Page 5: The FAO Penman-Monteith equation is equation (7) [not (5)]. Please correct.

Response: corrected

11. Page 6: Equation (9), please verify the equation. There may be a constant missing in the denominator.

Response: parenthesis was missing and was added.

12. Page 9: Please include Figure 2.1.

Response: included Figure 2.1

13. Figure 2.1, page 9: Suggest plotting same vegetation types, such as saltcedar, in sequence.

Response: done

2.2 Summary of Database Results

14. Per the contract, the report shall include the Scope of Work, however final draft report appears to be missing Scope of Work section 'Subtask 1e. Document the results of the study including the literature review'. Please reference Subtask 1e in report, possibly in Section 2.2 or add conclusion section to the report (as required in Contract Section VIII. Reports, subsection B requirements) and summarize accordingly.

Response: added Scope of Work Section in Introduction section

15. Section 2.2, pages 8-9: Suggest plotting other relationships such as ET versus technique used to estimate ET (how different are the various techniques when estimating ET for the same vegetation type) or ET versus location, such as latitude or longitude (how do the results using the same ET technique on the same plant type vary spatially? Possibly cross-reference to Section 2.4

and related figures) Does literature discuss findings of any correlation or relationship to soil types, plant maturity, plant density, or depth to water table?

Response: ET versus technique used to estimate ET was plotted and is included in the revised report. Locations of literature studies are included in GIS . Relationships between ET and plant density and depth to water table are described in section 3.

2.3 Task 1b. Evaluate Conceptual Models of ET Processes in Different Settings

16. Request for Qualifications required a description of the relative importance of saturated zone water (groundwater) versus unsaturated zone water for major phreatophyte species. Please include in report or clarify where in the report this is addressed. Please clarify if this was to be described in Section 2.3 on scaling issues or discussed elsewhere in the report.

Response: This material is included in Section 2.2 Summary of Database Results and we have added reference to this to Section 2.3 Task 1b.

2.4 Develop Conceptual Models of ET Processes in Different Settings

17. Section 2.2, page 8 suggests ET is not correlated with precipitation yet Section 2.4, on page suggests it is inversely proportional to precipitation. Please clarify in the appropriate section.

Response: We included the following statement to clarify the differences:
Although ET rates are not correlated with precipitation (Fig. 2.2), reference crop ET (equivalent to PET) is inversely proportional to precipitation and decreases from west to east in Texas.

18. Figure 2.6, Pages 17 and 18: Please include figure and caption on the same page.

Response: done

3.0 Relate ET Rates to Vegetation Parameters

19. Task 2 Scope of Work states Task 2 will review different remote sensing approaches for classifying phreatophytic vegetation and determine if these approaches can be applied in Texas. Please either describe remote sensing approaches for classifying phreatophytic vegetation in Texas in Section 3.0 or cross-reference to other sections of the report that address this.

Response: remote sensing approaches are described in Appendix 1. This material was developed under a separate contract with Texas Commission on Environmental Quality.

20. Section 3.5, pages 20 to 21, describes one study for measuring ET in the Edwards-Plateau region of Texas. Please clarify if this approach is applicable to other parts of Texas with different geology and vegetation types.

Response: We included a statement indicating that these micrometeorological approaches could be used throughout Texas.

21. Task 2 Scope of Work states Task 2 will provide information on rooting characteristics of different vegetation types collated relative to extinction depths for ET. Please update Section 3.0 with this information, explain in more detail, or cross-reference to other sections of the report that address this.

Response: We included a statement in section 3.6 that general information on rooting characteristics relative to extinction depths in MODFLOW models are described in Section 4.

22. Task 2 Scope of Work states Task 2 will attempt to obtain information on the degree to which rooting depths of different vegetation can vary in response to declining water tables.

Response: This information is provided in Section 3.6 in the revised report.

23. Page 18: Please spell out state names rather than using initials throughout the report.

Response: done

24. Page 19, paragraph 2: please spell out state names.

Response: done

25. Page 19, paragraph 2, last line: What does Table 1 refer to? Please clarify.

Response: Reference should have been to Appendix 1 rather than Table 1. This has been corrected.

26. Page 19, paragraph 3: please spell out Leaf Area Index (LAI) following acronym in parentheses on first use. Also, if possible, please briefly define Leaf Area Index.

Response: done

27. Page 19, paragraphs 2 and 3: Please use “to” rather than a dash to indicate a range of numbers. For example, use 0.7 to 1.2 m/y rather than 0.7 – 1.2 m/y.

Response: corrected

28. Page 19, paragraph 3, second to last line: Please add a comma at the end of the line “ ,….. range (between 1 and 1.6), …”

Response: done

29. Page 20, paragraph 2, line 2: Please change Table 1, to Table 2.1.

Response: Table 1 has been changed to Appendix 2.

4.2 Review of ET Simulations in MODFLOW

30. Page 21, bottom of page: Please move table caption and headings to the next page with the table.

Response: no longer relevant as formatting has changed due to other revisions

31. Page 22, paragraph 1, line 1: Please change The Queen City … to The Queen City and Sparta ….

Response: done

32. Section 4.2.1, page 22: We currently have 19 GAMs in Texas. Text references 23. Note: the Queen City/Sparta GAMs supersede the original Carrizo-Wilcox GAMs. Please either re-word this sentence to reference 22 models developed under the GAM program or state we currently have 19 GAMs.

Response: Initially our count included minor aquifers that had been modeled with larger aquifers. '23 GAMs' was changed to '19 GAMs' (no longer counting the minor aquifers that had been modeled with majors). Similarly, in the next sentence '15' was changed to '10'.

33. Beach et al., 2004a and 2004b are cited in reverse order in references than how it was cited in the text.

Response: corrected

4.3.4 Estimating the Necessary Parameters

34. Page 35, Figure 4.7: Please correct the following plot labels, saltcedar (not calt cedar), pecan (not pecan2000).

Response: corrected

35. Page 25, Lists ' 4.2 Guidance for Application to GAMs' should be updated to '4.3 Guidance for Application to GAMs'.

Response: corrected

36. Scope of Work Task 3 stated the report would include documentation of how other regional groundwater flow models have incorporated groundwater ET into their models and if sensitivity analyses were included in their studies with respect to ET. Table 4.1 documents how GAMs incorporated groundwater ET into the models, however sensitivity analysis was not addressed. Please update report with this information or explain why this was not included.

Response: done

37. Section 4.3.4, page 30: References Figure 2.3, which lists location of PET stations in Texas not the average annual PET values. Please review and clarify if meant to reference Figure 2.4 (long-term annual grass reference crop evapotranspiration) or if a figure showing average annual PET in Texas should be added and update accordingly.

Response: In table 4.1 a column was added that states whether a sensitivity analysis was performed with ET.

38. Subsection ‘Soil Types’, page 32: Please correct acronym ‘STATGO’ to ‘STATSGO’.

Response: Changed text to refer to Figure 2.4.

39. Table 4.4, page 34: Please add references cited in the table to the Reference Section.

Response: done

40. Figure 3.9 on page 39, please update to Figure 4.9 in caption and Table of Contents. Also please reference source in caption.

Response: corrected

41. Scope of Work Task 3 stated GAM developer will be provided with a relational database which will provide groundwater ET rates that can be used in the GAM program and scaling issues related to the regional GAMs will be evaluated. Please expand this section to discuss relational database, GIS deliverables, and scaling issues.

Response: GIS coverage of ETmax derived and discussed in section 4.4. Scaling issues also addressed in this section. Relational database part of deliverables for Task 2 and is discussed in the appropriate section.

Conclusions (missing)

42. Per contract Section VIII. Reports, subsection B, the report will include conclusion and recommendation sections. Please update the report with these sections.

Response: Conclusion section is included in revised report.

43. Per contract Section VIII. Reports, subsection B, suggest, at a minimum, the electronic copies of any computer programs, the GIS database of evapotranspiration rates, maps, or models along with an operations manual and any sample data set(s) developed under the terms of this contract be referenced in the report and summarized, possibly in an Appendix.

Response: GIS database of PET and GAP vegetation are included.

References

44. General: Please list all names for references rather than using et al. abbreviation.

Response: done

45. Bastiaanssen et al., 1998: Please distinguish these two references with a and b designations.

Response: done

46. Heywood, C.E. and R.M., Y., 2002: Please spell out Yager.

Response: done

47. R.W. Harden and Associates, 2004: Please list authors names, Bené, J., Harden, B., O'Rourke, D., and Donnelly, A. rather than the company name.

Response: done

48. The following references are missing, please include:

Pockman et al., unpublished
Changed reference to Jackson and others.
Heilman, J. and K. McInnes, TAMU, M. Litvak, UT (unpublished data)
The above two are unpublished data.
McElrone et al., unpublished
Changed reference to Jackson and others.
Cleverly, personal communication, 2005
Included this in reference
Dahm et al., 2000
There is no Dahm et al., 2000
Duell, 1990
This reference is in Appendix 2.
Huff, 2005
Included this reference
Scanlon and Healy, 2002
Changed Scanlon and Healy to Scanlon and others (2002)
Jensen et al., 1990
Changed to Jensen, 1990
Evett et al., 2000 (Is this really Evett, 2000?) Please verify and update.
This was changed to Evett, 2000
Cohen and Fuchs, 1981 (Is this really Cohen, Fuchs, and Green, 1981?) Please verify and update.
Cohen and Fuchs was changed to Cohen and others
NRC, 2005
Included this reference

Appendix 1

49. This appendix is very informative; however, it's not clear why it has been included as an appendix to this report. Was this work done as part of this project? If so the authors' names should be listed on the front of the report.

Response: This work was developed for a TCEQ contract and I have indicated this in the text.

50. Table of Contents: Section numbers should be A1.1, A1.2 etc. Please update.

Response: done

51. Figure 4, page A1.2-10. Caption: Should be "Natural areas of Texas" Not "National Areas" Also please remove the Figure caption at the upper right of the figure if possible.

Response: We corrected the caption but could not modify the figure.

Appendix 2

52. Please submit an electronic copy of this database.

Response: an electronic copy of the database is now included.

53. Please make sure headings coincide with the beginning of a page in the final report.

Response: done

54. Please provide guidance on how the growing season rates can be converted to annual rates. To apply these data for GAMs we need annual rates.

Response: there is no information in the literature that we could find on how to convert growing season rates to annual rates. ET during nongrowing season is low but there is no general correction available to convert between these two timescales. We provided a brief discussion on comparisons based on discussions with Dr. Russ Scott in 2.0 Task 1a section which shows that nongrowing season ET is generally equivalent to precipitation during the nongrowing season.

References for Appendix 2.

55. The following references are missing:

Leenhouts et al., 2005
Snyder, personal communication, 1989

Response : Leenhouts et al., 2005 was changed to Scott et al., 2005-12-21 Snyder reference was deleted.

56. Please do not use the abbreviation et al., in the references. Please list the complete set of names.

Response: done

<u>III. Editorial comments</u>:

57. Page iii, Table of Contents: Please indent text for section 3.3 to match heading 2 alignments. Please review and adjust page numbers listed in Table of Contents to correctly match corresponding pages in report. Please adjust space between heading '4.2' and 'Guidance…" and change numbering from '4.2' to '4.3'. Please update Table of Contents to include heading 3 and heading 4 level sections referenced in report.

Response: done

58. Page iv, List of Tables: Please verify correct page numbers are listed, for example, Table 4.1 is found on page 22 instead of page 21.

Response: done

59. Please use same font on all page numbers listed in report.

Response: done

60. Section 1.1, page 2: Suggest updating first sentence from '…(21 million in 2000 to 40 million in 2050)(Texas Water Development Board, 2002)' to '…(21 million in 2000 to 40 million in 2050: TWDB, 2002)' or '…growth: 21 million in 2000 to 40 million in 2050 (TWDB, 2002)', since Reference section lists this citation as 'TWDB'.

Response: changed

61. Multiple sentences throughout report include strings of items in parentheses. Suggest restructuring sentences.

Response: done

62. Prefer using 'and others' instead of 'et al.' when citing more than two authors in text.

Response: done

63. Please use consistent fonts in tables, for example tables 4.7, 4.8, and 4.9.

Response: done

64. Section 3.1, page 19, first paragraph. Please spell out et cetera and delete '…' at end of the second sentence.

Response: done

65. Please do not abbreviate states, ‘vs’, or ‘e.g.’ in Section 3.0 subsections.

Response: done

66. Please use the word ‘to’ instead of ‘- ‘when listing ranges throughout the report.

Response: done

67. Section 4.2.1, page 22: Please use ‘percent’ instead of the symbol ‘%’.

Response: done

68. Section 4.3.4, subsection Vegetation Distributions, page 31: please use ‘that is, that is to say, or in other words’ instead of ‘i.e.’ abbreviation.

Response: done

69. Subsection ‘Vegetation Distributions’, page 30: Please include reference for ‘GAP study’ and spell out TPWD before using the abbreviation.

Response: done

70. Subsection ‘Soil Types’, page 32: Please spell out SCS before using the abbreviation.

Response: done

71. Please consistently spell ‘saltcedar’ as one word throughout report (see pages 33 and 37).

Response: done