Protocol for Controlling Contaminated Groundwater by Phytostabilization

December 2001

Prepared for:
Air Force Center for Environmental Excellence
Technology Transfer Division
(AFCEE/ERT)
3207 North Road
Brooks AFB, TX 78235-5363

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Preface

This document guides Air Force Remedial Project Managers (RPMs) through the steps leading to design and implementation of phytostabilization to control groundwater movement at a site. Each step is discussed in the context of the information that RPMs will need to manage the project. The decisions required to determine whether phytostabilization is feasible are presented as a screening tool to aid in the decision-making process. The principal sections of this document address the following:

- An overview of phytoremediation in it various forms
- A description of phytostabilization
- The technologies and science behind phytostabilization
- Site selection and screening
- Design and implementation
- Operation, maintenance, and monitoring
- Technical appendixes to aid the RPM.

This document is intended to provide informative and practical guidance on the design of phytostabilization for an Air Force site. In most cases, the RPM will be overseeing the work of one or more contractors who will perform the field investigation, design the needed facilities, install the remediation, and provide long-term maintenance and monitoring. References are provided for those wanting more detailed information about design and installation.

Table of Contents

List of Figures

List of Tables

1 Introduction

The Air Force is responsible for a number of sites with water-soluble contamination in the vadose zone or in the groundwater. The contamination at many of these sites is confined by natural conditions to a relatively shallow depth below the ground surface (0 to 30 feet maximum, depending upon site characteristics). The contaminants may be transported by water both within the vadose zone and the shallow groundwater. In many cases the contaminants are naturally biodegradable but the rate of degradation and retardation is not sufficient to prevent continued migration into uncontaminated areas.

Contaminants sometimes migrate into deeper aquifers. This protocol does not address contaminants found in deep or confined aquifers. The focus here is restricted to remediation of the numerous, shallow water table sites.

Many shallow groundwater bodies are thin in profile, contain a limited amount of water, and have low hydraulic conductivity. As a result, water may move slowly and yields from extraction wells may be very small. Several methods are currently employed to remediate these shallow groundwater bodies, including: soil vapor extraction, bioventing, biodegradation, flow barriers, *in situ* passive treatment walls, and groundwater removal for treatment by horizontal or vertical wells or by drains. These methods are costly and rely on relatively homogeneous subsurface conditions and high hydraulic conductivity. These methods may fail to capture a groundwater contamination plume because of low extraction well yields or subsurface heterogeneity, or may require such a long duration of remediation effort as to make the method impractical. The Air Force needs more effective and less costly remediation methods that do not require homogeneous aquifers and high hydraulic conductivity.

Growing plants have been successfully used to remediate several types of contaminated sites. The technologies that utilize growing plants are known collectively as phytoremediation. One or more phytoremediation methods may be promising as the means to remediate shallow groundwater bodies at a particular site. There are numerous definitions of the field of phytoremediation and its sub-fields. This protocol follows the definitions found in *The Phytoremediation Resource Guide* [1] published by the U.S. Environmental Protection Agency (EPA), which are summarized below.

1.1 Phytoremediation’s Many Forms

Phytoremediation is a general term applied to the use of plants to remediate contaminated sites. However, there are significant differences in the way in which plants may be used. The contaminants and local conditions will determine which sub-field of phytoremediation is appropriate for a particular site.

The EPA describes phytoremediation as *“ ¼ the direct use of living plants for* in situ *remediation of contaminated soil, sludges, sediments, and ground water through contaminant removal, degradation, or containment. Growing and, in some cases, harvesting plants on a contaminated site as a remediation method is an aesthetically pleasing, solar-energy driven, passive technique that can be used to clean up sites with shallow, low to moderate levels of contamination. This technique can be used along with, or in some cases,* *in place of mechanical cleanup methods. Phytoremediation can be used to clean up metals, pesticides, solvents, explosives, crude oil, polycyclic aromatic hydrocarbons, and landfill leachates."* [1].

The definitions below generally follow those used by the EPA and are presented here to guide the discussion in this protocol. The prefix *phyto* means *plant* or *to grow.* The prefix *rhizo* means *root* and in the context of phytoremediation means *contact with plant roots.* The sub-fields of phytoremediation may be defined as follows:

- **Phytostabilization** is the use of selected plant species to immobilize contaminants in the soil and/or groundwater. It may be accomplished through use of plants to remove groundwater from the capillary fringe at a rate sufficient to stabilize movement of near-surface groundwater. Other mechanisms for phytostabilization include absorption and accumulation by roots, adsorption on the surface of roots and precipitation of chemicals within the root zone.
- **Phytoextraction**, also called phytoaccumulation, refers to the uptake by plant roots of contaminants from the soil or soil water and translocation into plant parts, preferably aboveground portions of the plant. Phytoextraction is usually associated with metal contaminants. Plants called hyperaccumulators absorb large amounts of metals in comparison to other plants. A single plant species or a combination of plant species is selected, based on the type of metals present and/or other site conditions, and planted at the site. The plants may be harvested and either incinerated or composted to recycle the metals. The procedure is repeated as required to bring soil contaminant concentrations down to allowable limits. Though the ash or compost derived from the plant material must be properly disposed, its volume is generally much less than that of the contaminated soil.
- **Rhizofiltration** is the adsorption or precipitation onto plant roots or absorption into the roots of contaminants that are in solution surrounding the root zone. The plants used for cleanup are grown in hydroponic culture in greenhouses or in a similar system where their roots are grown in the contaminated water and not in soil. As the roots or other plant parts become saturated with contaminants, they are harvested and either incinerated or composted to recycle the contaminants or are otherwise disposed in a protective manner.
- **Phytodegradation**, also called phytotransformation, is the breakdown through metabolic processes within the plants of contaminants that have been taken up by the plants, or the breakdown of contaminants external to the plants through the effect of compounds (e.g., enzymes) produced by the plants. Contaminants are degraded, incorporated into the plant tissues, and used as nutrients.
- **Rhizodegradation** is also called enhanced rhizosphere biodegradation, phytostimulation, or plant-assisted bioremediation/degradation. It is the breakdown of contaminants within the soil through microbial activity that is enhanced by the growth of yeast, fungi, or bacteria on natural substances released into the soil by plant roots (e.g., sugars, alcohols, and acids). The organic carbon in the released materials provides food for soil microorganisms that may also biodegrade the contaminants as they consume the plant-produced material.

- **Phytovolatilization** is the uptake by plants of contaminants that are, in turn, released in vapor form into the atmosphere from the plant. The contaminant may be modified chemically within the plant before release into the atmosphere.

The focus of this protocol is phytostabilization restricted to the use of plants to remove groundwater at a rate sufficient to stabilize movement of near-surface groundwater. Phytostabilization as discussed in this protocol may be used to supplement or replace pump-and-treat systems, infiltration barriers, soil vapor extraction systems, horizontal wells used as drains, drains placed in trenches, groundwater barrier walls, or treatment walls.

The reader should note that this protocol is an evolving document because phytostabilization is a new and rapidly developing field. The Air Force is conducting field tests that are likely to yield new information that may modify procedures in the protocol. This document will provide the Air Force Remediation project Manager (RPM) with the basic framework for evaluating the feasibility of phytostabilization and to oversee the work of contractors designing and implementing phytostabilization at Air Force sites.

1.2 Contents and Use of This Protocol

This protocol is organized into six main sections including this introduction. Section 2 presents an overview of phytostabilization and a discussion of its advantages and disadvantages. Section 3 describes the science and technologies necessary to design and implement a successful phytostabilization project. Section 4 provides a discussion of site selection and a decision support tool to guide the RPM in determining the feasibility of phytostabilization for their site. Section 5 describes the steps that should be followed by the contractor designing and implementing the project. Section 6 outlines the operations, monitoring, and maintenance requirements for the installed phytostabilization system. Extensive references are provided along with supplemental materials in the appendixes. A glossary, which includes agricultural terms, and a table of acronyms are included in the appendixes to aid the reader’s understanding of the text.

If used for project planning and implementation the entire document will be useful, but an emphasis should be placed on the material in Section 3 (Technology for Planning and Implementation). Section 4 (Preliminary Site Screening) may be used to make a quick estimate of the potential for phytostabilization before committing substantial funds for a complete evaluation.

2 Phytostabilization

This protocol is intended to explain the principles that govern the use of phytostabilization to withdraw sufficient groundwater to control the lateral movement of contaminants in the shallow groundwater. Phytostabilization is the use of plants to immobilize contaminants in the soil or to control groundwater movement. Figure 1 shows the concept with a cross-section of a typical phytostabilization site. Mechanisms for phytostabilization include absorption and accumulation by roots, precipitation of chemicals within the root zone, and control of water movement in shallow groundwater by extraction with plants (use of plants in lieu of or in support of extraction wells or physical barriers). Phytostabilization may lower the water table sufficiently to reduce or control vertical movement of contaminants downward into deep aquifers. The intention is to control contaminant movement until natural attenuation or other processes can reduce contaminant concentrations to meet remediation requirements.

This document focuses on phytostabilization as it is used to remove groundwater from the capillary fringe at a rate sufficient to stabilize movement of near-surface groundwater. The goal of a phytostabilization effort is to stabilize a contaminated plume and to assist in complete remediation at the site. Cleanup goals for remediating a dissolved phase contaminant plume are not likely to be achieved, however, if the source of the contamination is not remediated or contained. As with other site remediation efforts, phytostabilization requires

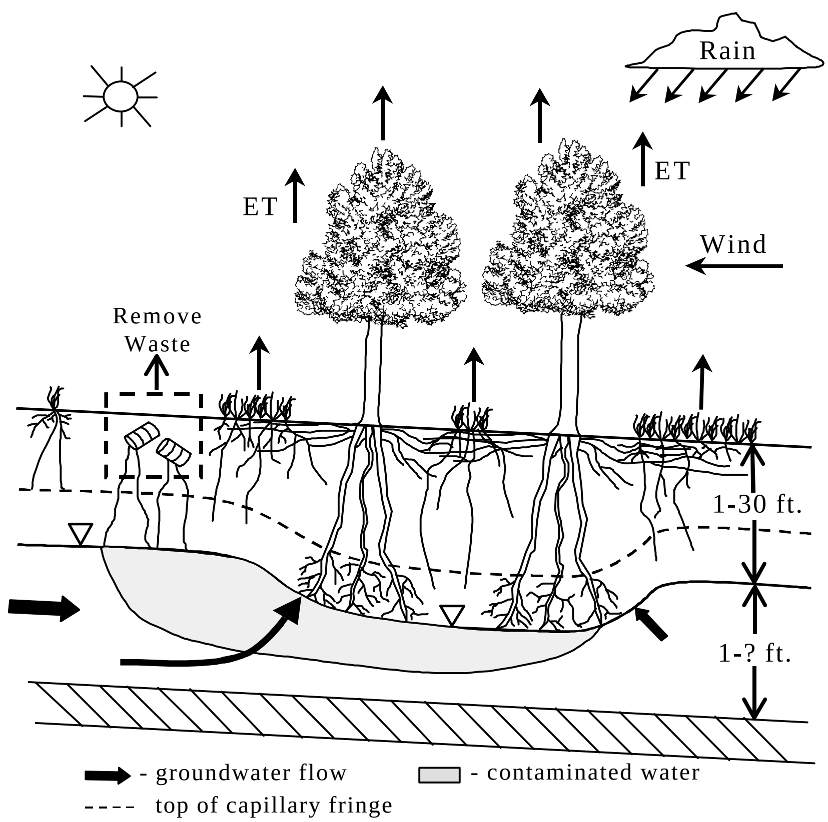

Figure 1. Cross-section through a Phytostabilization Site

that the source of the contaminant be removed, controlled, or remediated so that no additional contaminant will be introduced into the environment. For example, the source might be physically removed or be cut off from the environment by in-ground treatment walls. At sites with appropriate conditions, phytostabilization might completely replace traditional groundwater pumping as a method for controlling groundwater plume movement. At sites where complete year round containment of contaminant movement in the groundwater is not possible, it may be feasible to shut off the groundwater pumping during the growing season and consequently save considerable operating and maintenance costs. At other sites where the groundwater is too deep for plant roots to reach, it may still be economically attractive to pump groundwater to the root zone for irrigation and use the plants to remove the water rather than incur the expense of *ex situ* treatment and discharge of the groundwater.

2.1 Benefits, Cost-Effectiveness and Disadvantages

Phytostabilization may offer a number of advantages as part of the remediation effort at sites with shallow groundwater containing low to moderate contaminate concentrations. These may include some or all of the following:

- The technology relies on growing trees or other plants and thus is aesthetically pleasing
- It is a solar-energy driven, passive technique requiring little energy input
- It requires little operator attention or labor
- It requires minimal maintenance once established
- It is a “green technology” with public acceptance.

Though relatively unproven in full-scale, tests suggest that phytostabilization may produce substantial cost savings. The plant roots will typically come in direct contact with a much greater volume of soil than is possible for pumping wells. In addition, depending upon the contaminant and the plant species utilized, other forms of phytoremediation (e.g. phytodegradation or rhizodegradation) may occur as a by-product of plant growth, thus enhancing effectiveness.

The RPM must consider, however, that an application of phytostabilization might have the following limitations:

- Phytostabilization requires sunlight for the plants and thus adequate space over the contaminant plume is needed for planting
- Water removal is reduced during the winter which might allow contaminated water to migrate away from the capture zone
- Complete year round containment of groundwater and contaminant movement may not be possible in all regions of the country
- Groundwater removal is limited by the potential rooting depth of the vegetation, which may limit the number of applicable sites
- Plants, especially trees, may attract unwanted birds or animals to the site.

2.2 General Requirements for Successful Phytostabilization

The general requirements for a successful implementation of phytostabilization including the following:

- Plants must root deep enough to use large volumes of groundwater
- For complete year round containment of contaminant movement in groundwater, evapotranspiration must exceed precipitation and groundwater flowing into the containment zone.
- An adequate sized site must be available for planting
- Soil properties must support robust plant growth
- The hydrogeology of the site must be suitable.
- Plant establishment must be carefully planned and executed
- Project goals should be carefully defined to permit verification of performance
- Project completion should be carefully defined.

The remainder of this protocol examines these requirements in detail. Implementation of a field-scale phytostabilization project, however, may reveal additional site-specific requirements or suggest modification of the requirements listed above.

A successful phytostabilization project will go through a number of steps in checking the feasibility of the technology, selecting the plants and designing the phytostabilization site layout, and implementing the design. The following list outlines these steps and is provided as an overview of the topics to follow:

1 Collect Site Information
   - Depth of water table
   - Approximate rate of groundwater movement
   - Boundaries of the contamination plume and available planting area
   - Climate data
   - Soils data
   - Site-specific restrictions and limitations
   - Ground surface topography
   - Groundwater contaminants

2 Conduct Feasibility Screening

3 Design the Phytostabilization System
   - Project planning, including project closeout
   - Verify site data and screening assumptions
   - Select plants and layout plantings
   - Design site modifications
   - Design soil modifications and amendments
   - Design an irrigation system

4 Installation of the Phytostabilization System

5 Operation and Maintenance
   - Initial period of plant establishment
   - Long-term O&M

3 Technology for Planning and Implementation

Knowledge from several areas of science and technology are required for successful application of phytostabilization to control groundwater movement at a contaminated site. This section examines the hydrology, climate, evapotranspiration, plant science, and soil requirements necessary to plan and implement a phytostabilization project and provides the basic requirements that form the foundation for successful application of phytostabilization at any site, including those with less favorable site or climatic conditions.

Successful phytostabilization requires robust growth of selected species to achieve the remediation goals. It is sometimes assumed that plants can modify soils, but this may not be possible. While plants are found in nature growing in very difficult environments, these conditions are not suitable for phytostabilization. For instance, trees sometimes appear to grow out of a rock, but they are usually stunted and to grow under these conditions they must have roots that reach soil. Grasses and other plants grow in abandoned roadways suggesting that the plants modified the undesirable features of the soil in the roadway. However, close examination of the site usually shows that the plants are weedy species capable of producing a small amount of biomass under unfavorable conditions. Experimental evidence indicates that plants may need more than a century to remediate poor soil conditions. The Wadsworth wagon trail in Minnesota has been covered with native grasses for than 100 years since abandonment in 1871 [2]. Soil bulk density and water infiltration measurements showed that soil physical properties were poor within the trail area but good outside the trail area. These data show that 100 years of native grass cover and annual freezing and thawing had not significantly improved the soils within the trail. Phytostabilization cannot be applied in all circumstances and just "planting a tree" cannot overcome all adverse site conditions.

Good planning and active management are required to assure success of phytostabilization activities. Phytostabilization will be most effective and least costly if selected plants grow robustly and extend their roots into the capillary fringe of the water table. This can most effectively be accomplished if the site soils, plant nutrients, plant disease and insect control, and water supply are optimized for plant growth. Therefore, the active practice of agricultural engineering and the application of principles used in agricultural production apply to most aspects of phytostabilization and are included in this protocol.

3.1 Hydrogeology

Favorable hydrogeology at the site is a requirement for success. Hydrogeologic factors that are important include depth to groundwater, aquifer properties, degree of separation between the contaminated aquifer and other aquifers, quality of the water in the uppermost aquifer, and rate of contaminated plume movement.

3.1.1 Depth to Groundwater

Successful phytostabilization requires that plant roots reach into the capillary fringe. Therefore, the water table should be sufficiently close to the surface to be within reach of plant roots. The genetic makeup of the plant species controls the maximum depth of rooting under optimum conditions. The actual rooting depth is almost always less than the maximum because it is controlled by soil water supply and by soil properties including fertility, aeration, hardness, soil strength, and particle size. Hardpans or compacted layers in the soil may reduce the number of roots growing through them or prevent significant root penetration beyond the top of the layer. As a result, the maximum depth to the water table that is suitable for phytostabilization varies with site conditions.

Sites with water tables less than 3 m (10 feet) deep are generally amenable to phytostabilization. On the other hand, where the soil above the water table is loose and sandy, the maximum depth may be 9 m (30 feet) or more.

There are reports that tree roots can penetrate to great depths. For example, mesquite roots have been found as deep as 53 m (174 feet) [3]. Extremely deep rooting requires optimum soil and climatic conditions. Because few if any remediation sites provide optimum soils, there will be few instances where a sufficient number of roots can be produced at that depth to effectively phytostabilize groundwater. Effective rooting depths are likely to fall in the range of 6 to 12 m (20 to 40 feet), which is deep enough to remediate many sites by phytostabilization.

Water rises above the water table by capillary action, thus providing a layer containing both air space and ample water supply. This layer is called the capillary fringe. Figure 2 shows the capillary fringe above the water table in a sandy soil. Roots proliferate in the capillary fringe and most water extracted from the water table by phreatophytes (i.e., plants capable of using water from the water table or its capillary fringe) comes from that layer. The capillary fringe may extend several feet above the water table in loam and clay soils because the potential capillary rise becomes greater with increasing clay content (i.e., smaller soil pores). Therefore, where there is significant capillary rise above the water table, phreatophytes may extract water from the water table if they have enough roots in the upper layers of the capillary fringe.

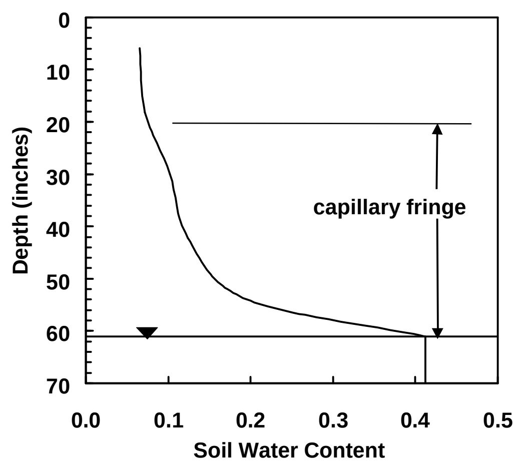

Figure 2. The capillary fringe above water table in sandy subsoil with sandy loam topsoil [4]

3.1.2 Aquifer Properties

The phytostabilization system should remove a volume of water from the aquifer that is equal to or greater than the annual groundwater outflow from the contaminated site. Several aquifer properties are required to estimate annual groundwater outflow from the site.

The hydraulic conductivity of the soil (frequently referred to as the “K value”) and the hydraulic gradient determine the rate (velocity) of water movement through an aquifer. In addition, the extent of the plume, the thickness of the aquifer and the effective pore space of the aquifer are needed. With these data, the planner may estimate the volume of water leaving the contaminated site on an annual basis and thus determine the volume that must be withdrawn by the phytostabilization system. Driscol [5] provides a detailed discussion regarding aquifer properties and the estimation of water movement.

3.1.3 Degree of Separation from Other Aquifers

The uppermost aquifer should be separated from other aquifers by a confining layer (i.e., a horizontal soil layer with low hydraulic conductivity restricting flow in the vertical direction) to minimize water flow into deeper aquifers. At some sites, the lower aquifers are under sufficient pressure to cause flow to move upward into the upper aquifer. If upward flow can reasonably be expected to continue during the remediation period, then the upper aquifer may be considered isolated, even though the hydraulic conductivity of confining layers are large enough to allow significant vertical flow of groundwater.

3.1.4 Contaminate Movement

The rate of lateral movement of the contaminated plume in an aquifer is limited by water table slope (gradient), the hydraulic conductivity of the aquifer and the effective pore volume of the aquifer. The volume and rate of lateral flow of groundwater is directly proportional to aquifer thickness. Therefore, a thin aquifer lends itself to phytostabilization while a thick aquifer may not. At many sites, it will be necessary to evaluate aquifer properties and groundwater movement with an appropriate groundwater model.

The chemical nature of the contaminant may also influence rate of movement. Soluble contaminants may move nearly as fast as the water, while less soluble contaminants, or those adsorbed onto the soil particles, may move much slower. Analysis of the contaminants found at the site may be required to determine the interaction, if any, with the aquifer and the resulting retardation value.

3.1.5 Water Quality of Uppermost Aquifer

Both contaminants and natural dissolved solids contained in the water of the uppermost aquifer might have a toxic effect on the plants grown to remove water from the aquifer and might result in a reduction to both plant growth rate and transpiration. If toxicity might be an issue, plants that are tolerant to the contaminant or natural dissolved solids should be selected for use. There are large numbers of publications that describe the effect of the salts of Na, Ca, Mg, and other common ions on plant growth and water use. Unfortunately, data showing the response of plants to many contaminants is not readily available. However, more toxic response data may be published for various plant species as phytoremediation systems become more widely used.

3.2 Climate

Climatic factors are important in assessing the potential value of phytostabilization at a site, designing the system, and assessing results. In order to estimate the potential for success, it is necessary to estimate (1) the volume of water that should be removed from the soil and/or uppermost aquifer and (2) the potential and actual rate of removal by phytostabilization. Climate is the major factor affecting both the incoming and outgoing water in the system.

Precipitation may be a large source of the water found in the soil or uppermost aquifer. However, groundwater may originate from leaking water or sewer lines, other point sources and subsurface flow from other sites. Precipitation should be determined from measurements at the site. If measurements from the site are unavailable, remotely measured precipitation values may be used. However, the accuracy of phytostabilization performance estimates made using off-site climate data decreases with increasing distance of the measurement location away from the site.

During periods with significant precipitation and low potential evaporation, the phytostabilization system may not remove enough water to control groundwater movement unless there was significant residual drawdown from an earlier period. Figure 3 shows the distribution of monthly precipitation for nine locations within the continental United States. In the southeastern United States, precipitation is relatively large all year, but the growing season is long. In the Great Plains, the period of highest precipitation coincides with the growing season. On the Pacific coast, precipitation is high in winter and very low in summer.

While it is true that climate conditions will vary throughout the United States, they are particularly variable in parts of the western United States. Both topography and elevation can create dramatic differences in the climate. An example of this is found in the differences between Norton and March AFBs, which are located near San Bernardino and Riverside, California respectively. The pan evaporation measured at each base is the same, 780 mm (70 inches) per year. However, the average annual precipitation is 380 mm (16 inches) at Norton AFB and only 190 mm (8 inches) at March AFB. This is a two-fold difference in precipitation between two bases located only 22.5 Km (14 miles) apart. While there is only a small elevation difference between these two sites, they are located near the mountain ranges of Southern California so the topography has a strong influence on climate. This illustrates the need to use site-specific data.

3.3 Evapotranspiration

Evapotranspiration (ET) is the evaporation of water from the soil surface and from plants (primarily through the stomata on the plant's leaves). ET is often the largest factor in the use of plants for remediation. It is also a factor that should be carefully considered before committing money for the design and installation of remediation systems that use plants. ET may be large or small and thus might limit plant effectiveness in two different ways:

- Limited *water supply* may reduce actual ET, and consequently plant growth, thus limiting remediation effectiveness for some plants.
- Limited *potential ET* may result in limited capacity to remove enough water from the vadose zone to perform the desired phytostabilization function.

ET may be measured directly at the site or estimated from other measured parameters. Direct measurement at the site, however, is normally impractical due to the high cost. The alternative is to estimate potential ET from climatic measurements. As previously mentioned (see Section 3.2), climatic measurements should be collected at the site for greatest accuracy. The number and kind of measurements required will be determined by the desired accuracy of the estimate.

The following sections present additional details about ET and estimated values of ET developed for Air Force facilities in the continental United States (CONUS). Appendix A presents additional detail regarding potential ET estimates.

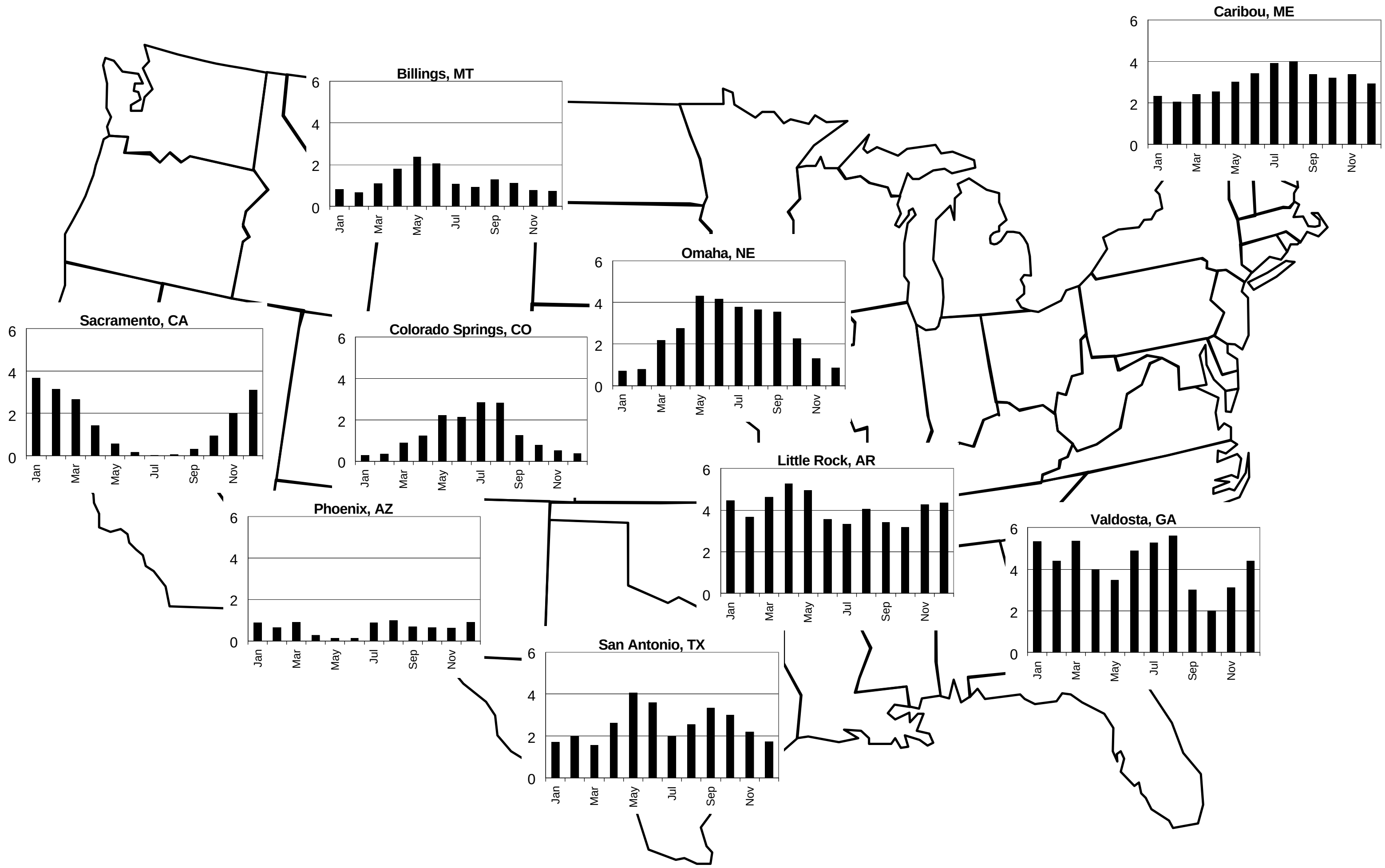

Figure 3. Distribution of monthly precipitation within the continental United States (inches/month)

3.3.1 Basic Physics of ET

The primary source of energy for evapotranspiration is solar energy. Evaporation of water requires heat input to the system, and the rate of evaporation is proportional to the rate of heat or energy input to the system. The solar energy received at the outer limits of the atmosphere is more intense than that measured on the earth's surface. Clouds, dust, and vapor in the atmosphere reduce the amount of solar energy reaching the surface of the earth. The earth's surface emits radiation to space, further reducing the net radiation at the surface.

Advected heat energy (i.e., heat energy carried laterally by the wind) may be an important source of heat. For example, hot dry winds are sources of advected energy. Water evaporates faster from a wet surface if the air is dry. Wind removes the moist air near a wet evaporating surface and thus increases the evaporation rate by increasing the vapor pressure gradient near the surface. A complete discussion of the physics of the ET process is beyond the scope of this protocol; however, a relatively complete discussion is available in the ASCE Manual on Evapotranspiration edited by Jensen et al. [6].

3.3.2 Potential ET

Potential ET (PET) is the maximum ET that can result from a set of climatic conditions. It is limited by the amount of energy available to evaporate water. For purposes of plant growth and production, PET is defined as the amount of water that would return to the atmosphere if abundant, freely transpiring plant leaves are available and the water supply to the plants is abundant and unrestricted. Evaporation from shallow water bodies is similar to PET as defined for plants. The magnitude of PET is useful for preliminary planning to identify the maximum possible performance that might be expected from phytostabilization and to serve as the basis for estimates of actual ET.

Methods for estimating PET were derived for irrigated agriculture where abundant water was presumed available for plant use. The PET value is sometimes referred to as the "reference crop ET." Appendix A presents a discussion of methods for estimating ET which may be used to prepare site-specific estimates for other locations within or outside of the continental United States Appendix A describes the equation sets used in six different methods derived for "reference crop" conditions. The resulting reference crop ET values may are used to estimate PET. The reader is referred to the handbook compiled by a committee of the American Society of Civil Engineers [6] for additional information on calculating estimates of PET.

3.3.3 Actual ET

Actual ET (AET) by a plant system is almost always less than PET and is reduced by any factor that limits plant growth. These limiting factors include water supply, incident solar radiation, humidity, air temperature, wind, dormant seasons, immaturity of the plants, dry soil layers, plant type, plant disease, insect attack, soil fertility, soil and/or water salinity, and soil physical properties. Hydrologic factors that control the amount of water actually removed from a contaminated site by ET include surface runoff, and area of soil surface available for planting. The climatic factors, however, have the largest potential affect on plant growth and typically control the value of PET.

Few surfaces—other than open water—will evaporate water at the potential rate all of the time, and most soil and vegetated surfaces will evaporate at the potential rate only part of the time [20]. The actual ET rate at a phytostabilization site will often be less and seldom greater than the estimated PET. However, PET estimates are useful because they provide the planner with an upper bound for expected results. However, it is often desirable to estimate the actual ET for the site.

The actual ET rate at a site may be reduced below the PET value by several limiting factors:

- **Soil water content.** As soils dry, the rate at which plants can extract water from the soil falls below the potential amount as the stomata begin to close in response to reduced water potential in the soil. When the soil water content reaches the permanent wilting point, the actual rate of extraction by plants is small. The soil evaporation rate drops below the potential rate when the upper soil layers become dry.
- **Leaf area index.** The leaf area index (LAI) is the ratio of total leaf area to the underlying soil-surface area. For LAI values less than three, the actual transpiration rate is typically less than the potential rate [21].
- **Stage of plant growth.** The actual rate of ET is less than the potential amount when perennial plants are dormant, early in spring when growing plant parts are small, or near plant maturity.
- **Soil nutrient status.** If the soil is deficient in one or more nutrients, plant growth may be restricted and actual water use reduced below the potential amount.
- **Restricting soil layers.** Soil layers that restrict or prevent root growth—such as compacted layers, hardpans, or cemented soil layers—may reduce the rate of root growth and reduce the ET rate below the potential amount.
- **Oxygen diffusion rate.** Roots require an ample supply of oxygen for robust growth. Soil conditions such as high clay content, excessive compaction, or high water content may reduce the rate of oxygen diffusion and thus reduce root growth. Reduced root growth may significantly reduce the actual ET rate.
- **Soil temperature.** If soil temperatures are less than or greater than the optimum range for root growth, roots may grow too slowly to explore the soil mass fully and as a result reduce the ET rate below the potential rate [3].

Estimating actual ET is complex because there are significant interactions between the limiting factors. Conditions for optimum root and plant growth may be poor in one soil layer and good in another. For example, the surface soil may be dry, but conditions at depth may be good for root and plant growth. In such case, roots may proliferate at depth and the actual ET rate may be relatively high but less than the potential amount. The Environmental Policy Integrated Climate (EPIC) computer model computes limiting factors and estimates actual ET under either dry-land or irrigated conditions for grasses, cultivated crops, and some trees [7, 8, and personal communication from Williams].

3.3.4 Potential for ET Based Remediation

If the annual PET for a site is greater than the annual precipitation, it is likely that phytostabilization may perform as expected. Where PET is less than annual precipitation, plants may not remove enough water to perform hydraulic control functions.

Values of PET were estimated for 60 Air Force sites distributed across the continental United States including bases from all climatic regions [19]. Sites were chosen to ensure representation for both seacoasts, as well as hot and cold regions. The availability of adequate climate data was another factor in the selection of sites for the PET estimates. Where two or more bases were in close proximity—for example, San Antonio with 4 bases—one base was chosen to represent the group. The estimated values of PET are presented in Table 1 and the geographic distribution of the 60 Air Force sites is shown in Figure 4.

Figure 4. Locations of PET Estimate Sites

The EPIC computer model was used to estimate PET and AET at each site. EPIC and its earlier versions [7, 8] meet the requirements for ET estimation.[1] The EPIC model is a comprehensive model that has been extensively tested for plant growth and water balance estimates, and is in use by the U.S. Department of Agriculture throughout the United States [9 through 18].

Table 1 presents the average annual values of precipitation, PET, AET, and number of days per year that plants are stressed due to water and temperature. The EPIC model computed the results for a 100-year period. The table also lists the difference between PET and AET, as well as the ratio of PET to precipitation.

Estimates of the number of days per year that plants are stressed by temperature or lack of water (plant-stress days) shown in Table 1 should be considered minimum values. EPIC counts the number of days per year when water stress is the most limiting stress on plant growth. It also counts the number of days per year when the temperature—either high or low—is the most limiting stress on plant growth. More than one plant stress may occur on any given day, but only one will be counted by EPIC as the most limiting stress.

It is important to note that the estimated values of AET in Table 1 are minimum values. If plants were growing in both warm and cool seasons or if some of the plants were drawing water from a shallow water table, then the AET could be substantially greater than shown in Table 1. The EPIC model calculated water use only from precipitation. Thus in the estimates shown AET cannot be greater than precipitation because the model assumes that the water supply to the plants was limited to precipitation only. For example, in the arid climates of George, Holloman, and Nellis AFBs, AET is limited by precipitation and the ratio of AET to precipitation has a value of one. However, where trees are used to control shallow groundwater the AET of the trees at bases in arid, semi-arid, and sub-humid climates could be substantially greater than the annual precipitation.

[1] Personal communication from J. R. Williams, Texas Agricultural Experiment Station, Temple, TX

Table 1. Annual Values of PET, AET, and Number of Days per Year of Plant Stress Estimated With the EPIC Model for 60 Air Force Bases in the Continental United States.

Base	State	100-Year Mean			Plant Stress Days Due To:		PET-AET	PET[4]
		PRCP[1]	PET[2]	AET[3]				
		Inches	Inches	Inches	Water	Temp.	Inches	Ratio
Air Force Academy	CO	12.8	68	12	130	180	56	5.3
Altus AFB	OK	24.6	75	23	110	190	52	3.1
Arnold AFB	TN	54.2	59	38	20	240	21	1.1
Barksdale AFB	LA	46.1	70	39	60	190	30	1.5
Beale AFB	CA	26.5	81	22	120	60	58	3.0
Bolling AFB	DC	37.2	57	29	<10	150	28	1.5
Brooks AFB	TX	28.7	78	27	120	150	51	2.7
Cannon AFB	NM	15.0	83	15	160	140	68	5.5
Castle AFB	CA	12.6	84	12	200	50	72	6.7
Chanute AFB	IL	34.8	50	26	10	170	24	1.4
Charleston AFB	SC	48.3	67	43	30	210	24	1.4
Columbus AFB	MS	54.1	66	42	40	200	24	1.2
Davis-Monthan AFB	AZ	11.5	95	11	220	60	83	8.2
Dover AFB	DE	37.4	53	28	<10	160	26	1.4
Dyess AFB	TX	23.1	77	22	120	170	55	3.3
Ellsworth AFB	SD	19.5	59	19	90	200	40	3.0
Fairchild AFB	WA	16.5	52	14	90	210	38	3.2
George AFB	CA	5.3	92	5	210	120	87	17.5
Goodfellow AFB	TX	18.2	84	18	170	100	67	4.6
Grand Forks AFB	ND	19.1	48	17	70	180	31	2.5
Hill AFB	UT	19.9	63	18	100	200	45	3.2
Holloman AFB	NM	10.7	91	11	190	110	80	8.5
Homestead AFB	FL	63.3	81	53	70	50	28	1.3
Keesler AFB	MS	69.3	62	49	<10	180	14	0.9
Kirtland AFB	NM	8.8	78	9	180	140	69	8.8
Langley AFB	VA	41.3	60	32	<10	130	29	1.5
Laughlin AFB	TX	16.9	87	16	190	60	71	5.2
Little Rock AFB	AR	49.8	64	39	50	210	26	1.3
Loring AFB	ME	36.8	39	21	20	210	18	1.0
Lowry AFB	CO	12.8	68	12	130	180	55	5.3
Luke AFB	AZ	7.7	108	8	250	70	100	14.1
MacDill AFB	FL	52.4	80	46	90	80	34	1.5
Malmstrom AFB	MT	15.4	51	14	100	210	37	3.3
Maxwell AFB	AL	51.5	70	43	50	190	27	1.4

Base	State	100-Year Mean PRCP[1] Inches	PET[2] Inches	AET[3] Inches	Plant Stress Days Due To: Water	Temp.	PET-AET Inches	PET[4] Ratio
McChord AFB	WA	40.9	53	29	40	150	24	1.3
McClellan AFB	CA	17.3	79	16	170	50	63	4.6
McConnell AFB	KS	29.3	70	27	70	230	42	2.4
McGuire AFB	NJ	46.4	50	28	<10	160	22	1.1
Minot AFB	ND	15.7	52	15	70	240	38	3.3
Moody AFB	GA	48.0	71	43	50	180	28	1.5
Mountain Home AFB	ID	7.7	73	7	160	160	66	9.6
Nellis AFB	NV	4.1	89	4	240	90	85	21.5
Offutt AFB	NE	30.9	55	27	10	180	29	1.8
Patrick AFB	FL	52.3	78	46	70	100	32	1.5
Plattsburgh AFB	NY	32.5	45	24	10	170	21	1.4
Pope AFB	NC	48.0	65	42	30	210	23	1.3
Reese AFB	TX	18.8	82	18	140	130	64	4.4
Robins AFB	GA	45.1	70	40	60	190	30	1.6
Scott AFB	IL	32.5	60	28	20	160	33	1.9
Seymour Johnson AFB	NC	47.7	62	40	20	230	23	1.3
Shaw AFB	SC	46.8	67	42	40	210	25	1.4
Sheppard AFB	TX	28.5	76	27	100	190	49	2.7
Tinker AFB	OK	31.9	71	29	70	220	42	2.2
Travis AFB	CA	28.8	82	24	130	70	58	2.8
Tyndall AFB	FL	55.4	70	36	30	180	34	1.3
Vance AFB	OK	25.9	73	24	90	210	49	2.8
Vandenberg AFB	CA	14.4	64	14	90	20	51	4.5
Whiteman AFB	MO	33.9	60	29	10	160	31	1.8
Wright-Patterson AFB	OH	39.1	55	29	<10	170	26	1.4
Wurtsmith AFB	MI	28.3	44	22	20	200	21	1.5

1. PRCP = annual precipitation
2. PET = annual potential evapotranspiration
3. AET = annual actual evapotranspiration
4. PET Ratio = annual PET/precipitation

PET Ratio

The ratio of PET to annual precipitation (PET ratio) is an indication of whether evapotranspiration could theoretically remove all of the water entering the soil due to precipitation. A PET ratio greater than one indicates that the PET at the site is sufficient to handle the precipitation. Note that the PET ratio is greater than one for almost all of the country as shown in Figure 5.

At sites where the PET ratio is small, site-specific analysis will be required to determine whether plant-based remediation is suitable. In small areas along the Gulf coast, in northern New England, and in the snow belt of the Great Lakes region phytostabilization in support of groundwater control may be restricted to use as a supplement to a pumped extraction-well system. However, only five of the 60 bases examined had PET ratios less than or equal to 1.2, as shown in Table 1.

Where PET is small, phytostabilization may still be feasible using trees or other plants to supplement extraction wells or in situations where the local recharge to the groundwater is reduced by buildings, parking lots, or other surfaces with diversion of runoff water outside the recharge area such that trees could stabilize groundwater movement without wells. In these cases where the PET ratio is small, robust plant growth is normally relatively easy to achieve because the precipitation is adequate to meet plant needs.

Water-Stress Days

Plants (including phreatophytes) preferentially use water held in soil layers near the soil surface. They use water most rapidly from the water table and deep soil layers when the plants are under water stress caused by dry surface soils. Figure 6 shows the estimated number of days per year when water stress is the limiting factor for grass growth in the continental United States, as estimated by the EPIC model [19]. On the days where EPIC estimates that water stress was the most limiting factor to plant growth, conditions were good for plants to consume substantial amounts of groundwater.

The data shown in Figure 6 indicates that phytostabilization has potential application across most of the United States.

A site-specific evaluation may be required for sites with a high number of water-stress days, such as in the desert southwest. Plant stress due to limited soil water has the potential to kill plants. Therefore, these sites with a large numbers of water-stress days per year should employ drought-tolerant plants and may require supplemental irrigation during the hottest periods of the year.

The PET–AET Difference

Table 1 also lists the numerical differences between PET and AET values for each base. Theoretically the potential minus actual ET (PET–AET) difference is the amount of water that could be transpired from the groundwater by phreatophytes. These data indicate that phytostabilization has good probability for success at most Air Force bases. Only two bases (Keesler and Loring) have PET–AET differences of less than 0.5 m (20 inches) per year. In actual practice, however, various other factors may act to substantially reduce the amount of water actually transpired and a site-specific evaluation is appropriate for all bases that have small PET–AET values, even though they may otherwise appear suitable for phytoremediation.

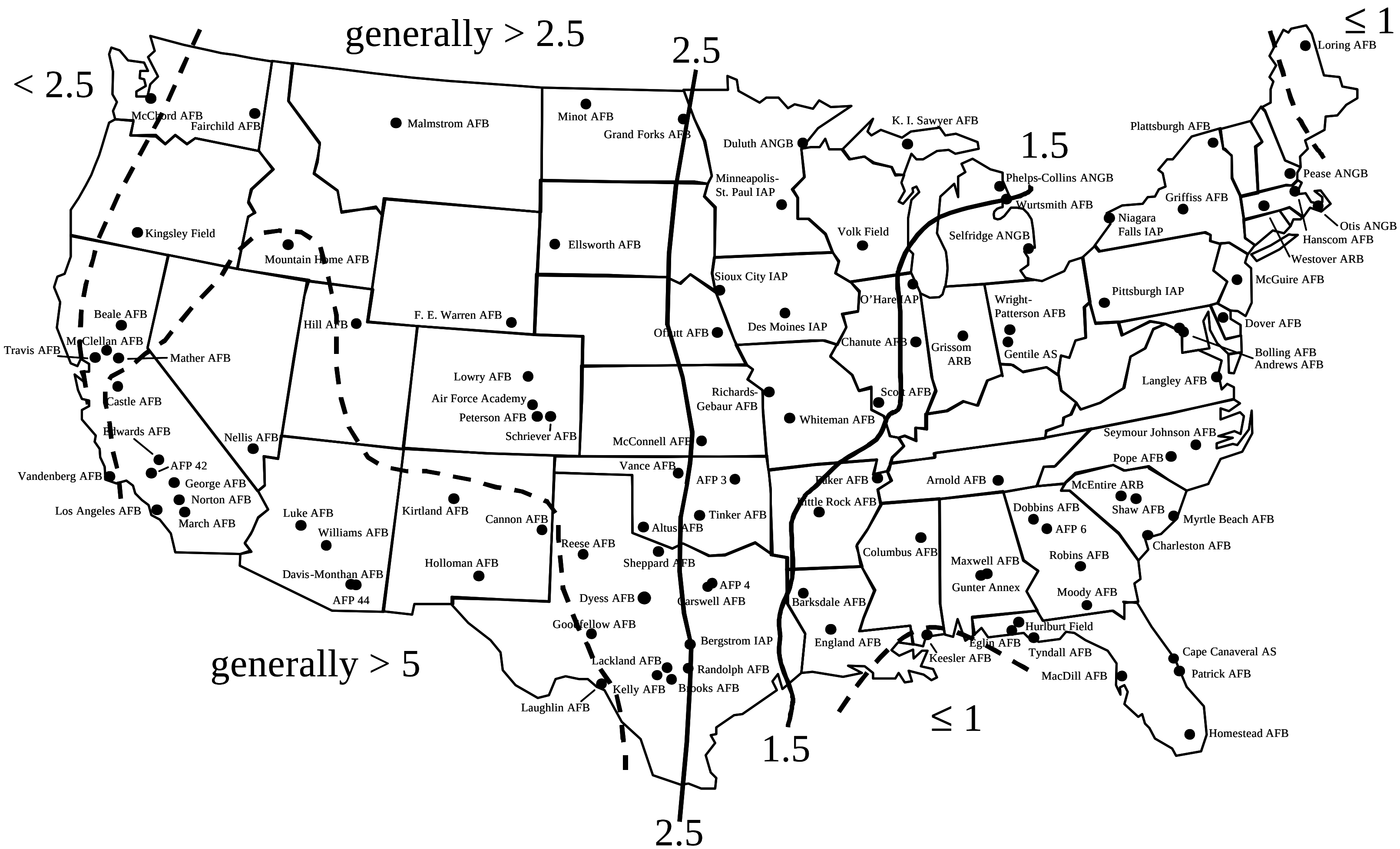

Figure 5. Ratio of Annual Values of PET/Precipitation

*See Table 1 for a list of the bases individually evaluated. Dashed lines are approximations.

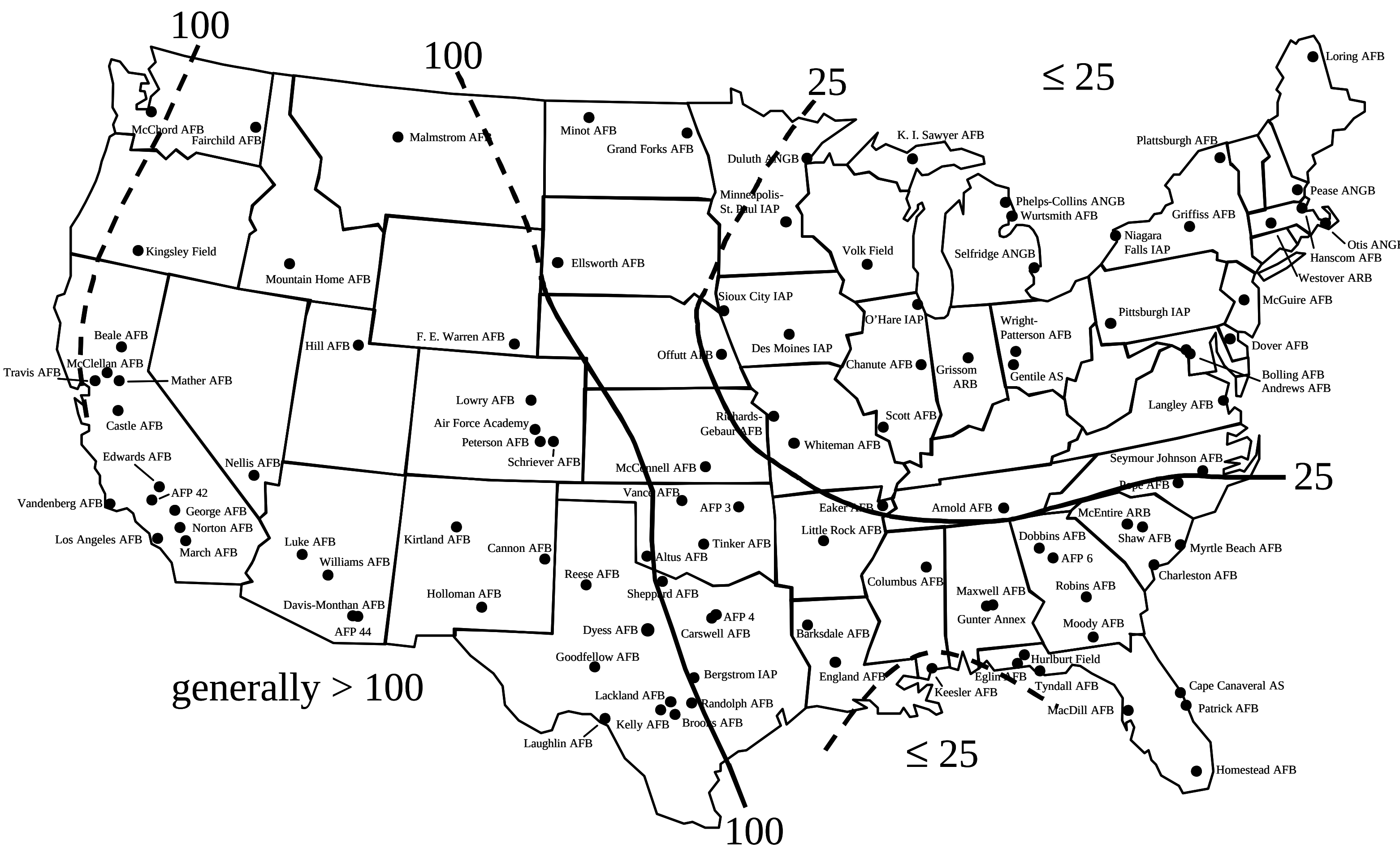

Figure 6. Number of Water-Stress Days per Year Limiting Grass Growth

See Tables 1 for a list of the bases individually evaluated. Dashed lines are approximations.

Data Interpretation

The PET values listed in Table 1 are basic estimates by the model and are controlled by the climate data input for each site. The choice of input data for soil or plant parameters has little influence on the estimate of PET. However, the values of AET and water stress days shown in Table 1 are influenced by the assumed soil and plant data input. A more accurate estimate of AET at a site requires model input data based on specific knowledge of the site (which was not available for this general study). The PET estimates contained in this document are most appropriately used in a feasibility analysis to answer the initial question of whether phytostabilization is worthy of further consideration for a particular site. The number of stress days due to water and the AET estimates for the 60 bases are presented as supporting data.

The estimated PET ratios for the 60 bases were sorted into three groups defined according to the appropriateness of phytostabilization for that location. The three classifications of opportunity are defined as follows:

Good: (PET ratio >= 1.5) High probability for success using plants for remediation (42 of 60 bases).

Fair: (1.2 =< PET ratio < 1.5) Successful application is likely, but may require site-specific analysis (14 of 60 bases).

Marginal: (PET ratio < 1.2) Prospects for successful use are limited and would require considerable site-specific design effort (4 of 60 bases).

Other Air Force Installations

In order to assist readers, the PET estimates for 49 additional Air Force Installations were added to the initial list of 60 bases discussed above. The total list of PET estimates for 109 Air Force bases, sorted by state, is presented in Table 2 [19]. Six installations were very near to sites listed in Table 1 and have similar climates. PET estimates were taken from Figure 5 for an additional 43 installations. The values taken from Figure 5 are conservative estimates because local conditions may influence the true value of PET.

PET estimates can be calculated for other locations outside of the continental United States. Appendix A contains the descriptions and equations for six estimation methods. Appendix A also contains a description of the assumptions used in preparing the PET estimates listed in Table 1.

3.4 Plants

Achieving successful phytostabilization of groundwater requires that the selected plants grow robustly under the conditions at the site. They must be able to remove large amounts of soil water at depth, and must tolerate the contaminant chemicals and naturally occurring soil salts found at the site.

Table 2. Annual Values of Precipitation, and PET Ratio for 109 Air Force Installations in the Continental United States 1 (sorted by state)

Installation	State	Lat.[2] Deg.	Long.[3] Deg.	Precip.[4] Inches	PET [5] RATIO	Estimated from [6]
Gunter Annex	AL	32.4	86.3	52	> 1.0	Figure 5
Maxwell AFB	AL	32.4	86.4	51.5	1.4	Calculated
Eaker AFB	AR	36.0	90.0	50	≥ 1.0	Figure 5
Little Rock AFB	AR	34.9	92.2	49.8	1.3	Calculated
AFP 44 - Tucson	AZ	32.2	110.9	12	> 5.0	Figure 5
Davis-Monthan AFB	AZ	32.2	110.9	11.5	8.2	Calculated
Luke AFB	AZ	33.5	112.4	7.7	14.1	Calculated
Williams AFB	AZ	33.6	112.2	8	> 5.0	Figure 5
AFP 42 - Palmdale	CA	34.6	118.1	8	> 5.0	Figure 5
Beale AFB	CA	39.1	121.4	26.5	3.0	Calculated
Castle AFB	CA	37.4	121.4	12.6	6.7	Calculated
Edwards AFB	CA	34.9	117.9	8	> 5.0	Figure 5
George AFB	CA	34.5	117.3	5.3	17.5	Calculated
Los Angeles AFB	CA	33.9	118.4	14	> 2.5?	Figure 5
March AFB	CA	33.9	117.3	8	> 5.0	Figure 5
Mather AFB	CA	38.5	121.4	17	4.6	*Calc. Near*
McClellan AFB	CA	38.7	121.4	17.3	4.6	Calculated
Norton AFB	CA	34.2	117.3	16	> 5.0	Figure 5
Travis AFB	CA	38.3	121.9	28.8	2.8	Calculated
Vandenberg AFB	CA	34.7	120.6	14.4	4.5	Calculated
Air Force Academy	CO	39.0	104.9	12.8	5.3	Calculated
Lowry AFB	CO	39.7	104.9	12.8	5.3	Calculated
Peterson AFB	CO	38.8	104.7	15	5.3	*Calc. Near*
Schriever AFB	CO	38.8	104.5	15	> 2.5	Figure 5
Bolling AFB	DC	39.0	77.0	37.2	1.5	Calculated
Dover AFB	DE	39.1	75.5	37.4	1.4	Calculated
Cape Canaveral AS	FL	28.5	80.6	45	≥ 1.0	Figure 5
Eglin AFB	FL	30.6	86.6	64	≥ 1.0	Figure 5
Homestead AFB	FL	25.5	80.4	63.3	1.3	Calculated
Hurlburt Field	FL	30.5	86.5	65	≥ 1.0	Figure 5
MacDill AFB	FL	27.8	83.5	52.4	1.5	Calculated
Patrick AFB	FL	28.2	80.6	52.3	1.5	Calculated
Tyndall AFB	FL	30.2	85.6	55.4	1.3	Calculated
AFP 6 - Marietta	GA	33.9	84.5	54	≥ 1.0	Figure 5
Dobbins ARB	GA	33.9	84.5	54	≥ 1.0	Figure 5
Moody AFB	GA	31.0	83.2	48.0	1.5	Calculated
Robins AFB	GA	32.6	83.6	45.1	1.6	Calculated
Des Moines IA	IA	41.5	93.7	33	> 1.5	Figure 5
Sioux City IA	IA	42.4	96.4	26	> 1.5	Figure 5
Mountain Home AFB	ID	43.1	115.9	7.7	9.6	Calculated
Chanute AFB	IL	40.3	88.2	34.8	1.4	Calculated

Installation	State	Lat.[2] Deg.	Long.[3] Deg.	Precip.[4] Inches	PET [5] RATIO	Estimated from [6]
O'Hare IAP	IL	41.8	88.0	34	≥ 1.0	Figure 5
Scott AFB	IL	38.5	89.9	32.5	1.9	Calculated
Grissom ARB	IN	40.6	86.2	39	> 1.0	Figure 5
McConnell AFB	KS	38.6	97.3	29.3	2.4	Calculated
Barksdale AFB	LA	32.5	93.6	46.1	1.5	Calculated
England AFB	LA	31.3	92.5	58	≥1.0	Figure 5
Hanscom AFB	MA	42.5	71.3	45	≥ 1.0	Figure 5
Otis ANGB	MA	41.7	70.5	46	≥1.0?	Figure 5
Westover ARB	MA	42.2	72.6	44	≥ 1.0	Figure 5
Andrews AFB	MD	38.8	76.8	37	1.5	*Calc. Near*
Loring AFB	ME	46.9	67.9	36.8	1.0	Calculated
K. I. Sawyer AFB	MI	47.3	88.3	37	≥ 1.0	Figure 5
Phelps-Collins ANGB	MI	45.1	83.5	29	≥ 1.5	Figure 5
Selfridge ANGB	MI	42.6	82.8	30	≥ 1.0	Figure 5
Wurtsmith AFB	MI	44.5	83.4	28.3	1.5	Calculated
Duluth ANGB	MN	46.8	92.2	31	> 1.5	Figure 5
Minn-St Paul IAP	MN	44.9	93.2	27	> 1.5	Figure 5
Richards-Gebaur AFB	MO	38.8	94.1	39	> 1.5	Figure 5
Whiteman AFB	MO	38.7	93.6	33.9	1.8	Calculated
Columbus AFB	MS	33.6	88.4	54.1	1.2	Calculated
Keesler AFB	MS	30.4	88.9	69.3	0.9	Calculated
Malmstrom AFB	MT	47.5	111.2	15.4	3.3	Calculated
Pope AFB	NC	79.0	35.2	48.0	1.3	Calculated
Seymour Johnson AFB	NC	35.3	78.0	47.7	1.3	Calculated
Grand Forks AFB	ND	47.9	97.4	19.1	2.5	Calculated
Minot AFB	ND	48.4	101.3	15.7	3.3	Calculated
Offutt AFB	NE	42.1	95.9	30.9	1.8	Calculated
Pease ANGB	NH	70.8	43.8	43	≥1.0	Figure 5
McGuire AFB	NJ	40.0	74.6	46.4	1.1	Calculated
Cannon AFB	NM	34.4	103.3	15.0	5.5	Calculated
Holloman AFB	NM	32.8	106.1	10.7	8.5	Calculated
Kirtland AFB	NM	35.0	106.6	8.8	8.8	Calculated
Nellis AFB	NV	36.2	115.0	4.1	21.5	Calculated
Griffis AFB	NY	43.3	75.5	46	> 1.0	Figure 5
Niagara Falls IAP	NY	43.1	78.9	39	≥ 1.0	Figure 5
Plattsburgh AFB	NY	45.8	73.4	32.5	1.4	Calculated
Gentile AS	OH	39.8	84.2	39	≥ 1.0	Figure 5
Wright-Patterson AFB	OH	39.8	84.1	39.1	1.4	Calculated

Installation	State	Lat.[2] Deg.	Long.[3] Deg.	Precip.[4] Inches	PET[5] RATIO	Estimated from[6]
AFP 3 - Tulsa	OK	36.2	95.9	39	≥ 1.5	Figure 5
Altus AFB	OK	34.7	99.3	24.6	3.1	Calculated
Tinker AFB	OK	35.4	97.4	31.9	2.2	Calculated
Vance AFB	OK	36.4	97.9	25.9	2.8	Calculated
Kingsley Field	OR	42.1	121.7	13	≥ 2.5	Figure 5
Pittsburgh IA ARS	PA	40.5	80.2	34	≥ 1.0	Figure 5
Charleston AFB	SC	32.8	80.0	48.3	1.4	Calculated
McEntire AFB	SC	34.0	81.0	48	≥ 1.0	Figure 5
Myrtle Beach AFB	SC	33.7	78.9	50	≥ 1.0	Figure 5
Shaw AFB	SC	34.0	80.5	46.8	1.4	Calculated
Ellsworth AFB	SD	44.1	103.1	19.5	3.0	Calculated
Arnold AFB	TN	35.4	86.1	54.2	1.1	Calculated
AFP 4 - Ft Worth	TX	32.8	97.3	32	≥ 1.5	Figure 5
Bergstrom AFB	TX	30.3	97.8	32	2.5	Figure 5
Brooks AFB	TX	29.3	98.4	28.7	2.7	Calculated
Carswell AFB	TX	32.8	97.3	32	> 1.5	Figure 5
Dyess AFB	TX	32.4	99.8	23.1	3.3	Calculated
Goodfellow AFB	TX	31.4	100.4	18.2	4.6	Calculated
Kelly AFB	TX	29.4	98.6	29	2.7	*Calc. Near*
Lackland AFB	TX	29.4	98.6	29	2.7	*Calc. Near*
Laughlin AFB	TX	29.4	100.8	16.9	5.2	Calculated
Randolph AFB	TX	29.5	98.3	29	2.7	*Calc. Near*
Reese AFB	TX	33.6	101.9	18.8	4.4	Calculated
Sheppard AFB	TX	34.0	98.5	28.5	2.7	Calculated
Hill AFB	UT	41.1	112.0	19.9	3.2	Calculated
Langley AFB	VA	37.1	76.3	41.3	1.5	Calculated
Fairchild AFB	WA	47.6	117.7	16.5	3.2	Calculated
McChord AFB	WA	47.1	122.5	40.9	1.3	Calculated
Volk Field	WI	43.9	90.3	32	> 1.5	Figure 5
F. E. Warren AFB	WY	41.2	105.9	13	> 2.5	Figure 5

1. Hauser, V.L. and D.M. Gimon, 2001 [19]
2. Lat–North Latitude
3. Long–West Longitude
4. Precip–Average annual precipitation from database used for PET estimates
5. PET Ratio–Ratio of annual PET/annual precipitation.
6. Estimated from–PET Ratio derived from an estimate for the site, interpolated from Figure 5, or calculated at a nearby base with similar climate.

3.4.1 Criteria for Potentially Useful Plants

Plants selected for phytostabilization applications should meet the following criteria:

- Grow robustly and consume groundwater in the climate at the site
- Have potential to use large amounts of groundwater
- Be perennials that are adapted to the winter weather at the site
- Have adequate potential rooting depth to reach the capillary fringe
- Tolerate occasional submergence of part of the root mass below the water table
- Grow rapidly to maximize interception of solar radiation
- Grow robustly in the presence of site contaminants
- Do not attract unwanted birds (near Air Force base flight lines)
- Transpire water over a long growing season

Plants that meet these requirements will often be phreatophytes. Phreatophytes are plants that are capable of using water from the water table or its capillary fringe (i.e., salt grass, Bermuda grass, alfalfa, cottonwood, or willow). The plants selected for a particular site may include monocultures or mixtures of trees, shrubs, perennial grasses, forage plants, sedges, and reeds.

3.4.2 Trees

Trees are advantageous for phytostabilization because (1) they are perennials, (2) they have large root systems, and (3) they may survive substantial periods of adverse growing conditions—such as drought or insect attack—and continue growing when conditions improve. Phreatophyte trees are preferred because of their ability to remove groundwater from near the water table. However, other trees may be useful in some situations. Evergreen trees may be advantageous in some climates because the water usage by deciduous trees is small after the leaves drop. However, water use by evergreens may also be small during winter as a result of cold temperatures and low PET.

The rooting potential is an important consideration when trees are used for phytostabilization. There are few data available that show rooting patterns of phreatophytes; however, there is a substantial body of data regarding the rooting patterns of cultivated trees. Knowing the general rooting patterns of cultivated trees will provide some guidance regarding the irrigation requirements to produce large phreatophyte trees with large aboveground biomass—a requirement for phytostabilization success.

Deciduous fruit trees normally have most of their root mass in the top 0.9 m (3 feet) of the soil. Their roots spread laterally to a distance of two or three times the spread of the branches in sandy soils and about 1.5 times the spread of the branches in loam and clay soils. Feeder roots are the small roots that extract water and nutrients from the soil. They decrease in density with increasing distance from the trunk and with increasing depth [22].

Citrus trees are mesophytes that are indigenous to the humid tropics but will grow in the subtropics as well. Orange trees grown with some soil-water deficit produced greater root density but less aboveground biomass than well-irrigated trees. Orange trees grown on clay loam soil under heavy irrigation produced small root mass because the soil contained inadequate amounts of oxygen. However, similarly irrigated trees on sandy soil produced large root mass because the sand was well aerated at all times in spite of heavy irrigation [23].

While the trees chosen for a phytostabilization site may have different rooting patterns and water requirements than the cultivated trees discussed above, the data from cultivated trees provides an indication of the size and possible limits for root growth in the top layers of soil. Most trees obtain the essential nutrients for growth and tree maintenance from the top layers of soil where soil aeration and microbial activity are closest to optimum. They will also consume available water from the uppermost layers before using water held deeper in the soil.

The rooting potential of trees considered for phytostabilization should be examined on a case-by-case basis. Trees should have the potential to extend roots deep into the soil. Some trees have potential to develop very extensive root systems. Plant rooting data shows that mesquite (*Prosopis glandulosa*) may extend roots as deep as 53 m (174 feet) [3]. Mesquite trees on the Jornada Experimental Range near Las Cruces, NM, that were only 0.6 m (2 feet) tall produced numerous roots descended to a depth of several feet, then grew upward to within 50 mm (2 inches) of the soil surface [24]. One of these trees produced a root that was 22 m (72 feet) long. One mesquite tree growing in a playa that was periodically flooded had one root that extended to a depth of 5.5 m (18 feet). In all cases, cemented soil layers stopped the downward penetration of roots.

Heitschmidt *et al*. [24] studied the root system of 13 honey mesquite *(Prosopis glandulosa* Torr.var.*glandulosa*) trees in central Texas. The soils contained impermeable clay subsoils formed over the C soil horizon. Their work supports the classification of honey mesquite as a facultative phreatophyte (it may grow either as a phreatophyte or a non-phreatophyte depending on site conditions). The lateral root system of mesquite was concentrated in the upper one-foot layer of the soil. They also found that one large lateral root turned downward for 0.2 m (8 inches), upward for 0.3 m (12 inches), then downward again all within a horizontal distance of 0.2 m (8 inches). The single tap root of a large mesquite turned laterally in the upper layer of the parent soil material in the vadose zone and divided into three tap roots. Two of the subdivided tap roots extended downward, and one extended horizontally then upward. They found that 81 percent of all roots were contained in the top three feet of the soil and that only 4 percent of the roots extended below 2 m (6.5 feet). A mature honey mesquite tree had a leaf area index (LAI) of only 1.1.

Studies of water uptake by jarrah (*Eucalyptus marginata*) trees in Australia showed that this eucalyptus variety could extract water from groundwater down to a depth of 14 m (46 feet) in deep sands [25]. Other Australian studies demonstrated the following:

- River red gums (*Eucalyptus camaldulensis*) used groundwater in summer.
- Roots of jarrah (*Eucalyptus marginata*) can extend to a depth of 20 m (66 feet) along preferred pathways in heavy clay soil.
- *"Most of the root length of jarrah is found in the surface horizon, which dries out during summer, resulting in the tree becoming increasingly dependent on relatively few roots penetrating deeper into the soil mantle."* [25]

Some eucalyptus varieties are adapted and grown in California and Florida and may be useful trees for phytostabilization.

Trees from the genus *Populus* (including poplar, cottonwood, and aspen) are frequently recommended for use in phytoremediation. The genus *Populus* is a member of the willow family *(Salicaceae)*, consists of 29 species and is widely distributed in North America, Europe and Asia [26]. They have a predisposition to hybridize naturally or through controlled crossing.

Populus will perform at their full potential only on the best soils and in the best climate [26]. There is an anomaly in their behavior because they grow almost anywhere, but on poor sites, they produce less biomass. For best performance, they require the following:

- Medium-textured soil greater than 1 m (~3 feet) deep
- Large amounts of plant nutrients
- Ample soil aeration
- Soil pH between 5.5 and 7.5
- No hardpan, gravel, or other obstructions to root growth
- Ample rainfall and/or a water table at 1 to 2 m (3 to 6 feet)

Factors that reduce the growth rate of poplar, cottonwood, or aspen trees may also significantly reduce their ability to extract water from a water table. However, they will grow at many poor phytostabilization sites. If growing conditions are less than optimum at the site, the design should include measures that will ensure successful remediation. These measures are discussed in Section 5.

In spite of the potential problems cited above, trees may be expected to consume large amounts of water at appropriately selected contaminated sites. Because remediation usually requires relatively quick action, fast growing trees will be preferred. Trees that grow fast and are widely adapted include poplar, cottonwood, and aspen. Eucalyptus trees are adapted to the climate in some states and grow rapidly.

3.4.3 Grasses, Forage Plants, Sedges, and Reeds

Any plant that can remove large amounts of water from the soil or capillary fringe should be considered for use in phytostabilization. Grasses, forage plants, sedges, and reeds are such plants. They may be used alone or in combination with other plants, such as trees.

A young tree planting cannot cover all of the ground until it has grown for a time, and thus cannot keep the vadose zone as dry as desired. Grass or other plants grown between the tree rows may quickly provide groundcover, control erosion, and dry out the soil profile. If the groundwater is less than 3 m (10 feet) deep, the grasses may also consume water from the capillary fringe. Grasses such as switchgrass, eastern gamagrass, Bermuda grass, and others can grow above shallow water tables and extract large amounts of water from the capillary fringe.

Alfalfa is a perennial, tap-rooted plant that requires large amounts of water and possesses many of the desirable plant traits required for phytostabilization. It has been successfully grown where it derives its primary water supply from a shallow aquifer.

Sedges and reeds grow on the edge of a pond or in the water. If the groundwater is near the surface, in contact with shallow surface ponds or emerges in seeps and springs, sedges, reeds, and associated plants can be used to consume large amounts of water. Under some conditions, they may also reduce the contaminant concentrations in the water.

Grass, sedges, and reeds have plant specific soil and environmental requirements. It is usually possible, however, to find local plant material that will perform satisfactorily. For example, soils with low pH often release excess aluminum into the soil solution. There are several grass varieties that grow well with high aluminum content in the soil solution.

At sites where trees will be the primary plants, grass or alfalfa should be considered as interim plants grown at the start of the project and as fill plants between the tree rows. Alfalfa, grass, sedges, or reeds might also be used successfully at a site in the clear zone of a runway or an area where trees may attract unwanted birds.

3.4.4 Requirements for Good Root Growth

Phytostabilization projects are highly dependent on the action of plant roots; therefore, it is necessary to understand the role of roots and their requirements. The following are some of the many complex functions that plant roots serve:

- Roots provide the plant with water and nutrients absorbed simultaneously from deep and shallow soil layers, from moist and partially dry soil, and from soil zones of different biological, chemical, and physical properties.
- Roots provide anchorage for the plant.
- Fleshy roots store nutrients.
- Some plants develop adventitious shoots when the main root is damaged.
- Roots may be the primary source of cytokinins (growth regulators) and gibberellins (growth promoters) and of ethylene in flooded soils.

Roots and shoots (aboveground plant parts) are interdependent. Shoots are the source for organic metabolites used in growth and maintenance, and roots are the source for inorganic nutrients and water. If the top of a plant or tree is pruned or cut to reduce biomass, there is usually a reduction of root mass.

Part of the roots, particularly the small feeder roots die in response to soil drying or other stresses in a particular layer, while, at the same time, new roots may be growing rapidly in another soil layer. Thus, the distribution of actively growing and functioning roots may change from upper to lower and back to upper soil layers during one growing season.

Under optimum conditions, some plant roots may grow 20 mm (0.8 inches) per day. During most of the time, however, limiting factors reduce the rate of root growth below the optimum for the plant in question. Limitations on root growth impose a similar limitation on the ability of the plant to extract water and plant nutrients from the soil. The following factors might limit root growth:

- High or low soil pH
- Chemical toxicity from site contaminants (e.g., Al, Be, Cd, Pb, Cu, Cr, Fe, Hg, Zn)
- Allelopathic toxicants (i.e., produced by other plants)
- Soil temperature
- Salinity of the soil solution (caused by excess Ca, Mg, Na and other salts)
- Soil strength and physical factors

- Soil water content
- Soil oxygen
- Air-filled porosity in the soil

Low or high soil pH may be corrected or avoided in most instances. Application of lime to the soil may correct low soil pH. High soil pH may be reduced by soil treatment and leaching; however, leaching will usually not be an option at phytostabilization sites because it would raise the water table. Potential problems arising from either low or high soil pH may be avoided by selecting plants that grow under the conditions found at the site.

Chemical toxicity as a limitation to plant growth should be evaluated for each site. Some remediation sites contain enough toxic material to reduce plant growth.

Allelopathic toxicants are chemicals produced by other plants that kill or limit growth of roots for the plant in question. Allelopathy is an unlikely source of problems because the site manager has the option of controlling the type of plants grown at the site. However, these toxicants may remain in the soil from previous vegetation and may create a problem. If for example, the site was occupied by salt cedar in the past, it is possible that some grasses or trees would grow poorly at the site.

Soil temperature exerts strong control over rate of root growth. The site design should insure that the plants selected are adapted to the expected soil temperatures of the root zone. Each plant has an optimum temperature for root growth and soil temperatures either above or below that temperature result in reduced rate of growth. At the high or low temperature limits for each plant, root growth stops.

Salinity of the soil solution may be an important issue. Many natural compounds can contribute to the salinity level of the soil solution. As plants dry the soil, the volume of soil solution decreases and the salinity level increases rapidly. Saline soil solution produces an osmotic effect that reduces or stops water movement into plant roots. During phytostabilization, plants consume water from the capillary fringe followed by movement of groundwater upward into the capillary fringe. The plants remove pure water and only a small amount of salts. As a result, the total quantity of salts found in the soil of the vadose zone will increase during the life of the phytostabilization project. The resulting concentration of salts in the vadose zone may become a problem; therefore, plants that tolerate high soil salts are preferred for phytostabilization.

Soil strength and physical factors may limit root growth. Soil water lubricates friction planes if an adequate amount is present. The physical condition of the soil, particularly the size and distribution of soil particles and pore spaces strongly affect the movement and availability of water in the soil. Soil oxygen is required for the root's respiration process and oxygen movement and availability to roots is strongly affected by soil physical properties. The following physical factors are important in soils supporting plant growth (Rendig and Taylor, 1989):

- **Soil strength** may exert more control over root growth than any other parameter. Excessive soil strength can arise as a result of high soil bulk density, increased friction between soil particles, increased cohesion between particles or low soil water content. Soil bulk density and water content may be controlled or changed to improve rooting. Providing optimum values of soil density and water content usually assures adequate root growth.

- **Soil bulk density** is the mass of dry soil per unit bulk volume. Its value is expressed as Mg/m^3 or gm/cm^3 (lb/ft^3). Where units are expressed in the metric system and water is the reference, it is often expressed as a dimensionless value. Soil bulk density is a physical parameter that strongly affects root growth, but it can be measured and sometimes may be modified. In most soils plant root growth is reduced by soil bulk density above 1.5 Mg/m^3 (94 lb/ft^3), and values above 1.7 Mg/m^3 (106 lb/ft^3) may effectively prevent root growth [27 through 32]. Particle size distribution in the soil interacts with soil density to control root growth. Roots often grow better in sandy soils. Jones [30] demonstrated that plant root growth is reduced at soil bulk density greater than 1.5 Mg/m^3 (94 lb/ft^3) for most soils, and reduced to less than 20 percent of optimum root growth for all soils containing more than 30 percent silt plus clay and having bulk density greater than 1.6 Mg/m^3 (100 lb/ft^3). Grossman et al. [33] summarized 18 laboratory studies and found that root growth was only 20 percent of optimum for soil bulk density greater then 1.45 Mg/m^3 (90 lb/ft^3) except for 3 soils in which root growth was restricted at soil bulk density of 1.3 Mg/m^3 (80 lb/ft^3). It is often suggested that soil freezing and thawing may amend compacted soils. However, Sharatt et al. [2] presented evidence that adverse effects of soil compaction by steel wheels was not remediated by a century of freezing and thawing under native grass cover in Minnesota. In addition to inhibiting root growth, high values of soil bulk density result in low soil water holding capacity because pore space is reduced.

Soil water must be available to the plant in sufficient quantity to maintain hydrostatic pressure within the root cells and thus allow them to divide. Water is required for cell walls, and growth of hormones needed to loosen the bonds within the cell walls.

Soil oxygen is required in the root respiration process that converts carbohydrates to carbon dioxide and water, thus releasing energy needed by the plant for all of its processes. Oxygen moves through the soil by diffusion through air-filled pores, and to a lesser degree, by mass flow through air filled pores in response to wind forces on the surface. In order to sustain plant life, an adequate supply of oxygen must be available at the roots. Although a few phreatophytes can obtain oxygen for root activity through aboveground plant parts and transfer it downward inside the root (e.g., cypress trees), this is not common and most plants used for phytostabilization require that oxygen be present in the soil. Most plants become stressed if the air-filled pore space in the soil is less than 10 percent of the soil volume. The rate of oxygen movement through the soil is also very important. If the air-filled pores are too small or not connected, little or no oxygen can move from the atmosphere to the roots.

Air-filled porosity in the soil is important because each root requires air and oxygen to the roots and because these pores become channels for water and air to move rapidly through the soil during rain or irrigation. Soil pore space includes both large and very small pores. Small pores contribute little to the movement of air, but much of the soil water is stored in small pores. In a desirable soil structure, large and small pores are connected so that water and air may move freely and there is a desirable distribution of pore size. Total pore space and soil bulk density are inversely related, as a result, dense soils have little pore space and less dense soils have more pore space. The reduction of large pore spaces is an adverse impact of soil compaction. Sandy soils tend to have large pore spaces, while clay soils often contain more total pore space, but as smaller pores.

3.4.5 Harmful Effects of Groundwater on Plants

Groundwater may harm plants used for phytostabilization in two major ways:

(1) Salts dissolved in the groundwater may concentrate to harmful levels in the vadose zone as a result of transpiration and evaporation, and

(2) Contaminants found in the groundwater may pose a hazard to plants whose roots extend into the capillary fringe.

Wherever possible, plants that tolerate moderate to high levels of salinity should be selected for planting at the site and the possible toxic effect of contaminants in the groundwater should be evaluated.

Many cultivated crops, nut trees, and fruit trees exhibit a tolerance to saline irrigation water [34, 35]. Figure 7 presents five divisions for classifying crop tolerance to saline irrigation water defined by the electrical conductivity (EC) of the water [34]. The Date Palm is the only cultivated tree on their list that is salt-tolerant, whereas numerous fruit trees are sensitive to salt. There are several varieties of grass that are salt-tolerant, including barley, wheat, Bermuda grass, and desert salt grass.

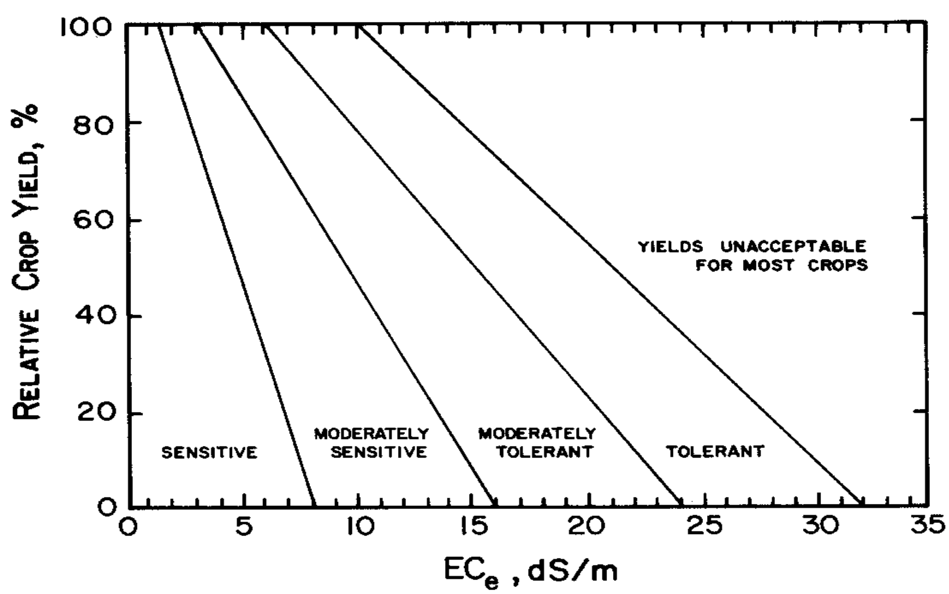

Figure 7. Divisions for classifying crop tolerance to salinity based on electrical conductivity [34]

3.4.6 Plant Selection

Trees and other plants selected for use at phytostabilization sites should be native to the area or well adapted to the local climate, resistant to local insects and diseases as well as capable of transpiring large quantities of water. The planner should consider the use of tap rooted perennials such as alfalfa, water-loving native grasses, plants that grow in water and trees. Because fast growing trees may have relatively short life, their expected life span should be evaluated to determine if it meets the requirements of the site. The plants selected should be capable of extending roots deep into the soil.

Trees may not cover all of the ground during their first years of growth, and a suitable grass may be planted between the rows to consume more water than the young trees alone. Where the water table is near the soil surface, grasses may extract significant groundwater. As the trees mature, they will kill the grass by shading.

3.4.7 Water Use by Plants

The goal of phytostabilization is to remove water from the aquifer; therefore, the planner needs realistic estimates of rate or quantity of water use by the plants selected. It is important to remember that trees or other plants generally consume readily available water from the top two or three feet of soil first in preference to extracting water from an aquifer at depth. When the upper soil layers begin to dry, the plant consumes more and more water from deep soil layers, including the aquifer.

When trees are small, they cannot cover all of the land at the site; therefore, the actual ET rate will be much less than for full tree cover. Actual ET rate of the trees may be estimated by considering the area covered by trees to be the shadow of the trees when the sun is directly overhead and measuring water use by individual trees. Actual ET rate for the site when the trees are young may be substantially increased by planting an adapted grass, alfalfa, or other plant species between the trees.

Water use by orange trees from producing orchards in Arizona and California shown in Table 3, indicate that some trees may not consume large amounts of water even in hot dry climates [23]. The climate in San Diego County is relatively cool and humid, whereas Maricopa County is hot and dry. These data were derived from field measurements; thus, they may contain errors. Fereres and Goldhamer, [36] state "information on estimated orchard ET is scant."

Table 3. Water Use by Oranges, April through October

County	Mean Temp. °F	Water Use (inches)
Maricopa, AZ	78	25
Riverside, CA	68	20
Orange, CA	68	16
San Diego, CA	66	9

From Hilgeman and Reuther [23]

In eastern Nebraska, alfalfa (a tap-rooted crop) used 20 to 25 percent more water from a water table at 0.9 to 1.5 m (3 to 5 feet) depth than did native grasses. Wallender *et al.* [38] found that cotton (another tap-rooted crop) consumed only 360 mm (14 inches) of water (60 percent of total water use) from a water table at 2.3 m (7.5 feet) below the surface during one crop year in California.

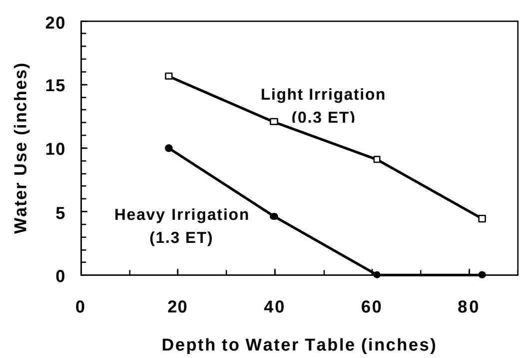

Figure 8. Growing season water use from the water table aquifer by irrigated alfalfa in North Dakota [4]

Benz *et al*. [4] reported on the effect of water table depth on water use by alfalfa from shallow water tables in North Dakota. Water use from the shallow water table aquifer varied from zero to

57 percent of total water use depending on treatment. Figure 8 shows the effect of water table depth on water use from the aquifer by alfalfa with either light or heavy irrigation.

Water use by alfalfa was measured in lysimeters operating with three different constant water table elevations [39]. The lysimeters were filled with disturbed, coarse-, medium- and fine-textured soils. The water tables were static at 0.6, 1.2, and 2.4 m (2, 4, and 8 feet) below the ground surface, and the treatments included no irrigation, irrigation with water table, and irrigation with no water table. The only water available to plants in the "no irrigation" treatment was groundwater. Figure 9 shows the ET rate from the "no irrigation" treatment. There was relatively small difference in the water use from groundwater between the water tables at 0.6 and 2.4 m (2 and 8 feet). There was good root development in the lysimeters and alfalfa roots extended below the water table into the saturated zone.

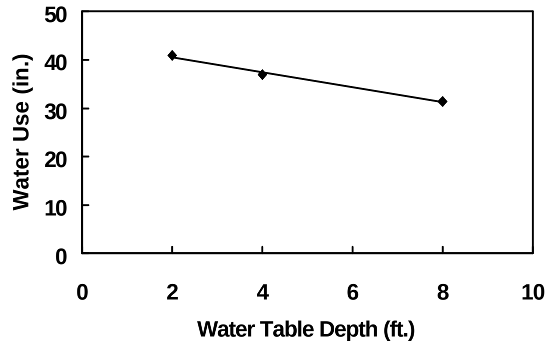

Figure 9. Annual water use from the water table aquifer by alfalfa with no irrigation, Reno, NV, [39]

There are few accurate data available on water consumption by trees from water table aquifers. Johns (ed.) [40] summarized water use by saltcedar in the deserts of California and Arizona. Saltcedar (*Tamarix gallica*) is an introduced phreatophyte that consumes large amounts of water from river flood plains in the Southwestern United States. Data derived from three field experiments showed that where the water table was at 1.2 m (4 feet) in a desert environment, saltcedar consumed more than 2,400 mm (78 inches) of groundwater per year, but where the water table was at 2.7 m (9 feet), it consumed less than half that amount. While there are differences in water use between sites because of elevation and climate, the trends are clear.

Johns (ed.) [40] conducted an extensive literature search on the use of groundwater by a wide range of plant species. The range of reported groundwater usage is summarized in Table 4 for a number of species that might be used for phytostabilization. The complete table of water usage complied by Johns is presented in Appendix B. Table 4 also lists the reported depth to the water table from which the plants are know to draw water for five of the species.

There is a wide variability in the amount of water consumed from the water table and the actual water consumption from water table aquifers appears to be less than the expected PET at all sites. In the case of the natural or unmanaged vegetation, it is likely that at some locations water use from the water table aquifer was limited by plant nutrients available to the plants, insect attack, or disease. It is also possible that root growth was limited at some sites by hardpans or other adverse soil conditions.

Water use from the water table aquifer by alfalfa was small in North Dakota. This appears to have been caused by preferential use of irrigation water from the uppermost soil layers because the "light" irrigation treatment used much more water from the water table aquifer than the "heavy" irrigation treatment.

Table 4. Range of Seasonal Water Use by Plants

Common Name	Scientific Name	Reported Range of Consumptive Use [1] (inches)	Water Table Depth (feet)
Aspen	Populus	9.9-24.18	
Cottonwood	Populus	40.6-72	10-20 [3]
Creosote Bush	Larrea Tridentata	9.25-10.2	
Fir-Douglas	Pseudotsuga Menzlesii	12.0-20	
Forbs and Grass Mix		17.0-29.6	
Forest (General)		14.5-21.0	
Grass		8.9-29.9	
Grass–Bermuda		28.8-73	
Grass–Meadow		4.8-33.47	
Grass–Native		5.12-24.3	
Grass–Pasture		8.4-27.2	
Grass–Prairie		7.6-36.3	
Grass–Salt		6.2-48.8	6-8 [3]
Kochia (Burning Bush)	Kochia Scoporia	22-26	12 [2]
Maple-Manitoba	Acer Negundo	16.1-20.8	
Meadow-Mountain		8.5-31.1	
Mesquite	Prosopis	14.5-40	40-100 [3]
Oak-Gambel	Quercus Ganbelii	11.39-18.8	
Oak-Scrub	Quercus Dunosa	16.3-24.8	
Pine	Pinus	12.3-47.0	
Pinyon-Juniper		14.53-27.53	
Poplar-Yellow	Liriodendron Tutipifera	26.2	
Russian Olive	Elaeagnus Angustifolia	18.6-114.6	
Saltcedar	Tamarix Chinensis	14.9-86	3.3-12 [2]
Sedge	Carex	21.8-76.9	
Spruce	Picea	14.9	
Willow	Salix	13.2-47.8	

1. Johns, Eldon L., 1989. *Water Use by Naturally Occurring Vegetation Including an Annotated Bibliography*, Task Committee, Am. Society of Civil Engineers, New York [40]

2. Gay [41]

3. Weaver et al.[42]

Note: 1 inch = 25.4 mm, 1 foot = 0.305 m

The data presented appear to support the following management recommendations to maximize the amount of water consumed from the groundwater:

- Place the phreatophytes to minimize depth from ground surface to the water table.
- Irrigate vegetation at phytostabilization sites only enough to establish and maintain healthy plants.
- Provide optimum soil conditions for root growth.
- Control disease and insect attacks by plant selection if possible, or if required, apply pesticides.

- Provide an adequate amount of plant nutrients to sustain growth. (Excess nutrients may contaminate the aquifer.).

3.5 Soils

Soil provides nutrients, water, and oxygen required for plant growth and mechanical support for the plant structure. Soil may also contain hard layers, contaminants, salts, and other features that limit or prevent plant growth. Most soils present minor to severe limits on plant growth and only a few are near perfect. The success of phytostabilization may be limited by the soil at the site, and thus it is important to know and understand the consequences of the soil properties at the site.

3.5.1 Soil Properties Required for Robust Plant Growth

Most phreatophytes grow best where the soils are deep and fertile and offer little or no mechanical resistance to root growth. For example, many grow best on sandy loam soils found in alluvium deposited along rivers and where the water table is less than 3 m (10 feet) below the soil surface. Many phreatophytes will grow in less desirable soils, however; their growth rate may be slow and water use from the groundwater may be affected.

The U.S. Department of Agriculture (USDA) soil textural classification system is shown in Figure 10. A desirable soil will often contain at least 20 percent or more sand. Soils that contain sufficient cation exchange capacity (CEC) to hold adequate plant nutrients and provide a good root growth environment will include sandy loam, loam, and silt loam in addition to clay soils that normally have high CEC. Sandy clay soils tend to have high soil strength. Soils high in clay may limit the oxygen supply to the plant roots.

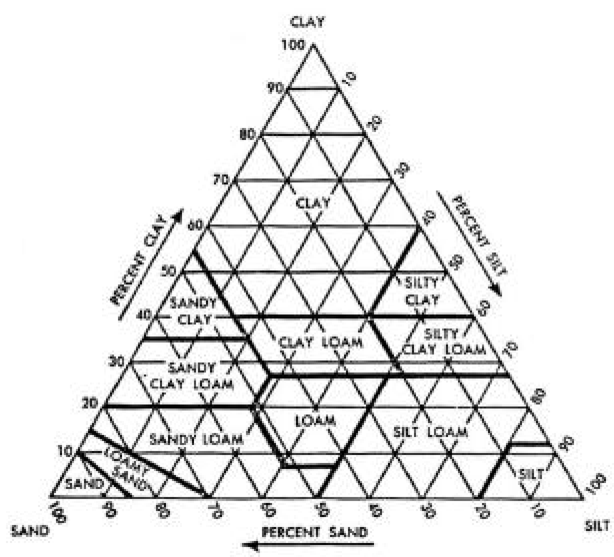

Figure 10. USDA Textural Classification of Soils

Humus is an important component of some soils. Humus or soil organic matter is composed of organic compounds in soil exclusive of undecayed organic matter. Manure, compost, and grass clippings are organic matter, but they are not humus [53]. Humus is relatively resistant to decay and provides significant additional cation exchange capacity in addition to improving the soil structure so that the soil is more favorable to plant growth. However, plants grow well in soils that contain little humus if they are fertilized (e.g., lava ash in Hawaii, irrigated and dryland soils of the western Great Plains and the 11 western states). The dark soils of the Corn Belt, northeastern states, and most of Canada typically contain large amounts of humus. Soils containing natural humus should be preserved and used carefully. The addition of organic material, other than peat, to provide long-term improvement of soil structure or soil tilth may not be worth the expense, because most other organic additives decay rapidly.

Where the soil contains hard or dense layers, the soil should be modified. Boreholes to the water table can be drilled and backfilled with desirable soil, peat-soil mixtures, or otherwise modified to allow good plant growth and root development. If it is impractical to modify undesirable soils, then an alternate remediation method may be required because plants cannot be forced to grow well in poor soil.

The soil pore space contains water and soil air. Rapid growth of plants requires adequate water content in the top one to two feet of soil for at least part of the growing season; the well-watered area should be at least as large as the shadow of the tree at noon. A few phreatophytes can grow with little or no oxygen in the soil. However, most plants require adequate soil oxygen. Soil below the water table normally contains too little oxygen to support robust root growth except by phreatophytes. The capillary fringe above the water table may contain a near optimum combination of water and oxygen.

All plants require an adequate amount of plant nutrients. The nutrient used in largest amount in plant growth is nitrogen. Plants can absorb nitrogen in the soil solution if it is in the nitrate form, and soil organisms normally modify existing forms of nitrogen to the nitrate form. Phosphorus is required in smaller amounts than nitrogen; however, it is often deficient in soils. Western U.S. soils may contain large amounts of phosphorus, but it may be held in unavailable forms because of the excess calcium found in these soils. Potassium is also an essential element and is frequently deficient in eastern U.S. soils that have been leached. There are a number of other essential plant nutrients; these nutrients are required in small amounts and are found in adequate amounts in many soils.

The soil should be free of harmful constituents such as manmade chemicals, oil, and natural salts. The natural salts of calcium, magnesium, and sodium can create high salinity in the soil solution, thus raising the osmotic potential of the soil solution high enough to prevent the plants from using all of the soil water. In addition to its part in soil salinity, sodium can cause deflocculation of clay particles, thereby causing serious soil crusts, poor soil aeration, high soil strength, and other problems.

3.5.2 Soil Properties at Remediation Sites

Most Air Force bases were built on fertile soils because the large areas of level land required for runway construction are frequently associated with fertile agricultural soils. However, during routine Air Force operations, soils are often amended with crushed rock, gravel, and other material and compacted by heavy, wheeled machinery and by trucks and cars. Therefore, the soils at the proposed phytostabilization site should be examined carefully during early stages of planning to determine their current suitability for growing plants. Additional details regarding soil physical properties may be found in *Environmental Soil Physics* by Hillel [43].

4 Site Screening

Because remediation activities are expensive, it is desirable to evaluate a site to determine whether phytostabilization may be appropriate there. The goal of this section is to assist the Air Force RPM in making the correct choice quickly and at low cost, and to reduce the risk of decision-making error. A decision that phytostabilization is a viable technology should then be confirmed by a more complete investigation during the design phase.

The site screening may typically be undertaken with existing information. Most Air Force remediation sites have been evaluated, and substantial factual information is available. Table 5 presents a list of the types of information needed for the feasibility screening. It will be rare that missing information will require new field investigations during screening evaluation of an Air Force site.

The following sections describe a ten step screening process to determine whether phytostabilization is suitable and feasible for this application. If each of the ten screening criteria described below and shown in Figures 11 and 12 are passed, there is a high probability that phytostabilization is both appropriate and feasible for the site in question. Funding for the design and implementation of a system should be budgeted and the design phase initiated as soon as funding is in place.

Table 5. Site Screening Data Requirements

Geological properties of the soil and groundwater
Surface and vadose zone soil types
Aquifer hydraulic conductivity and intrinsic permeability
Extent contamination plume [vertical (depth) and horizontal (lateral)]
Groundwater flow rate and water table elevations
Redox potential (400 mV > Eh > 800 mV optimal aerobic; 100 mV > Eh > 400 mV acceptable aerobic; Eh < 100 mV need stimulation; Eh < 0 reducing conditions)
Assessment of existing site vegetation
Agronomic conditions (soil and groundwater minerals, pH)
Climatic conditions (temperature, humidity, rainfall, and growing season)
Nutrient concentration (nitrogen, and phosphorous)

4.1 Objectives Screening Evaluation

The objectives for remediation of the site should be clearly defined before evaluating the possible use of phytostabilization. The questions posed below regarding site objectives should be answered to the extent possible by using available site information. A decision chart for the objectives screening evaluation is presented in Figure 11.

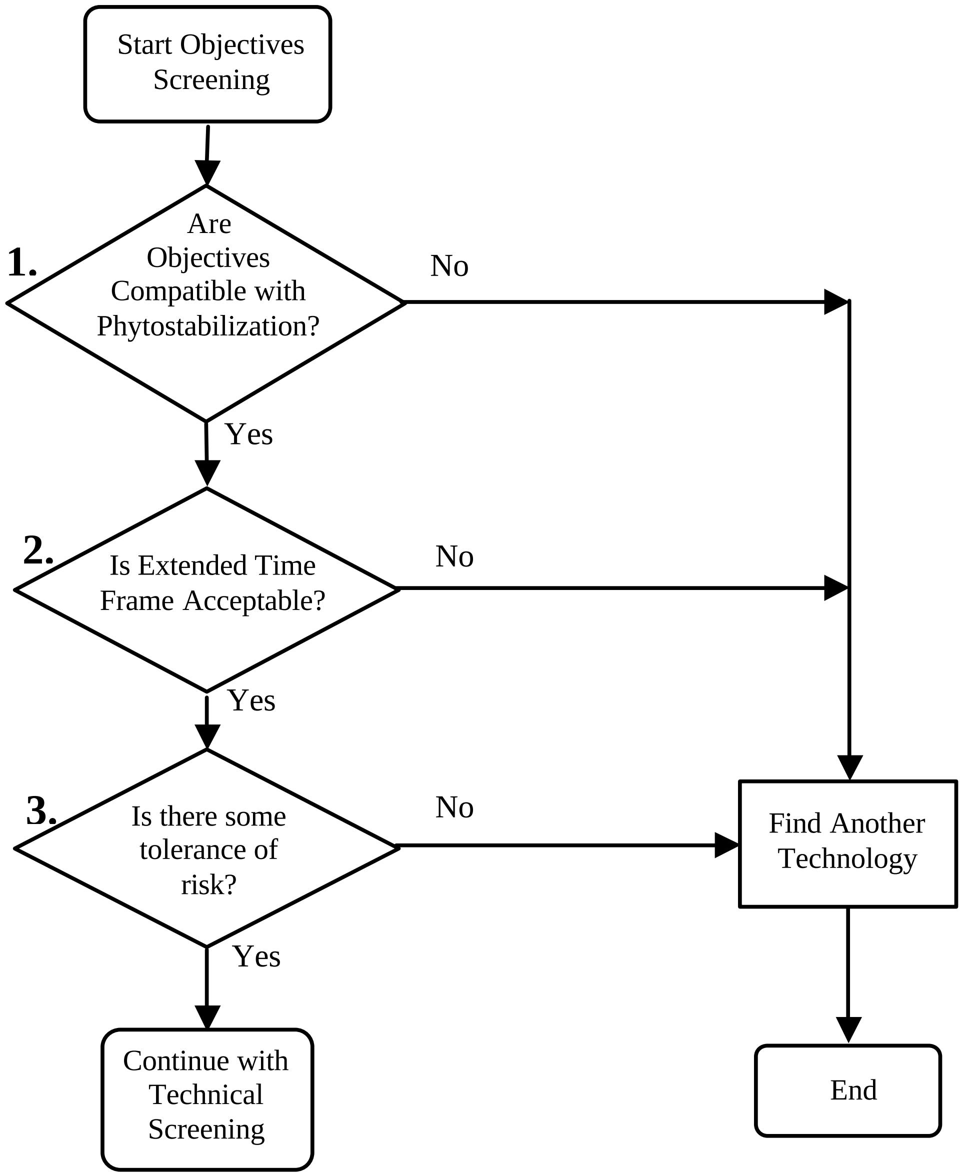

Figure 11. Decision chart for Objectives Screening

When the objectives are known, then a sound, technical decision that fits the objectives for the site and the expectations of the owner, the public, and the regulators is possible. If a decision is made to use innovative technology, the technical components, the reasons for the decision, and the expected outcome should be presented to the public and to the regulators. It is desirable to include all parties involved in the decision making process from the beginning.

4.1.1 Compatible Objectives

Phytostabilization must be compatible with the remediation objectives for the site (see decision box #1, Figure 11). If the intention is to use phytostabilization to control the movement of a shallow aquifer or to extract groundwater from the aquifer or soil, then phytostabilization may be appropriate. Other objectives may be beyond the scope of the technology and should be evaluated to verify that phytostabilization is indeed appropriate for this application.

4.1.2 Remediation Timeframe

The time schedule requirements to implement and to attain control of the groundwater movement should be considered (see decision box #2, Figure 11). It may take several years before the plants can be installed at the site and then reach sufficient maturity to provide the expected groundwater removal. Phytostabilization may be appropriate if such an extended implementation schedule is acceptable. If rapid implementation is required, however, then another technology may be more appropriate.

4.1.3 Risk Tolerance

Because of climate variations from season to season and year to year, phytostabilization might not perform to 100 percent of expectations at all times (see decision box #3, Figure 11). The RPM must consider whether 100 percent performance is important in this application or if there is some tolerance of risk and room for error.

4.2 Technical Screening Evaluation

The following sections discuss technical factors that should be considered as part of a technical screening evaluation following objectives screening. A decision chart for conducting the technology screening evaluation is presented in Figure 12. Keep in mind that a more detailed evaluation may be required to produce the data needed for the final design of a phytostabilization system.

4.2.1 Favorable Climate

There are several climatic variables that affect the performance of phytostabilization systems (see decision box #4, Figure 12). The suitability of two key factors, precipitation and evaporation, are best evaluated by the ratio of the potential ET to actual ET (PET ratio). A discussion of the PET ratio is presented in section 3.3.2 and estimated values are listed in Table 2 for 109 Air Force locations in the continental United States While it is true that specific site conditions will affect the efficacy of the technology, phytostabilization is probably appropriate for use in most areas where annual evaporation exceeds annual precipitation.

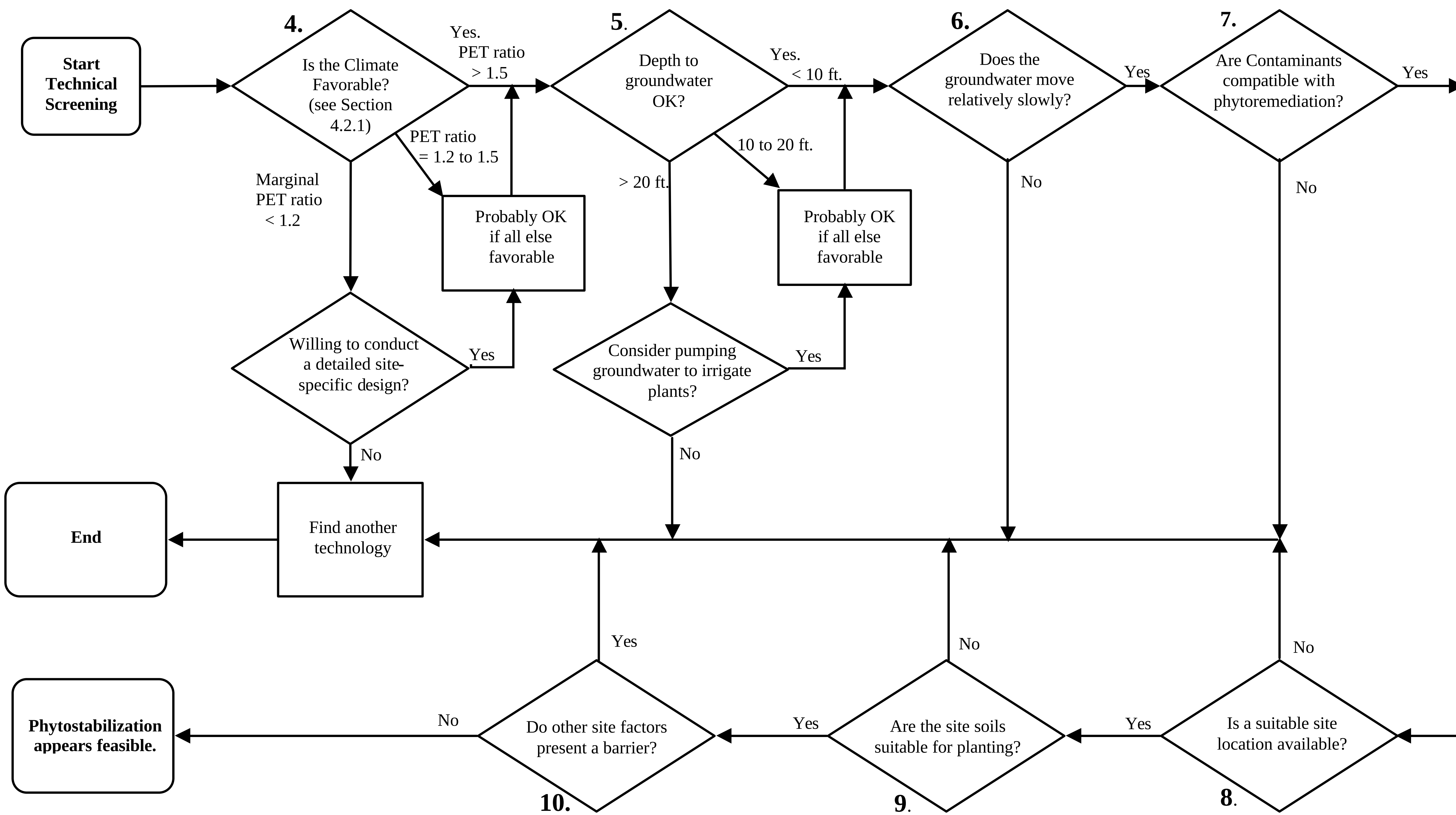

Figure 12. Decision Chart for Technical Screening

The relative harshness of the climate is reflected in the plant hardiness zone for the area. The colder climate of the northern tier of states requires plants that can survive hard freezing conditions while the hot climate of the desert southwest requires plants that can tolerate drought conditions. Appendix C contains a plant-hardiness zone map of the United States that indicates annual minimum air temperatures for each zone. This information will allow a quick determination of whether particular plant species might be adapted to the site.

The length of the growing season is also an important parameter because deciduous trees and other plants consume little water when dormant. If the growing season is short, it may be possible for the water table to recover sufficiently during dormancy so that the contaminant plume is not contained by the end of the dormant season. One might select evergreen species for the site, but they may or may not control the water table during winter because their rate of water use may be small during the cold months. The length of the growing season may be estimated as the time between the last spring frost (0 deg. C or 32 deg. F) and the first fall frost. The length of the growing season and the frost dates vary from state to state, but this information can be obtained by calling the agricultural extension service for the state where the site is located.

4.2.2 Depth to Groundwater

The depth that plant roots must penetrate to reach the water table is a key parameter to be considered (see decision box #5, Figure 12). Section 3.1.1 clearly indicates that phytostabilization will be most successful at sites where the groundwater is near the surface. The depth to groundwater should be obtained during screening and compared to the following simple rules-of-thumb:

- **Groundwater table less than 10 feet below grade—**phytostabilization is likely to be effective
- **Groundwater table between 10 and 20 feet below grade—**the amount of water consumed from groundwater by each plant will be less than might be expected from a shallow water table but may still be effective
- **Groundwater table deeper than 20 feet below grade—**difficult conditions with the probability for success low. Special analysis is required that may be beyond the scope of preliminary site screening.

4.2.3 Groundwater Movement

The amount of groundwater that the plants will be expected to remove is a function of the rate of groundwater movement. If the groundwater moves relatively slowly, phytostabilization might have a good chance of removing a substantial portion of the water moving through the area. Therefore, it is important to estimate the rate of groundwater movement (see decision box #6, Figure 12). Groundwater modeling may be needed to provide an estimate of the rate of groundwater movement. However, simple estimates make using the Darcy equation may be adequate for the preliminary evaluation.

4.2.4 Contaminant Compatible with Phytoremediation

The affect of the contaminant on plant growth should be investigated to determine whether the contaminants in the groundwater are compatible with phytoremediation (see decision box #7, Figure 12). A literature search showing that there is a history of phytoremediation applications with the same contaminants would provide assurance of compatibility over a range of concentrations. If no prior applications can be found in the literature, it will be necessary to investigate further to determine whether the groundwater contaminant concentrations will adversely affect the plants. The state agricultural extension service may be a good source of information, particularly about natural soil salts and agricultural chemicals.

4.2.5 Suitable Site Location

A suitable location to install the phytostabilization must be found (see decision box #8, Figure 12). The site selected must be on the path of the groundwater contamination plume and must have sufficient planting area for the required number of plants. Be aware of other site restrictions that may also limit site selection. For example, height restrictions imposed near flight lines will limit where trees may be planted.

If there are currently buildings, pavement, utilities, or other infrastructure on site the cost of removal or relocation must be considered. Current or previous construction activities on the site may also have compacted the soils to the extent that root growth would be impeded or prevented (see Sections 3.4.4 and 3.5.1), and additional effort and cost may be required to make the soil suitable for planting.

4.2.6 Site Soils

During screening, all of the available data that describe the surface soils, vadose zone soils, and the uppermost aquifer should be assembled and evaluated (see decision box #9, Figure 12). Data describing the soils at the site are often available from the Natural Resources Conservation Service of the U. S. Department of Agriculture at either county or state offices. These data are very useful in defining the soil materials likely to be found at the site if no significant construction or cutting and filling have occurred at the site. Particular attention should be paid to soil compaction or other modifications resulting from Air Force activities.

Phytostabilization will perform best where the soils are deep and fertile and composed of sandy to medium-textured particles (e.g., sandy loams and loams.). The soil should contain no hard layers, few rocks or gravel, and no soil layers more dense than a bulk density of 1.6 Mg/m^3 (100 lb/ft^3). Soil bulk density less than 1.45 Mg/m^3 (90 lb/ft^3) is even more favorable to successful phytostabilization. Soils that do not meet these criteria may be used, but they may require modification to allow rapid downward growth of roots. For soils that may allow slow root growth (e.g. heavy clay), but not stop root growth, it may be necessary to plan for an extra season in which to establish adequate root growth to achieve the goals of phytostabilization.

As discussed at length in section three, cemented, high-density layers of soil may be strong enough to prevent root penetration. Such layers should be identified during preliminary screening, and if they exist they must be modified to assure success of the phytostabilization effort. In addition, chemical spills, soil compaction, or the addition of rocks and gravel to the soil by the Air Force during normal operations in the past could create undesirable soil or vadose zone conditions.

4.2.7 Other Site Factors

Other factors peculiar to the site may be important (see decision box #10, Figure 12). The following factors should be considered during the site screening:

- Nearby springs and connection to streams or other surface water
- Use or non-use of the uppermost aquifer for domestic, livestock, or irrigation water
- Wildlife issues
- Attractiveness of the vegetation to birds and the proximity of the site to runways or other locations where aircraft operate
- Access to the site by roads, availability of power, and water supply for irrigation

5 Design and Establishment

This section on design and establishment discusses issues common to other *in situ* remediation technologies and those specific to phytostabilization. This document is not a complete design or establishment guide but rather a summary to help the RPM manage a phytostabilization project. It is assumed that the RPM's contractors will have the necessary remediation design expertise to successfully complete the project.

Design Team

Design of a phytostabilization application will typically be done by a contractor working for the RPM, and require the integration of a number of technical disciplines. The contactor should have access to the following disciplines or have personnel on the team capable of completing each of the tasks:

- ***Agricultural Engineer.*** Evaluate the phytostabilization application, coordinate all the gathered information and design field systems (i.e., irrigation, pumping, water control, rooting, security, automated sensors, etc.).
- ***Soil Scientist/Agronomist.*** Evaluate the ability of the soil conditions to support plants and develop a soil amendment plan.
- ***Hydrologist.*** Complete groundwater modeling, conduct a site-wide water balance, and control runoff from irrigation systems.
- ***Plant Biologist/Botanist/Agronomist.*** Evaluate a range of suitable plants and determine if the soil or groundwater are sufficient to support the plants of choice. Determine planting requirements and develop plans for planting in the field.
- ***Risk Assessor/Toxicologist.*** Formulate exposure pathways and risk scenarios, as needed.
- ***Cost Engineer/Analyst.*** Review the projected cost of the system and compare alternatives.

5.1 Planning for Implementation

The earliest stages of design should begin with defining the remediation objections, performance criteria, and the closure criteria.

5.1.1 Remediation Objectives

The system designer and design team should develop the remediation objectives from the standpoint of the outcome expected by the site owner, regulators, stakeholders, and the public. The remediation objective for phytostabilization will usually be to contain/control groundwater and contaminant movement. Interviews with regulators, site owners, and system designers should establish that all parties share the same objectives and cleanup criteria. The team should also determine if there have been other similar phytostabilization projects (contaminant, environmental conditions, plants, etc.) from which operational and closure data is available.

Phytostabilization is a groundwater containment technology, with essentially identical remedial goals as a pump and treat remedy. Like pump and treat, phytostabilization is presumed to be effective in containing and remediating the dissolved phase plume only. A successful phytostabilization project usually requires the removal or containment of the source of groundwater contamination in order to achieve cleanup goals.

5.1.2 Performance and Closure Criteria

Performance criteria for the phytostabilization system should be established by the RPM working with their contractor. After performance criteria have been established a monitoring protocol can be developed for the project. The RPM, site owner, system designer, regulators, and stakeholders must come to a consensus on how, when, and where the data will be collected and analyzed and how the results and data will be documented and reported. Performance evaluation results and closure requirements should be included in this documentation. A protocol for the submission of a request for no further action at the site should also be established and have the consensus or approval by the regulating authority.

5.2 Data Validation

The site screening conducted to determine the feasibility of phytostabilization (see Section 4) was based primarily on information from the initial site characterization supplemented with site-specific data. It is prudent to verify that the information and assumptions used in the screening are current and valid. This section describes some of the information gathering and data validation that might be included as part of the design procedure.

5.2.1 Site Visit

The design team should become familiar with site conditions by conducting a site visit. Initially, the design team should determine what areas are available to be planted, what potential obstructions may exist (above, below, and on the surface), and what existing vegetated areas there are at the site. Photographic records of the relevant areas will provide documentation for future reference as the designs and plans are developed.

During the site visit individual team members will focus on specific information pertinent to their area of responsibility. Topics of interest include the following:

- Agronomic parameters of the soils and soil conditions
- Soil amendment and irrigation requirements
- Surface flooding or erosion
- Existing vegetation that is applicable to the proposed phytostabilization.

5.2.2 Site Climatic Conditions

All the information related to the seasonal changes in climate, including temperature, humidity, precipitation (rain and snow), wind (speed and prevailing direction), and the probabilities of floods or droughts (25-, 50-, 100-year events, etc.) should be available from local weather stations (nearby cities, airports, major operating facilities). These site characteristics affect the design (plant selection and planting density) and maintenance (irrigation, mowing, etc.) of the phytostabilization system. Furthermore, these factors are paramount to successfully designing systems to affect local hydrology. Flood and drought tolerances are criteria that can be used during plant selection.

5.2.3 Verification of PET and AET Estimates

The estimates of PET and AET presented in Section 3.3.2 and listed in Table 2 were based upon assumed soil conditions and plant selections for each base. After the site has been chosen and the plants selected for this application, the estimates of PET and AET should be revised using the proposed design. This will verify the feasibility determination and provide site-specific data for design of the planting layout.

5.2.4 Groundwater Modeling

Since phytostabilization is a long-term remedial action, the use of groundwater modeling will be necessary to estimate a cleanup time and demonstrate that the contamination will not migrate to sensitive receptors during the projected cleanup time. Modeling can also be used to estimate the amount of groundwater that must be removed by the plants in order to achieve containment or control of the contaminant plume. For the simplest applications involving groundwater remediation, simple capture zone calculations might be used to estimate whether the phytostabilization can be effective as a biological pump to entrain the contaminant plume [44, 45]. In most cases, however, more extensive modeling with Modflow or similar models will be required to adequately model the groundwater movement. As a minimum, the verifications modeling should be of the same sophistication as used in the original site characterization.

The plants may take several years of growth to become established during which time they will typically require irrigation to supply their water requirements. Hydrologic modeling may be required to estimate the rate of percolation to groundwater during this period when the plants are irrigated. Typical models used for these purposes include EPIC (Erosion/Productivity Impact Calculator), which is used to estimate PET, and HELP (Hydrologic Evaluation of Landfill Performance). These models will require weather data specific to the site in order to model the evapotranspiration capabilities of the various plants.

5.3 Plant Selection

5.3.1 Plant Selection Criteria

Plant selection is one of the most important factors determining the success or failure of the phytostabilization project. Once the planting site has been selected and growing conditions at the site have been identified, the next goal of the plant selection process is to choose plants with characteristics appropriate for these conditions. Specific information needed for plant selection includes tolerance to various factors including temperature, moisture, diseases, and pests (see Appendix C: U.S. Department of Agriculture climate zones). Information can be gathered from the state Agricultural Extension Service and other local, state, or federal agencies and offices, or from universities. The Internet also has abundant information on plants. One very useful source is the Plant Materials Program of the USDA Natural Resources Conservation Service (http://Plant-Materials.nrcs.usda.gov/). Another is the USDA national plants database (http://plants.usda.gov/).

The use of a mixed variety of vegetation is generally preferred over monostands due to several advantages including the following:

- Monostands can be susceptible to diseases that can destroy the entire phytostabilization system, while mixed stands may only lose one or two species.
- Mixed stands support more diverse microbial communities (promoting potentially more complete rhizodegradation by further breaking down by-products).
- Synergistic effects such as nutrient cycling can be obtained in mixed stands.
- Mixed stands contain a more naturalized appearance.
- Mixed stands promote biodiversity and potential habitat restoration qualities.

The plant selection process begins by examining (listed in order of suitability) pre-existing species; native species that are already populating the region; hybrid species related to or grafted from pre-existing, literature, or native species. These categories of potential candidate species are discussed in detail below.

Plant species already growing at the site and in the contaminated groundwater have already exhibited tolerance to site conditions. However, tolerance does not equate necessarily to the ability to remediate, and the suitability of these plants for phytostabilization would need to be confirmed. If the species that are already growing at the site also appear in a phytostabilization literature database, then species selection becomes relatively simple.

Other native species from surrounding areas should also be evaluated because these are acclimated to the climatic conditions of the region. This can include native, crop, forage, and other types of plants that grow under the regional conditions. A list of these plants can be obtained from a local agricultural extension agent.

In most applications, plants that are adapted to local conditions will have more chance of success than non-adapted plants. The use of mixed species of vegetation can also lead to greater chance of success than the use of monocultures. Care should be taken to avoid introducing plant species that are invasive or a nuisance. In cases where the spread of the plant is undesirable, sterile varieties should be chosen to prevent plant reproduction.

Even though a native species may not appear in a phytostabilization databases, there are several advantages of pursuing these species as potential candidates rather than introducing a new species to the region. Specifically, two Executive Orders address the protection and use of native plants. The first was signed on April 12, 1994, and requires all federal agencies to use regionally native species whenever federal funds are expended for landscaping. It promotes recycling of green wastes, reducing fertilizers and pesticides, and directs agencies to create outdoor demonstration projects using native plants. The second Executive Order specifically addresses invasive species and was signed on February 3, 1999. It requires federal agencies to prevent the introduction of invasive species and to detect and respond rapidly to control established populations of invasive non-native species. Native, “non-food” plants are desirable for ecosystem restoration.

If suitable pre-existing or native species cannot be found, cultivated species might be considered. Forage, crop, and horticultural species have been used extensively for landscaping and re-vegetation efforts and serve as a primary source of selected plant materials for species propagation and cultivation (see hybrid species below). The seed and planting stock of this group is readily available and less expensive than native species. Furthermore, through years of selection, growers have found varieties that contain natural resistances to diseases, various climate conditions, pests, and other potential growth deterrents. In many cases, vigorous, locally adapted varieties of grasses or other species may be appropriate choices.

Hybrid species have been utilized for decades in landscaping, agriculture, horticulture, and forestry, and hybrid poplar and willow species have been used extensively in phytostabilization. The advantage of using hybrid species is that they are usually selected for specific characteristics that can optimize the phytostabilization system. For example, a fast growing variety can be combined with a disease-resistant variety to incorporate the qualities of both in the hybrid.

Because of public concern, hybrids should not be mistaken for genetically engineered plant species. These differ from genetically engineered species (described below) since genetic manipulation is conducted at the cellular level (transferring DNA from one species to another), whereas hybridization occurs at the tissue level (typically within a species). Hybridization (particularly cross-pollination) is an occurrence in nature itself.

5.3.2 Use of Grass and Trees Together

Use of grass and trees together is recommended to maximize the total ET at a site. Using a grass (or other surface vegetation) cover between trees will control erosion and help keep the shallow soil zone dry. Low-growing vegetation between tree rows will increase the rate of drying for the upper soil layers. As a result, infiltration of rainwater to the water table will be limited and trees must draw their water supply from the groundwater. A grass cover will be limited and the trees will extend their roots to draw their water supply form deeper in the soil profile. Ideally, under these conditions phreatophyte trees will draw their water from the capillary fringe. After the tree canopy closes, the low-growing vegetation will no longer be needed and will probably die because of inadequate sunlight.

Grass, sedges, forbs, and forage plants like alfalfa may be used alone or in combination with trees and may be adequate alone (i.e., without the trees) on sites with very shallow groundwater.

5.3.3 Performance Estimates for Plants

In order to accomplish planning and design objectives, and to assess performance of the system, the rate at which plants consume water from the groundwater must be determined. Because it is impossible, for practical purposes, to measure water consumption directly on grass, sedges, alfalfa, etc., their water use must be estimated from climatic data. Water use by large stemmed and woody plants like trees may be measured in the field; however, it is seldom practical to measure water use by more than 2 or 3 percent of the trees. As a result, the water use by a phytostabilization system must be estimated from calculated values of PET and ET. Each of these components of performance estimation was discussed in Section 3.3.

5.3.4 Ecological Risk Assessment

In some cases it will be important to consider the hazard from consumption of the plants and the transfer of contaminants through the food chain because the contaminants could accumulate in the plants. For phytostabilization projects where the contaminant might be accumulated or transported into the plant estimating the exposure to wildlife that could be incurred by ingesting the plants can reassure regulators and the public that the project itself will not represent a conduit to further environmental exposures. These calculations can also be used to target the species that may be exposed to potential risk so that institutional controls for the site can be targeted toward those species. For example, calculations may show a possible risk to grazing mammals but not to insectivorous or carnivorous birds; therefore, fencing alone may be adequate protection for such a site. Ecological risk calculations for some sites may show no risk to wildlife that trespasses onto the site; therefore, this information could be used to reduce costs for the project by demonstrating that institutional controls are unnecessary.

5.4 Implementation Design

5.4.1 Site Selection

Once the site-specific data validation is complete, the selected planting site can be evaluated to verify that it meets all of the project requirements. The area of evaporative surface required, and hence the number of trees or other plants, can be calculated from the estimated groundwater removal requirement (see Section 3.1.2) and the site-specific estimates of water removal by each plant (see Section 3.4.7). The required planting area can then be calculated and the selected site checked to verify that sufficient area is available. A planting layout should be produced and compared to the planted area assumed in the revised groundwater modeling. Variations between the planting layout and the planted area assumed during preliminary groundwater modeling should be evaluated to determine if the groundwater modeling needs to be revised.

The planting layout should be check for existing buildings, pavement, utilities, or other infrastructure in the planting area. Conflicting infrastructure must be removed or rerouted to allow room for the new planting. Additionally, any previous development on the site will likely have resulted in compacting of the soil. As described in Section 3.4.4, soil compaction will making it difficult for roots to penetrate to the groundwater table and capillary fringe. The soil densities in previously developed areas should be investigated further to determine if some form of mitigation will be necessary when preparing the soil for planting.

5.4.2 Water Balance

Both design and assessment of system performance require a complete water balance. Some of the elements of the water balance can be measured at the site but not all (e.g., for practical purposes, water use can not be measured directly at the site for grasses or alfalfa). Other elements of the water balance must be obtained from modeling or other sources.

Design of a phytostabilization system requires precipitation data measured at the site. Precipitation is an important component of a performance estimate and it should be measured at the site daily.

Most of the precipitation falling at the site will be lost back to the atmosphere by ET if plants or bare soil exist at the site. A primary design and monitoring parameter is the expected increase in ET resulting from the management of the vegetation planted to achieve phytostabilization of the groundwater at the site. Values of potential ET (PET) and actual ET (AET) were calculated and are presented for many Air Force facilities in the continental United States in Section 3.3.2 [19].

Soil water content and soil water potential may be measured in the field to estimate flow of water through the vadose zone. However, in order to achieve acceptable accuracy these measurements will require substantial expense and generally cannot be justified. It is often more practical to measure water table elevations and evaluate groundwater flow. Estimates of water flow through the vadose zone can be made with an appropriate model such as EPIC.

The amount of groundwater flowing into or away from the site must be known to complete the water balance at the site. Groundwater flow must be calculated from field measurements and may require a numerical groundwater model to estimate flow rates and volumes. A calibrated groundwater model can be used throughout the life of the project to evaluate hydrogeologic data as it is collected.

5.4.3 Soil Modification

Because groundwater contamination at Air Force bases often occurs under industrial sites, the soils in available planting areas may have been significantly altered by past activities. These modified soils may or may not provide a suitable medium in which to grow trees or other plants. One condition commonly found in the soil of disturbed sites is excessive compaction of soil. This single condition can adversely affect several important soil parameters including soil bulk density, water holding capacity, porosity, and aeration. Often, however, the soils may be modified to produce suitable growing conditions.

The soil at the site should be investigated for its suitability for growing the plants of choice, and if necessary, appropriately amended. The soil properties that should be investigated are listed in Table 6. A more extensive discussion of these and other conditions for good root growth (and therefore robust plant growth) is presented in Section 3.4.4 Requirements for Good Root Growth. Three publications from the Soil Science Society of America are excellent references for soil testing methods to determine the suitability of phytostabilization at a site [46, 47, 48].

Gravel or rock material is often found in disturbed soils and the impact of their presence should be evaluated. Gravel and rock reduce soil-water–holding capacity, soil aeration, and pore space. In addition, the gravel and rock may disrupt or prevent normal plant rooting and could reduce the effectiveness of phytostabilization. There is no practical way to remove the gravel or rocks except by removing all of the soil, which is an expensive process. If the soil is adequately loosened and friable between the gravel and rock pieces, plants may grow sufficiently well to achieve the goals of the project. However, the plants may require additional irrigation, fertilizer, and other treatment.

Table 6. Summary of Soil Properties for Optimum Root Growth

Property	**Optimum Conditions**
Soil bulk density	1.35 Mg/m^3 to 1.45 Mg/m^3, (maximum 1.6 Mg/m^3)
Particle size distribution	Sandy loam, loam and silt loam
Pore space and soil oxygen status (aeration)	>10% pore space should be air-filled, with pores well connected to allow oxygen flow though soil
Water-holding capacity	Greater than 0.1 volume fraction
Soil temperature (plant-specific parameter)	Temperature should be within optimum range for selected plant(s) during the growing season.

Surface Soils: In most cases, trees are planted because of their deep rooting capabilities, but it is also highly desirable for tree roots to grow laterally in all of the soil, including the upper two feet. This is important to the overall health and stability of the tree. Soils that have been compacted to a soil bulk density in excess of 1.5 Mg/m^3 (94 lb/ft^3) should be thoroughly loosened.

The planting operation should avoid compaction by tools (such as augers and backhoes), heavy machines, and wheeled vehicles. Track-mounted machines are preferred to reduce soil compaction. Wheel traffic should be minimized, and the soil should be sufficiently dry to prevent wheel tracks more than one-fourth–inch deep in the surface. Machines on wheels that operate in the planting area should be mounted on low-pressure tires (tires designed for less than 10 pounds per square inch pressure).

If the surface soil is too dense, it may be loosened by chiseling or moldboard plowing to a depth of 0.45 to 0.9 m (18 to 36 inches). It is preferable to do this before irrigation supply lines or other objects are buried on site in order to avoid damaging them.

Subsurface Soils: If the subsoil or vadose zone contain compacted, hard or cemented layers above the water table, it may be impossible for plants to extend an adequate number of roots downward to the water table. Boring holes beneath each tree planting location is an experimental method intended to permit roots to grow downward. The auger holes remove dense clay or hardpan layers that might stop or slow root growth. They should be filled with a mixture of soil and peat to hold the hole open and provide an avenue of preferred root growth. Additional data on the effectiveness of this planting method will become available as additional phytostabilization systems are installed and evaluated.

5.4.4 Agronomic Optimization

As part of the design requirement, initial treatability field studies should be conducted to determine if site conditions can support the plant growth. Soil samples should be used to assess the concentration of contaminants in the soil surrounding any plants that are growing at the site. Soil samples should also be analyzed for soil parameters influencing plant growth. These soil parameters may consist of soil pH, soil salts, soil fertility, soil structure, soil texture, soil temperature, and soil depth. Saline groundwater/surface water conditions may adversely affect plant growth of some species of plants. The site soils should be amended as necessary to optimize plant growth conditions.

Agronomic inputs include nutrients necessary for vigorous growth of vegetation and rhizosphere bacteria. Soil samples will establish the natural conditions at the site. The soil may require lime addition, fertilization (nitrogen, phosphorous, potassium, and other mineral nutrients), carbon addition, and soil conditioners, such as aged manure, sewage sludge, compost, straw or mulch [49]. The site soil must have sufficient water-holding capacity to sustain vegetation. The pH of the soil may have to be altered to improve the efficiency of the system. Some states are now requiring agricultural operations (loosely defined) to develop and comply with a nutrient management plan. The possible need for this type of study/document should be considered. While remedial activities are not classic agricultural operations, the loose definition that some states are applying encompasses golf courses, parade/athletic fields, and other large grassed areas. Phytostabilization operations or activities need to check with local regulations for applicability.

5.4.5 Root Zone Aeration

Inadequate aeration at depth may slow or prevent root growth. Air inlet wells made of perforated pipes may be installed at the time of planting in holes drilled under each tree location. They may extend from the bottom to a few inches above grade. These wells may or may not enhance gas exchange substantially within the vadose zone, but they are inexpensive and provide access deep into the profile if problems develop in the future.

5.4.6 Fertilization

It is important that plants have access to adequate nutrients during establishment. Slow-release fertilizers are a good way to meet the needs of trees, yet minimize environmental damage caused by possible loss of nutrients not used by the plants in the area. Slow-release fertilizers are available in pellets that will release the nutrients over a period of one year and will support the tree during the important initial growing season.

5.4.7 Irrigation System Design

At all sites, irrigation will be required during plant establishment; at some sites, irrigation may be required for several years to ensure adequate production of plant biomass. All living trees transpire some water. Dormant trees consume less water than trees with leaves. Trees should have an adequately wetted root ball at all times during planting and should be copiously irrigated immediately after planting.

Irrigation will be required at all sites to aid in establishing the vegetation. At arid sites, periodic irrigation may be required to maintain healthy plants after the establishment phase. Drip irrigation should be used for trees because it ensures accurate placement of the water and limits losses due to runoff, evaporation or deep percolation. Grasses, alfalfa, and similar vegetation may be watered by sprinkler or drip irrigation. Flood irrigation is a poor choice because it is likely to cause excessive water losses by deep percolation to the water table, thus increasing the amount of water that must be withdrawn from the aquifer to achieve containment.

Irrigation water may either be clean water or contaminated groundwater, depending on regulatory approval. Contaminated water from the site may actually be preferred because it will allow the plant to adapt to the contaminant concentrations in the groundwater and provides a way to utilize contaminated water. To utilize the contaminated groundwater, it may be necessary to install wells with sufficient yields to supply irrigation. For contaminants that may volatilize into the air, a drip irrigation system may be preferred over sprinkler irrigation.

For many applications, a timer-controlled drip irrigation system will produce good results. They are commonly used and normally very reliable. Soil moisture sensors can also be used to directly control the application of irrigation water. Irrigation control by soil moisture sensors provides more precise application of water and reduces waste, but it may be less reliable than timer-controlled systems.

Plants can also be watered by hand but this is expensive and impractical in the long term. Hand watering should normally be used only at planting time for trees. It is also an option for short-term use should the installed irrigation system fail.

Excessive irrigation can mobilize contamination from soil to ground or surface water. Therefore, in these cases, evapotranspiration estimates should be used to estimate the amount of water necessary to sustain growth without recharging the groundwater. Automated soil moisture monitoring systems are also available to control when irrigation is necessary.

The irrigation system should be equipped with a water meter so that the amount of water applied can be measured. The water meter, control system and control valves should be located close to each other and clearly marked to make them easy to locate and repair. Detailed irrigation system design is beyond the scope of this protocol. There are numerous books available for designing agricultural and commercial irrigation systems and Agricultural Engineers are well trained in irrigation system design.

5.5 Installation

The planting design will describe the planting technique and labor required for the site and will include provisions to prevent animals, vectors, and disease from harming the plants. Any needed special protection should be identified in the work plan. Utilizing information gained during the plant selection process and the preliminary studies, an optimal planting depth and plant spacing can be identified. Initial planting densities may be greater than required, and the plants may be thinned after reaching a specific height.

After the soil has been exposed and the utilities and other structures have been removed or reconfigured, the soil should be prepared for planting. For proper root development, the soil profile will need to be loose to a depth of 0.5 m (20 inches) or more. Following the tilling of the soil, soil amendments identified to be necessary for plant growth should be worked into the soil. The plants should be planted, utilizing the optimal plant density identified in the system design process. Blowing dirt and dust may be a problem and can be controlled by keeping the surface of the soil moist, gravel mulch, or spray-on materials. It may be necessary at some sites to monitor the air for possible volatilization of contaminants.

During the plant selection process and site investigation, nutrient deficiencies in the soils at the site should have been identified. An initial fertilizer application can be made at planting time and tilled directly into the soil. Care should be given to monitor the growth of the plants closely to determine when additional fertilization is necessary. Fertilizer can be applied in granular form, which is broadcast on the ground, or in liquid form, which is applied directly through the irrigation system.

Weed control may be necessary for the first few years of a project. Weed control can be accomplished by mowing or through the use of herbicides. Care should be taken to select an herbicide that is not detrimental to the desired plant, and the application time and methods should minimize overspray or drifting off site. Weed control by mowing is the preferred method because it does not introduce new chemicals to the site and will provide adequate control. Pesticides should be required if the selected plants are prone to insect infestations or disease. Selecting plants that are disease- and insect-resistant, such as hybrid poplars is advantageous.

Pruning of trees at regular intervals may be needed to keep the plantings healthy and minimize damage from storms. However, the primary objective is production of biomass and tree shape is of little concern. It may be necessary to replace plants that die from disease or rootstock that doesn't survive for other reasons.

5.5.1 Transplants or Seeds

Most grasses and alfalfa should be established from seed. Sedges and other emergent vegetation require special planning and consultation with local plant experts is recommended. Trees may be transplanted as growing plants because they are difficult to establish from seed and they are normally widely spaced. They may be small, bare-rooted seedlings or trees up to 4.5 m (15 feet) high that were grown in containers. Small trees less than 1.5 m (5 feet) high are preferred because they are less expensive than larger trees, and due to their size, less likely to suffer severe shock during transplanting. In most cases, small transplanted trees will establish a large root mass extending to the water table as quickly as larger transplants. Some trees have also been successfully established from green cuttings or whips bearing no leaves or roots.

5.5.2 Plant Establishment and Growth

Trees should be planted before the beginning of the growing season so that they can take advantage of the entire season and establish a good root system before the arrival of hot, dry weather. Trees may be planted in fall or early spring. Fall planting offers an advantage because roots will begin to grow during the dormant season.

Inspect trees before planting to verify that they are healthy and growing well. If leaves are present healthy trees should have no visible discoloration of leaves, and no scars or signs of damage or disease on the trunk and the branches. Growing tips of branches should indicate recent robust growth. Several new, immature leaves at the tips of branches indicate recent growth. If the tree is dormant, a healthy bud at the tip of each branch is an indication of a healthy tree. Trees should be delivered in an enclosed truck, or otherwise protected from wind damage and excessive drying during transport.

5.5.3 Site Security

Entry into the site may need to be restricted and the site secured by constructing a fence to prevent wildlife from damaging or destroying the plants. Small animals such as rabbits and deer may need to be fenced out to prevent destruction of the plants. For phytostabilization projects using plants that translocate or accumulate the site contaminants in the plant material, it may be necessary to protect wildlife from exposure to contaminated biomass by preventing their access to the area. Posting signs on the fence that explain the project can inform the public regarding the potential for exposure to the contaminant.

5.6 Contingency Plan

A contingency plan should define the actions taken if the phytostabilization system does not meet remedial objectives. The contingency plan may be needed if there is large-scale failure of the plants, if the system does not protect human health or the environment, or if remedial objectives are not met. The plan should cover a wide range of possible failure mechanisms (drought, floods, disease, animals). Implementation of the contingency plan might be triggered based upon a number of site-specific factors.

The remediation plan should contain a timeline that shows the expected reduction of the contaminant of concern over time. It may take several years of monitoring to determine whether the phytostabilization is meeting the remedial goals. If the phytostabilization system is not achieving the expected goals, the RPM, site owner, designer, regulators, and stakeholders should examine the cause and review the remediation plan.

6 Operation and Maintenance

The performance of a phytostabilization system must be assessed during operation to ensure that the goals for the system are met. The monitoring required is different from that used for conventional remediation systems and requires measuring fewer parameters. System monitoring should collect only the data needed to assess performance of the phytostabilization system. The field operation should be performed by a person familiar with the system, its parts, and the requirements visiting the site weekly during plant establishment (perhaps less often during operation) to observe, and if needed, to change operating parameters in the field.

6.1 Assessment of Performance

The primary goal of phytostabilization is hydraulic control of contaminated groundwater plume movement. The goal of assessment is to obtain the minimum essential measurements required to demonstrate the effectiveness of the system.

6.1.1 Water Balance

Preliminary evaluation and design require an estimate of water balance for the site. A water balance includes all water entering and leaving the site. The major components are precipitation, groundwater flow and actual ET. Precipitation should be measured at the site. ET is typically not measured at the site because field measurements of ET are too costly and instead is estimated from PET using climate data measured at the site. The groundwater flow component may sometimes be approximated by a simple model with hand calculations [5] or, more often, estimated using a computer model (e.g., Modflow) if the site is complex.

During operation of a phytostabilization system, control of groundwater movement should be monitored using a minimum of two monitoring wells in which water level is measured and recorded during each hour, or more often. One well should be located inside the vegetated area and one located nearby at a site that is unaffected by the phytostabilization system. Many sites will require more than two monitoring wells. The monitoring well data should be included in a complete evaluation of water table elevations for all monitoring wells in the area; and all area monitoring wells should be measured at the beginning and end of the growing season.

6.1.2 Soil Water

Soil water content and soil water potentials can be measured in the field to estimate flow of water through the vadose zone. However, in order to achieve acceptable accuracy, these measurements will require substantial expense that generally cannot be justified. Measurements of this kind on a smaller scale are desirable and affordable for assessing the need for irrigation, maintenance, or changes in operating procedure (see Section 6.2.4).

6.2 Site Monitoring

Site-monitoring data are collected to meet the requirements of performance assessment that are stated above.

6.2.1 Analytical Requirements

The growth rate of a plant will directly affect the rate of remediation and should be monitored closely. Monitoring must be done to assess the performance and optimize phytotechnologies as well as to prevent and/or minimize any possible ecological risk. The following parameters should be monitored during phytotechnology applications to assess the performance of the system:

- Agronomic conditions, including rate of plant growth
- Field measurements, including pH, salinity, available nutrients and climatic conditions
- Organic compound contaminant and degradation product concentrations, including byproduct composition and concentrations in all media
- Transpiration gases
- Biomarkers
- Microbial analysis

In addition, regulatory agencies may require sampling of several media until it is demonstrated that contaminants are not transferred to a receptor. The use of established and published sampling protocols such as USEPA/American Society for Testing and Materials (ASTM) methods during any remediation project is highly recommended. Table 7 lists sampling methods applicable to typical phytostabilization projects.

Location, duration, and frequency of groundwater monitoring are determined from site characterization data. The exact sampling protocol and frequency will be determined on a site-specific basis.

6.2.2 Groundwater

The rate of water consumption by plants reaches a maximum after solar noon on clear days and a minimum during the night. As a result of this natural process, phreatophyte vegetation with roots in or near the water table often produces a measurable daily cyclic variation of water table elevation. Cyclic variation of the water table is acceptable if the rate of inflow of groundwater to the site is less than the rate of withdrawal by the vegetation during the day.

Cyclical change in groundwater elevation in shallow aquifers may also result from barometric pressure change and other causes; however, the two cycles are normally out of phase with each other. The magnitude of water-level change resulting from barometric pressure or other causes is often less than that induced by phreatophytes. Continuous measurement of water-table elevation both in the planted area and in an area unaffected by the phytostabilization will permit assessment of phreatophyte influence on the groundwater surface and provide evidence that the trees are removing water from the groundwater.

Groundwater movement may be assessed by establishing the groundwater levels and contours at the site to determine if groundwater is flowing into the site area from all directions. The groundwater gradient should be established at the beginning and end of each growing season and more often if conditions at the site warrant the expense of measurements.

Table 7 Analytical Methods for Phytostabilization Monitoring

Parameter to be Monitored	Analytical Method
pH	Standard Method # 423 or SW-846, Method 9040
Ammonia-N	Standard Method # 417 or equivalent
Nitrate-N	Standard Method # 418 or equivalent
Kjeldahl-N	Standard Method # 420 or equivalent
Available Phosphorus	Check with State Dept. of Agriculture
Total Phosphorus	Standard Method # 424 or equivalent
Temperature	Standard Method # 212 or equivalent
Metals such as Fe, Mg, Ca and other elements	Standard Method # 300 series or equivalent
Conductivity	Standard Method # 205 or SW-846, Method 9050A
Redox Potential	Eh measurements
Water table	Field instruments (e.g., inter-phase probe)

Adapted from: *Phytotechnology Technical and Regulatory Guidance Document*, Interstate Technology and Regulatory Cooperation Work Group, April 2001 [50]

Measure and record groundwater elevation hourly at a minimum of two locations at each site. A single groundwater elevation measurement per day may not reflect actual water table behavior because of the diurnal water use by vegetation. One monitoring well should be in the vegetated area and one should be outside the zone of influence of the phreatophytes. These measurements allow continuous monitoring to determine if water is moving toward or away from the phytostabilization site.

In addition, water levels should be monitored in the area and extend out beyond the zone of influence of the phytostabilization system. Because the water table fluctuates seasonally, its elevation should be measured seasonally (in the same months each year). Measurements should employ enough wells to define the water table contours and flow direction both within the site area and extending far enough out from the site to define the zone of influence of the system.

Groundwater quality should be measured if the possibility exists for reduction of contaminants in the groundwater as a result of phytoremediation mechanisms or by natural attenuation. The sampling and analysis should be performed annually or as required to determine the change in the concentration of contaminants in the aquifer.

6.2.3 Climate Parameters

Irrigation of trees or other plants during establishment requires knowledge of daily or weekly water use, which may be estimated from PET. Estimating PET requires current measurements of climatic data. After establishment, the effectiveness of trees can be inferred from estimates of PET derived from daily measurements of climatic data and periodic measurements of water use by individual trees. The hydraulic control effectiveness of alfalfa, grass, or other plants may be estimated by a suitable model or groundwater elevations. Both historical and current data are needed to predict performance of the system, manage the planted trees and evaluate actual performance.

Measure and record precipitation, solar radiation, maximum and minimum air temperature, relative humidity and wind run for daily or shorter time periods. If accurate estimates of daily potential ET are required then soil heat flux data is also required. If only annual or monthly estimates of potential ET are required, soil heat flux may be assumed equal to zero or estimated for each day by an approximate equation. The estimate of site conditions is more accurate when the climatic data are measured at the site. Automated weather stations are available that will record all of the above parameters at programmed intervals. The data can be transferred in the field to hand held computers or transmitted to a remote computer by radio or telephone.

6.2.4 Water Use by Trees and Other Vegetation

Evaluation of system performance requires an estimate of water use by the vegetation. Actual water use by alfalfa, grass, or "crop type" plants may be satisfactorily estimated from PET estimates if derived from site measurements of climatic data. There are no commercially available methods to measure actual ET by alfalfa and grass at a reasonable cost. The water use by trees is poorly defined in the literature; therefore, some measurements are required to estimate the performance of trees. Instruments are commercially available to obtain water use measurements from individual trees at reasonable cost.

Measure and record daily water use by at least two trees at each site. Water use may be accurately estimated by commercial sap flow gauges or similar instruments. Water use by individual trees should be measured for several days during late spring when abundant water is available and the trees are growing actively. It should be measured again during late summer when the soil is dry and it is likely that most or all water use is derived from groundwater. The water use measurements for individual trees should be accompanied by a complete set of climatic measurements for each hour of the measurement period.

Measure the volume of irrigation water applied to all trees. Record the volume of irrigation water monthly and calculate a total for each irrigation season.

6.2.5 Soil Water Conditions

To evaluate the effectiveness of the irrigation system, measure and record soil water pressure or content at least four times per day. Soil water conditions should be measured and recorded at a minimum of four locations and at two depths per measuring location. Soil water may be measured by simple instruments such as resistance blocks or by more sophisticated instruments such as Time Domain Reflectometry. The simple instruments will produce the minimum required information; more sophisticated instruments will provide more precise data. Soil water conditions should be measured in the upper root zone at a depth of about 0.3 m (12-inches) and deep in the soil profile but above the capillary fringe (e.g., 6 to 8 feet deep if the capillary fringe is expected to end at 9 feet). The upper measurement assesses the effectiveness of irrigation and the lower measurement will provide an index of system performance.

6.2.6 Monitoring Plant Performance

The overall health of the plants should be monitored on a regular basis through on-site inspection. The plants should be inspected as required to determine whether disease, insects, wildlife, or lack of adequate plant nutrients is affecting rate of growth, water consumption, and plant health. The frequency of inspection may vary; for example, a tree planting may require inspection twice each month during the establishment years, but only monthly or quarterly inspection thereafter.

Local experts should be consulted to determine what hazards exist locally that might affect the project's vegetation. These experts can provide advice on potential hazards and actions to be taken to prevent or minimize their effects. For instance, an arborist would be able to determine what local diseases and insects might attack the chosen tree variety.

Measure tree height, trunk diameter, canopy diameter, and LAI annually to verify inspections and observations of trees. On small projects with relatively few trees, measurements should be made on each tree. On larger projects, enough data should be taken to develop reasonable estimates of the average value for each parameter. For other plants such as alfalfa, measure plant height, density, and LAI as required to develop reasonable estimates of the average values.

Table 8 contains a list of the parameters that should be measured and recorded to provide guidance during plant establishment, monitor operations, and provide the basis for evaluation of the phytostabilization system. Each site-specific parameter is required for all sites, as are daily measurements of precipitation. The other climate parameters may be needed if new site-specific PET estimates will be required.

6.3 Maintenance

Maintenance is just as important for phytostabilization as it is for any mechanical remediation system. The primary operation and maintenance requirements consist of weed control, plant maintenance, and disposal of plant material.

6.3.1 Operations and Maintenance Plan

An operations and maintenance plan will help in achieving optimal long-term performance from the phytostabilization system. The operation and maintenance plan, at a minimum, should address the following topics:

- Irrigation of the plants during establishment and/or to keep them growing
- Soil amendments for pH control and fertilization requirements
- Plant pruning, thinning, and mowing
- Replanting to replace dead plants (if necessary).
- Fencing to provide animal and pest control
- Disposal of plants and plant litter if the plants accumulate the contaminants and are considered a hazardous waste.

6.3.2 Weed Control

Weeds are controlled to maintain a healthy stand of the desired species and to prevent the spread of nuisance plants. Mowing is the best control method. Weed control is of greater importance early in the project when the leaf cover canopy is open. As the selected plants mature and the leaf canopy closes, sunlight penetration to the ground surface is limited and weed growth substantially reduced.

Table 8. Parameters that Should Be Measured and Recorded

Parameter	Purpose	Recording Frequency [2]
Climate		
Solar radiation	Potential ET	Daily (*hourly*)
Maximum air temperature	Potential ET	Daily (*hourly*)
Minimum air temperature	Potential ET	Daily (*hourly*)
Relative humidity or dew point	Potential ET	Daily (*hourly*)
Wind movement	Potential ET	Daily (*hourly*)
Soil heat flux	Potential ET	Daily (*hourly*)
Precipitation	Water balance, plant management	Daily (*hourly*)
Site-Specific		
Groundwater elevation	Water balance, performance assessment	Hourly from a minimum of 2 wells and readings from all area wells at beginning and end of growing season
Soil water condition, electrical resistivity or other	Plant water requirement, irrigation control, and performance assessment	4 times per day
Water use by trees (sap flow gage)	Performance assessment (measure 2 or more trees)	Daily for at least 4 days in spring and late summer
Irrigation volume (total water applied)	Water balance, plant management	Monthly
Tree height/plant height	Performance assessment, operation	Annually
Tree-trunk diameter	Performance assessment, operation	Annually
Tree-canopy diameter	Performance assessment, operation	Annually
Leaf area index	Performance assessment, operation	Annually

1. Adapted from ITRC, *Phytotechnology Technical and Regulatory Guidance Document*, April 2001 [50]
2. Frequencies in *italics* are desirable for the Penman-Montieth (PM) Method for Estimating PET although daily measurements may be used.

6.3.3 Fertilization and Irrigation

Provide adequate plant nutrients at all times to maintain healthy plants. The primary nutrients required are nitrogen, phosphorus, and potassium (NPK). Plants use nitrogen in the largest amounts, and they are most likely to be deficient in nitrogen. Other nutrients, in addition to NPK, are needed in small amounts and are generally available in adequate amounts in most soils. It is advisable to consult local experts and/or to test the soil for plant nutrient status. Some forms of nitrogen are highly soluble and thus are potentially highly mobile. Thus over application of soluble forms of nitrogen can result in contamination of the groundwater. Phosphorus is normally bound to clay particles or organic matter in the soil. However, phosphorus applied as fertilizer on the soil surface may be carried away in surface runoff during heavy rains and may create surface water or groundwater contamination. If the soil surface is maintained to minimize surface runoff and soil erosion, the loss of phosphorus should be small and of little concern.

Slow-release fertilizers—particularly for nitrogen—greatly reduce the probability that the fertilizer will cause water pollution. Slow release fertilizers are more expensive than other fertilizers, but they are typically well worth the extra cost.

6.3.4 Ground Cover

In the interests of reducing fire danger at the site, weeds and grass should be mowed at the end of the growing season when both the soil and vegetation are dry. The top growth should be left on the ground to increase the amount of organic matter in the soil and to protect against soil erosion or loss of applied fertilizer.

Because soil compaction can cause serious reduction in root growth, increased runoff, erosion, and may affect plant health; all mechanical operations on the site, including mowing, should be conducted when the soil is dry enough to avoid compaction by the machinery used. Either track-type tractors or machines with low-ground-pressure tires (normal operating pressure less than 10 pounds/square inch) should be used.

6.3.5 Tree Pruning and Plant Harvest

The purpose of tree planting for phytostabilization is to maximize water consumption from an aquifer. High rates of water consumption require large aboveground biomass. Tree pruning should, therefore, be kept to the minimum amount required to allow access to the site. As the tree matures, pruning may sometimes be required to maintain the health of the trees as well.

If grasses or phreatophytes such as alfalfa are used for phytostabilization, they may require periodic harvesting to maintain healthy plants. This issue should be evaluated during planning and design.

6.3.6 Plant Loss and Replacement

Phytostabilization should be treated as a specialized farming operation. For example, loss of several trees in one spot or reduction in stand density of an alfalfa planting may require action to achieve the goal of remediation. The design and installation should ensure that the loss of a few isolated plants would not cause system failure. For example, trees may be planted closer to each other than would normally be desired for shade trees or wood production. Closely spaced trees will begin to consume the desired volume of groundwater much sooner than widely spaced trees. After the trees have been growing for a few years, the loss of isolated trees in a closely space planting will have little or no effect on performance of the system as a whole.

Plant failure can occur due to killing frosts, windstorms, drought, flood, animals (e.g., deer, beaver), disease, or infestation (fungus, insects). Part of the maintenance budget should include funding for periodically replanting a certain percentage of the site [49].

7 Project Completion

7.1 Defining the Ending Point

The closure of a phytostabilization site is similar to the closure of a pump-and-treat site. A final cleanup goal should be stipulated in the Record of Decision (ROD) or other decision document. A monitoring plan should be agreed upon, and the site should be monitored until the cleanup goal is met. After the trees (or other plants) are sufficiently mature to contain the contaminated plume, it should be possible to significantly reduce the amount and frequency of monitoring at the site. The mature trees should "operate" effectively for years or decades with little operation or maintenance expense.

After a source area is contained, it might be possible to model the site and predict the amount of time it will take to remediate the dissolved phase plume. The duration of the required phytostabilization containment may be as long as for a pump-and-treat system. However, the time required may be less depending on the rate of groundwater withdrawal by the plants and whether the plants remediate contaminated groundwater as well as remove it.

The closure of the site should be based on a confirmation using a sampling protocol negotiated at the time of the ROD or other decision document. The sampling protocol should define the number of sample points and the number of sampling events to confirm that the cleanup goals have been met. Once the cleanup goals have been attained, the site should be formally closed with the regulatory authority.

7.2 Disposal of Aboveground Plant Parts

One of the advantages of a phytostabilization site is the aesthetically pleasing nature of the trees. If the site does not require removal of the trees, they can be left in place. It is unlikely that the aboveground tree materials will contain a significant amount of accumulated volatile organic contaminants, particularly at the end of the remediation period when the concentration of contaminants in the water is low enough to meet cleanup goals. As a result, there should be no obstacles to the disposal of tree parts or other biomass if they must be removed.

If significant semi-volatile or metal contamination is present at a site, limited sampling of the plant material is recommended to confirm that there are no disposal issues. If contamination is discovered in the plant material, regulated disposal procedures must be followed.

7.3 Contaminant Storage in Roots

If there is significant metal contamination in the groundwater plume, elevated concentrations of metals may be retained in roots. Metals may form stable compounds within the organic matrix of the roots and thus they should not leach out of the soil and recontaminate the groundwater. However, if significant metals were present in the groundwater plume, additional sampling of the roots, and possibly some continued monitoring of the groundwater, may be required to confirm that the metals are not leaching.

Similarly, if excavation of the site is contemplated, then a limited amount of confirmatory sampling of roots and the surrounding soils should be undertaken to ensure worker safety.

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Appendix A Estimating PET

Section 3.3 describes the use of potential evapotranspiration (PET) for estimating the potential performance of a phytostabilization system and presents estimated values for 109 Air Force facilities in the continental United States (CONUS). This appendix describes methods to estimate PET of other locations within and outside of the CONUS.

This Appendix presents equations, coefficients, and constant values used to estimate PET by six different methods. These methods were taken from the American Society of Civil Engineers (ASCE) publication entitled *Evapotranspiration and Irrigation Water Requirements* [2] [6]. The methods in the ASCE manual were designed to estimate ET from "reference crop" conditions, which are defined as well watered grass or alfalfa that is transpiring at the maximum rate for the climate. The estimates of ET made by these methods are good estimates of PET even though no similar methods are available for trees or forest.

ASCE Manual 70 is the most complete reference available that discusses both the complex physics of water evaporation from the earth and presents methods for estimating ET. It presents extensive testing of each method against measured values of ET along with evaluations of the accuracy of each method. Because the physics of water evaporation are complex, the manual contains numerous methods, equations and systems of units. This appendix contains a unified set of method equations and units that may be used for phytostabilization design and site evaluation.

Every effort was made to provide accurate equations and coefficients in this appendix. However, before making estimates for a site, the user should verify the equations and coefficients contained herein against the original or the equations, definitions, and references contained in the ASCE manual.

Appendix A is divided into three sections:

Section A-1: Comparison of selected methods for estimating PET

Section A-2: PET estimating methods, secondary equations, and symbols

Section A-3: Method used to estimate PET for Air Force facilities

Each method is presented with a brief description of whether it is appropriate for use in a humid or arid climate, the required data, the primary equation and specific constants or coefficients required by that method only. Many of the coefficients are used in more than one PET estimation method. The appropriate equations and explanations for these commonly used coefficients are listed separately in alphabetical order by name rather than by symbol.

To make it possible for the user to reference the original source for further information, the equation numbers from the ASCE manual have been used verbatim

[2] Jensen, M.E., R.D. Burman, R.G. Allen (Eds.). 1990. *Evapotranspiration and Irrigation Water Requirements*, Manual on Engineering Practice No. 70, American Society of Civil Engineers.

in this appendix. Where equation numbers were not used in the original text, the page number is given here. The units of measurement are displayed to the right of each equation and are followed by the equation number.

There may be cases where suitable data is not available to for estimating ET using one of the methods described in this appendix. In those cases a less precise, but perhaps acceptable, estimate of ET may made using Class A pan evaporation data and an appropriate Class A pan coefficient. The Class A pan is the standard apparatus used by the United States Weather Service to measure evaporation rates. However, measurements made with the Class A pan consistently exceed the true evaporation rate, and the values obtained must be multiplied by a coefficient to arrive at a reasonable estimate of reference evaporation as shown in the following equation:

Reference Evap = (Class A pan evap * Class A pan coefficient)

Values of Class A pan evaporation may be measured in the field or obtained from published values [51]. Values of Class A pan evaporation coefficient are usually obtained from published maps or tabulated values [51, 52].

Appendix A-1 Comparison of PET Estimation Methods

There are numerous methods that may be used to estimate PET for a site. The ASCE manual (Jensen et al. [6]) presents the results from testing 20 methods for estimating reference (potential) ET. Each of the tested methods was compared to experimentally measured lysimeter and climate data from 11 sites. Elevations at the selected sites ranged from 30 m (100 feet) below sea level to 2,774 m (9,100 feet) above sea level. Latitudes ranged from 38° S at Aspendale, Australia, to near the equator at Yangambi, Zaire, to 56° N at Copenhagen, Denmark. The manual contains 17 pages of pertinent references which are the results of effort by a dozen of the world's leading ET research scientists and engineers.

The ASCE manual shows that the Penman-Monteith method produced the most accurate estimates of PET. However, the Penman-Monteith method also requires the greatest amount of data input and the solution of several equations to estimate ET. Other methods discussed in this appendix require the input of fewer measured data values and still produce acceptable accuracy if used appropriately.

The data, coefficients, and constants required to estimate PET are presented with the methods in Section A-2. This Appendix contains the same symbols and definitions as ASCE Handbook 70 by Jensen et al. [6] and uses a consistent set of units. The methods, symbols, coefficients, and constants are defined where used and in the glossary in Appendix G.

The ASCE manual [6] states *"In selecting a practical method, it is important to remember that all existing methods of estimating crop* (ET) *from climatic data involve some empirical relationships. Consequently, some local or regional verification or calibration is advisable with any selected method."* Normally, it will be not be possible for the Air Force to verify an ET method prior to using it in phytostabilization design or evaluation. Therefore, this protocol includes only those methods that produced small errors when tested at a number of sites. The type of data available will often limit which method may be used and was a factor in selecting the methods presented here.

This appendix presents six methods for estimating PET selected from the twenty ET estimation methods contained in ASCE manual. These six methods are believed to produce most appropriate estimates of PET for use in phytostabilization system design:

- Penman-Monteith
- Penman (1963)
- Priestly-Taylor
- FAO-24 Radiation
- Jensen-Haise
- Hargreaves

Table A-1 presents a list of the data that are required for each of the methods discussed along with estimates of the method's accuracy and Table A-2 describes qualification on the use of some data items. Most of the methods require additional coefficients that may be estimated from these data and universal constants.

Table A-1. Data Parameters for Estimating Reference ET (PET), Standard Error of Estimate and Seasonal ET Estimate

Required Data Daily Total, Maximums, etc. [a]	Penman-Monteith	Penman (1963)	Priestly - Taylor	FAO-24 Radiation	Jensen-Haise	Hargreaves (1985)
Daily solar radiation MJ m^{-2} d^{-1}	X	X	X	X	X	
Extraterrestrial solar radiation MJ m^{-2} d^{-1}						TE[b]
Net radiation MJ m^{-2} d^{-1}	X	X	X			
Maximum air temperature ^{O}C	X	X	X	X	X	X
Minimum air temperature ^{O}C	X	X	X	X	X	X
Mean daily air temperature ^{O}C	X	X	X	X	X	X
Dew-point temperature ^{O}C	X	X	X	X		
Wind movement at height z m m s^{-1}	X	X		X		
Wind movement at 2 m (adjusted) m s^{-1}		X		X		
Soil heat flux[c] MJ m^{-2} d^{-1}	X	X	X			
Standard error of estimate for ET estimates at **Arid** locations, <u>mm/day</u>	0.4	0.6	**<u>1.8</u>**[d]	0.6	0.9	0.9
Standard error of estimate for ET estimates at **Humid** locations, <u>mm/day</u>	0.3	0.6	0.6	0.8	0.8	0.9
Seasonal ET estimate as <u>*percentage*</u> of lysimeter measurement, **Arid** locations.	*99*	*98*	***<u>73</u>***	*106*	*88*	*91*
Seasonal ET estimate as <u>*percentage*</u> of lysimeter measurement, **Humid** locations.	*104*	*114*	*97*	***<u>122</u>***	*82*	***<u>125</u>***

(a). Penman-Monteith method developed for hourly values, however, commonly used with daily values with slightly reduced accuracy.

(b). TE = estimate from table or equation.

(c). May be calculated, but this reduces accuracy of ET estimate.

(d). Bold, underlined numbers show large differences from lysimeter measured values.

The input data, table 1, are described as follows:

- Hourly or daily solar radiation, net radiation and soil heat flux are the total amount in an hour or a day, respectively.
- Hourly or daily values of maximum or minimum temperature are the maximum or minimum values for each hour or day, respectively.
- Hourly or daily values of mean air temperature usually mean the average of the maximum and minimum values for the hour or day. The specific use must be defined with the equation in which the value is used.
- The ASCE manual states, "*The dew-point temperature does not change greatly during the day, and a single dew-point observation during the day is adequate for most estimates of reference evapotranspiration.*"
- Hourly or daily values of wind movement are the average of all wind speed measurements made during the hour or day in question.

Table A-2. Qualifications on the Selection and Use of Data

Soil heat flux is relatively expensive to measure in the field. Since the Air Force is engaged in environmental remediation rather than research and needs annual estimates of ET calculated values of soil heat flux should be adequate. On an annual basis soil heat flux is near zero therefore calculated values are adequate. Monthly or daily values of heat flux can be estimated using Equation 3.31.
Net radiation should be measured (on an hourly or daily basis) however if this is not possible estimates may be made using Equation 3.5; this will decrease the accuracy of the PET estimate.
Extraterrestrial solar radiation is not measured by the user; it may be obtained from tables found in Allen and Pruitt (1986) or calculated using Equations 7.28 through 7.31.
Wind speed at 2 meters height is required for the Penman (1963) and FAO-24 Radiation methods. If wind speed was measured at a height other than 2 m the speed at 2 m may be estimated from the measured speed at known height using the Wind Speed Adjustment equation (Equation 7.23) found in the section of supporting equations.

As mentioned above, the Penman-Monteith method is the most accurate of the twenty methods tested and of the six chosen for inclusion in this appendix (see Table A-1). It also requires more calculations than the others and the greatest number of measured daily input data. It is most accurate when used with hourly data and the hourly values summed to obtain daily values of ET, but it may be used with input of daily data [6]. It may be used as a standard and is preferred for use in phytostabilization design or evaluation if the required daily input data are available. However, when used as a standard for checking other methods, the user should remember that it produces results containing some error. The other five methods discussed here only require input of daily data values.

The Penman (1963) method was the foundation for the Penman-Monteith and not surprisingly produces accurate estimates (see Table A-1). However, it also requires a substantial amount of daily data and is less accurate than the Penman-Monteith method. The remaining four methods discussed here, require fewer data, but produce acceptable results, Table A-1. Some of them are acceptable in either a humid or arid climate, but not both.

An arid climate is defined in the ASCE manual as “generally any extremely dry climate”. Because there are more issues involved than precipitation and relative humidity, this definition may be misinterpreted by persons unfamiliar with the details of each calculation method was tested. For purposes of phytostabilization design and evaluation within the continental United States, an arid climate may be assumed for most locations west of 104° longitude (western border of North and South Dakota) with the exception of some locations in humid, cool, coastal locations on the West Coast. The remainder of the country may be considered “humid”. Another exception is that, in the Great Plains region of eastern Montana and Wyoming, methods suited to “humid” regions may apply.

The ASCE manual suggests minimum data collection frequencies for estimating ET with the various estimating methods: Penman-Monteith—hourly or daily; Penman—daily; Jensen-Haise and FAO-24 Radiation—5 days; and Priestly-Taylor and Hargreaves—10 days. In practice, one estimates daily values of ET with the Jensen-Haise, FAO-24 Radiation, Priestly-Taylor, and Hargreaves and sums the daily values to obtain the ET for the minimum time period. Because the primary interest in phytostabilization work is the annual amount, these restrictions have little or no impact on the estimates of ET to be used in practical design or decision processes.

The FAO-24 Radiation method is poorly suited to phytostabilization work because it overestimates ET in both humid and arid climates. But, its standard error of estimate is similar to the other methods selected for inclusion in the protocol, and it may prove useful at some sites.

The Jensen-Haise method is a robust engineering design tool; it underestimates PET in both humid and arid climates by 18 and 12 percent, respectively. Because the underestimate of ET will produce a conservative design, it may be used for engineering design of phytostabilization systems. The Jensen-Haise method was developed from and tested on a very large amount of field data; thus, it is a predictable and reliable engineering tool. However, where a method is desired to evaluate an existing phytostabilization system, it may not be the appropriate choice because sufficient data should be collected at the site during operation of the system to enable use of a more accurate method.

Both the Hargreaves and Priestly-Taylor methods require a limited but usually available data set, and they produce acceptable accuracy. Therefore, they are recommended for use in phytostabilization design and evaluation. The Priestly-Taylor method was extensively tested and is widely used for humid regions. The Hargreaves method was developed from and tested against large data sets in arid regions. These equations, when used together, provide adequate estimates of ET for all parts of the country with the minimum amount of measured input data. The Hargreaves method should be used for arid locations but not for humid locations. The Priestly-Taylor method should be used for humid locations but not for arid locations.

There are 14 other estimating methods described in the ASCE manual that were not selected for inclusion in this appendix although some might be useful in specific cases. The reasons for not including each method are stated below:

- The **Thornthwaite** method was developed for the valleys of the east central United States. It has validity only in areas that have climates similar to that in east-central United States and seldom fits conditions found in other locations.
- The **Penman (1963) VPD #3, 1982 Kimberly-Penman, 1972 Kimberly-Penman, FAO-PPP-17 Penman, FAO-24 Penman,** and the **FAO-24 Corrected Penman** are all based on the Penman (1963) equation that was included. None of them offered a better approach than those selected for inclusion in the protocol.
- The **Businger-van Bavel** method had poor accuracy for both arid and humid locations.
- The **SCS Blaney-Criddle** and **FAO-24 Blaney-Criddle** methods are both intended for seasonal estimates only, and they are based on cultivated crop coefficients. As a result, they are not useful for phytostabilization estimates. Neither was as accurate as the methods included in the protocol.
- The **Pan Evaporation, Christiansen Pan,** and **FAO-24 Pan** methods are all based on pan evaporation measurements. The nature of and seasonal changes in upwind fetch for evaporation pans significantly changes the potential evaporation from pans; therefore, these methods have poor accuracy.
- The **Turc** method is radiation-based and performed well in humid regions, but it produced large errors for arid regions. It offers no significant advantage over the Priestly-Taylor method, and has been used little, whereas the Priestly-Taylor method has been widely used and tested.

Appendix A-2 PET Estimation Methods

Penman-Monteith

For use in both humid and arid climates.

While the Penman-Monteith equation is the most accurate of the six methods included in this report, it is by far the most complex and requires a large amount of measured data. It produces accurate results in both humid and arid climates.

This method is most accurate when hourly data is input to the equation to compute hourly values and the values summed to obtain daily estimates of ET (Jensen, et al, 1990). This method can also be used to calculate daily values of ET using daily measured input data. (See secondary equations on page 89 and list of symbols on page 96.)

The Penman-Monteith Method for Estimating ET (E_t):

$$E_t = \frac{1}{l}\frac{\Delta}{\Delta + g^*}\left(R_n - G\right) + \frac{g}{\Delta + g^*}K_1\frac{0.622\,l\,r}{P}\frac{1}{r_a}\left(e_z^0 - e_z\right) \qquad \text{mm d}^{-1} \qquad [6.17b]$$

Required Data:

Solar radiation, MJ m^{-2} d^{-1} or MJ m^{-2} h^{-1}
Net radiation[3] (R_n), MJ m^{-2} d^{-1} or MJ m^{-2} h^{-1}
Maximum air temperature, °C (hourly or daily)
Minimum air temperature, °C (hourly or daily)
Mean air temperature, °C (hourly or daily)
Dew-point temperature, °C (hourly or daily)
Mean wind speed at height z cm, m s^{-1} (for hour or day)
Soil heat flux (G), MJ m^{-2} d^{-1} or MJ m^{-2} h^{-1}

Height of wind speed measurements, cm
Height of temperature and humidity measurements, cm
Canopy height, cm
Elevation of site, m
Latitude of site, radians

Coefficient Specific to Penman-Monteith:

K_1 = dimension coefficient

$$K_1 = 8.64 \times 10^4$$

where units of $\boldsymbol{u_z}$ (wind speed at height z) is in m s^{-1}

[3] Net radiation should be measured at the site. However, if this is not possible, it may be estimated using Equation 3.5.

Penman (1963)

For use in both humid and arid climates.

The Penman method is the foundation of the Penman-Monteith method and produces accurate results for both humid and arid locations (albeit, not as accurate as Penman-Monteith). It also requires the maximum amount of daily data of all the methods presented in this report. (See secondary equations on page 89 and list of symbols on page 96.)

The Penman (1963) Method for Estimating ET (E_t):

$$E_t = \frac{1}{l}\frac{\Delta}{\Delta + g}\left(R_n - G\right) + \frac{g}{\Delta + g}6.43W_f\left(e_z^0 - e_z\right) \qquad \text{mm d}^{-1} \qquad [6.15c]$$

Required Data:

Solar radiation, MJ m^{-2} d^{-1}
Net radiation[4] (R_n), MJ m^{-2} d^{-1}
Maximum daily air temperature, °C
Minimum daily temperature, °C
Mean daily air temperature , °C
Daily dew-point temperature, °C
Mean daily wind speed at height *z* m, m s^{-1}
Soil heat flux (G), MJ m^{-2} d^{-1}

Height of wind speed measurements, m
Elevation of site, m
Latitude of site, radians

Coefficient Specific to Penman (1963):

W_f = wind function

$$W_f = 1 + 0.536u_2 \qquad \text{m s}^{-1} \qquad [p140]$$

where
u_2 = mean daily wind speed at 2 meters height, m s^{-1}

Notes:

If wind speed was not measured at a height of 2 m, use the Wind Speed Adjustment equation (7.23) to calculate estimated wind speed at 2 m height.

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[4] Net radiation should be measured at the site. However, if this is not possible, it may be estimated using Equation 3.5.

Priestly-Taylor

For use in humid climates only.

The Priestly-Taylor method produces results of acceptable accuracy, but only for humid regions. It should not be used in arid regions. It also requires less measured data than the Penman or Penman-Monteith methods. (See secondary equations on page 89 and list of symbols on page 96.)

The Priestly-Taylor Method for Estimating ET (E_t):

$$E_t = \frac{1}{l} x \frac{\Delta}{\Delta + g}\left(R_n - G\right) \qquad \text{mm d}^{-1} \qquad [6.35]$$

Required Data:

Solar radiation, MJ m^{-2} d^{-1}
Net radiation[5] (R_n), MJ m^{-2} d^{-1}
Maximum daily air temperature, °C
Minimum daily air temperature, °C
Mean daily air temperature, °C
Daily dew-point temperature, °C
Soil heat flux (G), MJ m^{-2} d^{-1}

Elevation of site, m
Latitude of site, radians

Coefficient specific to Priestly-Taylor:

x = calibration coefficient

x = 1.26 for humid or wet climates
x = 1.7 for arid and semi-arid climates

[5] Net radiation should be measured at the site. However, if this is not possible, it may be estimated using Equation 3.5.

FAO-24 Radiation

For use in arid climates only.

The FAO-24 Radiation method *overestimates* ET in both humid and arid climates (less so in arid climates) so it is poorly suited to phytostabilization work, where an underestimate is preferable. However, the standard error of estimate is similar to the other methods selected inclusion in the protocol and it may prove useful at some sites. (See secondary equations on page 89 and list of symbols on page 96.)

The FAO-24 Radiation Method for Estimating ET (E_t):

$$E_t = a + b\left[\frac{\Delta}{\Delta + g} R_s\right] \quad \text{mm d}^{-1} \qquad [6.47]$$

Required Data:

Solar radiation (R_s), MJ m^{-2} d^{-1}
Maximum daily air temperature, °C
Minimum daily air temperature, °C
Maximum relative humidity, percent
Minimum relative humidity, percent
Mean daily air temperature , °C
Mean daily daytime wind speed at height *z* m, m s^{-1}

Elevation of site, m

Coefficients specific to FOA-24:

a = -0.3 mm d^{-1}
b = adjustment factor

$$b = 1.066 - 0.13\times10^{-2} RH_m + 0.045 U_d - 0.20\times10^{-3} RH_m U_d - 0.315\times10^{-4} RH_m^2 - 0.11\times10^{-2} U_d^2 \qquad [6.48]$$

$\boldsymbol{RH_m}$ = mean relative humidity, percent
$\boldsymbol{U_d}$ = mean daily daytime wind speed at 2 m height, m s^{-1}

Notes:

Note that the mean wind speed is for daytime wind speed only. Daytime can be assumed as the hours between 0700 and 1900.

If wind speed was not measured at a height of 2 m, use the Wind Speed Adjustment equation (7.23) to calculate estimated wind speed at 2 m height.

Jensen-Haise

For use in both humid and arid climates.

The Jensen-Haise method *underestimates* ET in both humid and arid climates so it is well suited to phytostabilization work, where an underestimate will produce a conservative engineering design. It also requires minimal measured data. However, this method may not be appropriate to use to evaluate a phytostabilization system, because sufficient data should be collected at the site to permit use of a more accurate method. (See secondary equations on page 89 and list of symbols on page 96.)

The Jensen-Haise Method for Estimating ET (E_t):

$$E_t = \frac{1}{l} C_T (T - T_x) R_s \quad \text{mm d}^{-1} \qquad [6.40]$$

Required Data:

Solar radiation (R_s), MJ m^{-2} d^{-1}
Maximum daily air temperature, °C
Minimum daily air temperature, °C
Mean daily air temperature (T), °C

Elevation of site, m

Coefficients specific to Jensen-Haise:

$\boldsymbol{C_T}$ = temperature coefficient

$$C_T = \frac{1}{C_1 + C_2 C_H} \qquad [6.41]$$

where

$$C_1 = 38 - (2z/305) \qquad C_2 = 7.3 \ {}^\circ\text{C}$$

and

$$C_H = \frac{5.0kPa}{(e_2^0 - e_1^0)} \qquad [6.42]$$

$\boldsymbol{T_x}$ = intercept of the temperature axis

$$T_x = -2.5 - 1.4(e_2^0 - e_1^0) - z/550 \qquad [p101]$$

$\boldsymbol{z}$ = elevation, m
$\boldsymbol{e_2^0}$ = saturated vapor pressure at mean maximum temperature, kPa
$\boldsymbol{e_1^0}$ = saturated vapor pressure at mean minimum temperature, kPa

Notes:

The above saturated vapor pressure values ($\boldsymbol{e_2^0}$, $\boldsymbol{e_1^0}$) should be calculated using data for the warmest month of the year at the site in question.

Hargreaves (1985)

For use in arid climates only.

The Hargreaves method produces results of acceptable accuracy, but only for arid regions. It should not be used in humid regions. It requires the least amount of measured data of all the methods presented. (See secondary equations on page 89 and list of symbols on page 96.)

The Hargreaves Method for Estimating ET (E_t):

$$E_t = 0.0023 R_A TD^{1/2}(T + 17.8) \qquad \text{mm d}^{-1} \qquad [6.46]$$

Required Data:

Extraterrestrial solar radiation (R_A), mm d^{-1} water equivalent
Maximum daily air temperature, °C
Minimum daily air temperature, °C
Mean daily air temperature (T), °C

Latitude of site, radians

Coefficients specific to Hargreaves:

TD = mean monthly max temperature – mean monthly min temperature, °C

Notes:

$\boldsymbol{R_A}$ is not measured by the user; it may be obtained from tables found in Allen and Pruitt (1986), or calculated using Equations 7.28 through 7.31.

In this method, $\boldsymbol{R_A}$ (extraterrestrial solar radiation) must be converted to the equivalent in water evaporation. To convert $\boldsymbol{R_A}$ from MJ m^{-2} d^{-1} to mm d^{-1} of water evaporation, divide by l (latent heat of vaporization of water) in units of MJ kg^{-1}. (The conversion is based on the fact that 1 cm^3 of water has a mass of 1g.)

$$\frac{MJ/m^2 d}{MJ/kg_{water}} = \frac{mm_{water}}{d}$$

Secondary Equations

Use the equations and constants in this section to determine the values of common coefficients in the six methods of PET estimation. (If an equation or value is required by only one method it is presented on the same page as that method.) Each coefficient is listed by its symbol and description. Accompanying the equation for each coefficient are any secondary equations or constants that may be required to perform the calculation.

r ¾ **Air density**

$$r = 1.23 - 0.112z\left(10^{-3}\right) \qquad \text{kg m}^{-3} \qquad [7.5]$$

where ***z*** = elevation, m

P ¾ **Atmospheric pressure at elevation *z* (estimated)**

$$P = 101.3 - 0.01055z \qquad \text{kPa} \qquad [7.4]$$

where ***z*** = elevation, m

r_a ¾ **Diffusion resistance of air layer**

$$r_a = \frac{\ln\left[\left(z_w - d\right)/z_{om}\right]\ln\left[\left(z_p - d\right)/z_{ov}\right]}{\left(0.41\right)^2 u_z} \qquad \text{s m}^{-1} \qquad [6.18]$$

where z_w = height of wind speed measurement, cm

z_p = height of humidity and temperature measurements, cm

u_z = mean wind speed at height z_w, m s^{-1}

z_{om} = roughness length for momentum transfer

$$z_{om} = 0.123h_c \qquad \text{cm} \qquad [6.20]$$

z_{ov} = roughness length for vapor transfer

$$z_{ov} = 0.1z_{om} \qquad \text{cm} \qquad [6.21]$$

d = zero plane displacement of wind profile

$$d = \frac{2}{3}h_c \qquad \text{cm} \qquad [6.22]$$

where

h_c = height of crop canopy, cm

l ¾ **Latent heat of vaporization of water**

$$l = 2.501 - 2.361 \times 10^{-3} T$$ MJ kg^{-1} [7.1]

where ***T*** = mean temperature, °C

g ¾ **Psychrometric constant**

$$g = \frac{P}{0.622\, l}$$ kPa $°C^{-1}$ [7.15]

where *P* = atmospheric pressure (may be estimated with Equation 7.4)
l = latent heat of vaporization of water (see Equation 7.1)

g***** ¾ **Psychrometric constant modified by the ratio of canopy resistance to atmospheric resistance**

$$g^{*} = g\left(1 + \frac{r_c}{r_a}\right)$$ kPa $°C^{-1}$ [6.19]

where *g* = psychrometric constant (see Equation 7.15)
r_a = diffusion resistance of air layer (see Equation 6.18)
r_c = canopy resistance

$$r_c = 100/0.5LAI$$ s m^{-1} [6.23c]

LAI = Leaf area index

LAI can be estimated for nonclipped grass and alfalfa greater than 3 cm in height and harvested only periodically with:

$$LAI = 1.5\ln(h_c) - 1.4$$ unitless [6.23b]

where
$\boldsymbol{h_c}$ = canopy height, cm

For other crops, LAI should be measured in the field.

***R**$_A$* ¾ **Radiation, extraterrestrial**

This method of calculation is only valid for lower latitudes $(\Phi < 55°)$. Values of ***R**$_A$* may also be found in tables found in Allen and Pruitt (1986)

$$R_A = \left(24(60)/p\right) G_{sc} d_r$$
$$\times\left[(w_s)\sin(\Phi)\sin(d) + \cos(\Phi)\cos(d)\sin(w_s)\right] \qquad \text{MJ m}^{-2}\text{ d}^{-1} \qquad [7.28]$$

where ***J*** = day of the year (Jan. 1st = 1, Jan. 2nd = 2…Dec. 31st = 365), unitless
f = latitude of site (use negative for southern latitudes), *radians*
***G**$_{sc}$* = solar constant, 0.0820 MJ m^{-2} min^{-1}

d = Declination
$$d = 0.4093\sin\left(2p(284 + J)/365\right) \qquad \textit{radians} \qquad [7.29]$$

***d**$_r$* = Relative distance of the Earth from the sun
$$d_r = 1 + 0.033\cos\left(2pJ/365\right) \qquad \text{unitless} \qquad [7.30]$$

w$_s$ = Sunset hour angle
$$w_s = \arccos\left(-\tan(\Phi)\tan(d)\right) \qquad \textit{radians} \qquad [7.31a]$$

1 degree = 0.0175 rad
1 radian = 57.296°

Notes:

To calculate monthly values of ***R**$_A$*, use values of ***J*** equivalent to the 15th day of a month and sum them to get the total radiation in that month. (Example: To calculate value of radiation in March, calculate the radiation for March 15th and multiply by 31.) More accurate results can be obtained by summing individually calculated daily values over each month.

The water equivalent of ***R**$_A$* can be obtained by dividing by the latent heat of vaporization (l). If ***R**$_A$* is in units of MJ m^{-2} d^{-1}, divide by l in units of MJ kg^{-1} to obtain water equivalent in mm d^{-1}. (The conversion is based on the fact that 1 cm^3 of water has a mass of 1 g.

Note that the conversion from MJ m^{-2} min^{-1} (units of the solar constant) to MJ m^{-2} d^{-1} (units of the final output) is built into the equation. No additional conversion is necessary.

Latitude and longitude (in degrees) for selected Air Force installations are given in Appendix B.

R_n ¾ **Radiation, net**

Net radiation should be measured in the field on either an hourly or daily basis. However, if this is not possible, it may be estimated using the following:

$$R_n = (1 - a)R_s - R_b \qquad \text{MJ m}^{-2}\text{ d}^{-1} \qquad [3.5]$$

where a = short-wave reflectance or albedo; 0.23 is commonly used

R_s = measured solar radiation at the Earth's surface, MJ m^{-2} d^{-1}

R_b = net outgoing long-wave radiation

$$R_b = \left[a \frac{R_s}{R_{so}} + b \right] R_{bo} \qquad \text{MJ m}^{-2}\text{ d}^{-1} \qquad [3.16]$$

a = 1.0 ***b*** = 0 for humid climates

a = 1.2 ***b*** = -0.2 for arid climates

R_{so} = estimated solar radiation on a cloudless day

$$R_{so} = 0.75 R_A \qquad \text{MJ m}^{-2}\text{ d}^{-1} \qquad [7.27]$$

where ***R_A*** = extraterrestrial solar radiation, MJ m^{-2} d^{-1}
(see previous page for information on R_A)

R_{bo} = net outgoing long-wave radiation on a clear day

$$R_{bo} = \left(a_1 + b_1 \sqrt{e_d^0}\right)\left(4.903 \times 10^{-9}\right)\left(T_x^4 + T_n^4\right)/2 \qquad \text{MJ m}^{-2}\text{ d}^{-1} \qquad [3.17]$$

where ***T_x*** = mean maximum temperature, K

T_n = mean minimum temperature, K

e_d^o = saturation vapor pressure at mean dew point temperature (see Equation 7.11)

a_1 = 0.39

b_1 = -0.158

RH ¾ Relative humidity: maximum, minimum and mean

Note that the minimum relative humidity is calculated using the maximum air temperature and the maximum relative humidity is calculated using the minimum air temperature. Use Equation 7.11 to calculate the saturation vapor pressures (e^0).

Minimum relative humidity:

$$RH_n = \frac{e_d^o(T_d)}{e_x^0(T_x)}100$$ percent [p149]

where T_d = mean dew point temperature, °C
T_x = mean maximum temperature, °C
e_d^0 = saturation vapor pressure at mean dew point, kPa
e_x^0 = saturation vapor pressure at mean maximum temperature, kPa

Maximum relative humidity:

$$RH_x = \frac{e_d^o(T_d)}{e_n^0(T_n)}100$$ percent [p142]

where T_d = mean dew point temperature, °C
T_n = mean minimum temperature, °C
e_d^0 = saturation vapor pressure at mean dew point, kPa
e_n^0 = saturation vapor pressure at mean minimum temperature, kPa

Mean relative humidity:

$$RH_m = (RH_n + RH_x)/2$$ percent

e^0 ¾ Saturation vapor pressure

$$e^0 = \exp\left[\frac{16.78T - 116.9}{T + 237.3}\right]$$ kPa [7.11]

where T = mean temperature, °C

Notes:

This equation is used in several methods to calculate saturation vapor pressure at various temperatures. If the method requires e^0 at dew-point, use the mean dew-point temperature; if the method requires e^0 at daily maximum temperature, use the mean maximum daily temperature. If hourly calculations are being made, use mean hourly data.

With respect to dew-point temperature, since it does not normally change significantly during the day, a single observation should be adequate.

a ¾ **Short-wave reflectance coefficient or albedo**

Short-wave reflectance is unitless. Mean daily value for most green field crops with full cover range from 0.20 to 0.25. A commonly used value is 0.23.

D ¾ **Slope of the saturation vapor pressure – temperature curve**

$$\Delta = \frac{de^0}{dT} = 0.200(0.00738T + 0.8072)^7 - 0.000116 \qquad \text{kPa °C}^{-1} \qquad [7.12]$$

where
T = mean temperature, °C
$T \geq -23°C$

G**$_i$* ¾ **Soil heat flux for time period *i

This equation is more accurate for larger time steps.

$$G_i = 4.2\left(\frac{T_{i+1} - T_{i-1}}{\Delta t}\right) \qquad \text{MJ m}^{-2}\text{ d}^{-1} \qquad [3.31]$$

where ***T*** = mean air temperature °C for time period ***i***
Dt = time in days between the midpoints of the time periods

Notes:

For example, to calculate estimated soil heat flux for July, use the mean August air temperature for T_{t+1}, the mean June air temperature for T_{t-1} and 60 for Δt. This calculation may be made with other time steps as well, such as daily, 10-day, annual and so on.

(e_z^0 – e_z) ¾ **Vapor pressure deficit**

Use Equation 7.11 to calculate saturation vapor pressure (e^0).

$$\left(e_z^0 - e_z\right) = \frac{\left[e_x^0(T_x) + e_n^0(T_n)\right]}{2} - e_d^0 T_d \qquad \text{kPa} \qquad [p138]$$

where ***T_d*** = mean dew-point temperature, °C
T_x = mean maximum temperature, °C
T_n = mean minimum temperature, °C
e_d^0 = saturation vapor pressure at mean dewpoint temperature
e_n^0 = saturation vapor pressure at mean minimum temperature
e_x^0 = saturation vapor pressure at mean maximum temperature

Wind Speed Adjustment

To estimate wind speed at a specified height above grass or a field crop using measured wind speed at another height, use the following equation. This equation can be used to calculate the estimated wind speed at 2 m height that is required by the Penman (1963) and FAO-24 Radiation methods.

$$W_2 = W_1 \left[\frac{z_2}{z_1} \right]^a \qquad \text{m s}^{-1} \qquad [7.23]$$

where
W_2 = estimated wind speed at height z_2, m s^{-1}
W_1 = measured wind speed at height z_1, m s^{-1}
a = 0.2

List of Symbols

Symbol	Explanation	Common units
a	Short-wave reflectance coefficient or albedo	—
g	Psychrometric constant	kPa $°C^{-1}$
$g*$	Psychrometric constant modified by the ratio of canopy resistance to atmospheric resistance	kPa $°C^{-1}$
D	Slope of the saturation vapor pressure-temperature curve, de/dT	kPa $°C^{-1}$
l	Latent heat of vaporization	MJ kg^{-1}
p	3.14159	—
F	Latitude	radians
d	Declination	radians
r	Air density	kg m^{-3}
$(e_z^0 - e_z)$	Vapor pressure deficit	kPa
w_s	Sunset hour angle	radians
a, b	Constants	varies
C_T	Jensen-Haise temperature coefficient	
d	Day	
d	Zero plane displacement of wind profile (used only in calculating diffusion resistance of air layer – r_a)	cm
d_r	Relative distance of the Earth to the Sun	—
e_d^0	Saturation vapor pressure at dew point air temperature	kPa
e_n^0	Saturation vapor pressure at minimum air temperature	kPa
e_x^0	Saturation vapor pressure at maximum air temperature	kPa

Symbol Explanation Common units

E_t	Evapotranspiration rate	mm d^{-1}
g	Gram	
G	Soil heat flux	MJ m^{-2} d^{-1}
G_{sc}	Solar constant — 0.0820 MJ m^{-2} min^{-1}	MJ m^{-2} min^{-1}
h	Hour	—
J	Numerical day of year (Jan. 1st = 1, Jan. 2nd = 2…Dec 31st = 365)	—
K_1	Dimension coefficient — 8.64×10^4 where units of wind speed are in m s^{-1} (used only in Penman-Monteith)	
LAI	Leaf area index	—
min	Minute	—
P	Atmospheric pressure	kPa
R_A	Extraterrestrial solar radiation received on a horizontal surface	MJ m^{-2} d^{-1}
r_a	Diffusion resistance of air layer (aerodynamic resistance)	s m^{-1}
R_b	Net outgoing long-wave radiation	MJ m^{-2} d^{-1}
R_{bo}	Net outgoing long-wave radiation on a cloudless day	MJ m^{-2} d^{-1}
r_c	Crop canopy resistance	s m^{-1}
RH_m	Mean relative humidity	percentage
RH_n	Minimum relative humidity	percentage
RH_x	Maximum relative humidity	percentage
R_n	Net radiation	MJ m^{-2} d^{-1}
R_s	Solar radiation received at the earth's surface on a horizontal plane	MJ m^{-2} d^{-1}
R_{so}	Solar radiation on a cloudless day	MJ m^{-2} d^{-1}
Symbol	Explanation	Common units

s	Second	
T	Temperature	°C, K
TD	Temperature difference – used in Hargreaves method	°C
T_d	Dew point temperature of the air	°C
T_n	Minimum air temperature	°C, K
T_x	Intercept of temperature axis – used only in Jensen-Haise method	
T_x	Maximum air temperature	°C, K
U_d	Daytime wind speed	m s^{-1}
u_2	Wind speed at height 2 meters	m s^{-1}
u_z	Horizontal wind speed at height z	m s^{-1}
W_f	Wind function – used only in Penman (1963) method	—
z	Elevation	m
z_{om}	Roughness length, momentum	cm
z_{ov}	Roughness length, heat, and water vapor	cm
z_p	Height of humidity and temperature measurements	cm
z_w	Height of wind speed measurement	cm

Appendix A-3 Method used to estimate PET for Air Force facilities

The Environmental Policy Integrated Climate (EPIC) model was used to estimate the values of PET and AET for the 60 Air Force sites described in Section 3.3.4 and listed in Table 1. The EPIC model is a comprehensive model that has been extensively tested for plant growth and water balance estimates. The EPIC model is in use by the U.S. Department of Agriculture throughout the United States.

ET Estimation

Table A-3 lists the source of climatic data, the plant cover selected, and the ET estimation method used for each base. The Priestly-Taylor ET estimation method was used east of 100º W longitude, and the Hargreaves method was used for bases west of that line. The Penman-Monteith ET estimation method is the most accurate of the 20 ET estimation methods tested by ASCE [6]. However, the Penman-Monteith method requires a complete climate data set, including daily wind run and relative humidity. Daily precipitation and maximum and minimum air temperatures were available for all bases; however, wind and humidity are time-consuming and expensive to collect for the large number of bases included in this evaluation. The Priestly-Taylor and Hargreaves methods produce acceptable accuracy for the selected regions and do not require wind and humidity data (Tables 7.18 and 7.19 in [6]). The EPIC model was used to create 100-year average annual estimates of PET, AET, and the number of plant-stress days.

The value of PET for each site is controlled almost exclusively by the climate. By we using appropriate, site-specific climate data, the estimates of PET presented in Section 3.3.2 and Table 1 are also appropriate for each site. The value of AET, however, is strongly influenced not only by climate but also by the plant and soil properties evaluated in the model.

Climate Data

Accurate climatic data are available within the EPIC model data sets for locations within a reasonable distance of each of the 60 locations selected except for Hill Air Force Base (AFB). The required data for Hill AFB was calculated from National Climatic Center records for a nearby site. EPIC stochastically generated daily values of radiation, precipitation, and temperature from monthly mean values, standard deviation of rainfall and temperature, and probability of rainfall for each base. The stochastically generated climate data have statistical properties and variations similar to those found in measured data.

Plant Cover

The plant cover was modeled as a monoculture of grass that is adapted to the region and climate of each base (Table A-3). Each grass has the potential to root to a depth of two meters in the soil and to extract water from that depth. Because a monoculture was used, the amount of AET estimated is smaller than would be expected with a diverse

Table A-3. Climate Data Sources, Plant Cover, and Estimation Methods Used

Base	State	Region	Weather Station		Plant Cover	ET Method
			Name	Dist. (mi)		
Bolling AFB	DC	Northeast	Owings Ferry Landing, MD	19	Russian Wild Rye Grass	Priestly-Taylor
Chanute AFB	IL	Northeast	Farmer City, IL	23	Russian Wild Rye Grass	Priestly-Taylor
Dover AFB	DE	Northeast	Middleton, DE	25	Russian Wild Rye Grass	Priestly-Taylor
Grand Forks AFB	ND	Northeast	Grafton State School, ND	29	Russian Wild Rye Grass	Priestly-Taylor
Langley AFB	VA	Northeast	Mathews, VA	25	Russian Wild Rye Grass	Priestly-Taylor
Loring AFB	ME	Northeast	Caribou, ME	6	Russian Wild Rye Grass	Priestly-Taylor
McGuire AFB	NJ	Northeast	Indian Mills, NJ	20	Russian Wild Rye Grass	Priestly-Taylor
Offutt AFB	NE	Northeast	Syracuse, NE	34	Russian Wild Rye Grass	Priestly-Taylor
Plattsburgh AFB	NY	Northeast	Plattsburgh, NY	3	Russian Wild Rye Grass	Priestly-Taylor
Scott AFB	IL	Northeast	Sparta, IL	28	Russian Wild Rye Grass	Priestly-Taylor
Whiteman AFB	MO	Northeast	Harrisonville, MO	39	Russian Wild Rye Grass	Priestly-Taylor
Wright-Patterson AFB	OH	Northeast	Dayton, OH	5	Russian Wild Rye Grass	Priestly-Taylor
Wurtsmith AFB	MI	Northeast	Hale Five Channel Dam, MI	19	Russian Wild Rye Grass	Priestly-Taylor
Air Force Academy	CO	Rockies	Parker, CO	38	Crested Wheat Grass	Hargreaves
Ellsworth AFB	SD	Rockies	Fort Meade, SD	28	Crested Wheat Grass	Hargreaves
Fairchild AFB	WA	Rockies	Spokane, WA	9	Crested Wheat Grass	Hargreaves
Hill AFB	UT	Rockies	Riverdale, UT	2	Crested Wheat Grass	Hargreaves
Lowry AFB	CO	Rockies	Parker, CO	18	Crested Wheat Grass	Hargreaves
Malmstrom AFB	MT	Rockies	Great Falls, MT	8	Crested Wheat Grass	Hargreaves
Minot AFB	ND	Rockies	Foxholm Wildlife Refuge, ND	13	Crested Wheat Grass	Hargreaves
Mountain Home AFB	ID	Rockies	Bruneau, ID	16	Crested Wheat Grass	Hargreaves
Altus AFB	OK	Southeast	Altus, OK	5	Switch Grass	Priestly-Taylor
Arnold AFB	TN	Southeast	Shelbyville, TN	22	Switch Grass	Priestly-Taylor
Barksdale AFB	LA	Southeast	Shreveport, LA	5	Switch Grass	Priestly-Taylor
Brooks AFB	TX	Southeast	San Antonio, TX	10	Switch Grass	Priestly-Taylor
Charleston AFB	SC	Southeast	Kingstree, SC	54	Switch Grass	Priestly-Taylor
Columbus AFB	MS	Southeast	State College, MS	28	Switch Grass	Priestly-Taylor
Dyess AFB	TX	Southeast	Abilene, TX	13	Switch Grass	Priestly-Taylor
Homestead AFB	FL	Southeast	Homestead Exp. Sta., FL	6	Switch Grass	Priestly-Taylor
Keesler AFB	MS	Southeast	Saucier EXP Forest, MS	18	Switch Grass	Priestly-Taylor
Little Rock AFB	AR	Southeast	Little Rock, AR	13	Switch Grass	Priestly-Taylor
MacDill AFB	FL	Southeast	Bradenton, FL	23	Switch Grass	Priestly-Taylor

Base	State	Region	Weather Station Name	Weather Station Dist. (mi)	Plant Cover	ET Method
Maxwell AFB	AL	Southeast	Montgomery, AL	7	Switch Grass	Priestly-Taylor
McConnell AFB	KS	Southeast	Wichita, KS	7	Switch Grass	Priestly-Taylor
Moody AFB	GA	Southeast	Tifton, GA	38	Switch Grass	Priestly-Taylor
Patrick AFB	FL	Southeast	Titusville, FL	32	Switch Grass	Priestly-Taylor
Pope AFB	NC	Southeast	Laurinburg, NC	39	Switch Grass	Priestly-Taylor
Robins AFB	GA	Southeast	Macon, GA	7	Switch Grass	Priestly-Taylor
Seymour Johnson AFB	NC	Southeast	Greenville, NC	42	Switch Grass	Priestly-Taylor
Shaw AFB	SC	Southeast	Orangeburg, SC	41	Switch Grass	Priestly-Taylor
Sheppard AFB	TX	Southeast	Henrietta, TX	22	Switch Grass	Priestly-Taylor
Tinker AFB	OK	Southeast	Oklahoma City, OK	11	Switch Grass	Priestly-Taylor
Tyndall AFB	FL	Southeast	Chipley, FL	48	Switch Grass	Priestly-Taylor
Vance AFB	OK	Southeast	Cherokee, OK	40	Switch Grass	Priestly-Taylor
Cannon AFB	NM	Southwest	Melrose, NM	19	Range Grass	Hargreaves
Davis-Monthan AFB	AZ	Southwest	Tucson, AZ	5	Range Grass	Hargreaves
George AFB	CA	Southwest	Victorville, CA	2	Range Grass	Hargreaves
Goodfellow AFB	TX	Southwest	San Angelo, TX	6	Range Grass	Hargreaves
Holloman AFB	NM	Southwest	Alamogordo, NM	10	Range Grass	Hargreaves
Kirtland AFB	NM	Southwest	Albuquerque, NM	<2	Range Grass	Hargreaves
Laughlin AFB	TX	Southwest	Del Rio, TX	2	Range Grass	Hargreaves
Luke AFB	AZ	Southwest	Litchfield Park, AZ	2	Range Grass	Hargreaves
Nellis AFB	NV	Southwest	Las Vegas, NV	13	Range Grass	Hargreaves
Reese AFB	TX	Southwest	Lubbock, TX	10	Range Grass	Hargreaves
Beale AFB	CA	West Coast	Oroville, CA	29	Annual Rye Grass	Hargreaves
Castle AFB	CA	West Coast	Denair, CA	14	Annual Rye Grass	Hargreaves
McChord AFB	WA	West Coast	Puyallup 2 W Exp Stn, WA	10	Annual Rye Grass	Hargreaves
McClellan AFB	CA	West Coast	Sacramento, CA	14	Annual Rye Grass	Hargreaves
Travis AFB	CA	West Coast	Vacaville, CA	7	Annual Rye Grass	Hargreaves
Vandenberg AFB	CA	West Coast	Lompoc, CA	9	Annual Rye Grass	Hargreaves

plant cover. For example, Switch grass is a warm-season grass and was used in the Southeastern area of the country. Its growth and water use is primarily during the warm months. Where both warm- and cool-season plants are grown, the total annual AET will be substantially more than for a monoculture consisting of a warm-season grass (Switch grass in this example).

Soil Data

The same soil was used in each model estimate (see Table A-4 for a list of soil properties). The soil described is a mixture of the top 3.3 ft. of the Pullman silty clay loam soil found in the Southern Great Plains. It is a fertile soil with good water-holding capacity. Since the intent was to focus on defining the climatic limitations on plant growth, the soil properties used for the estimates present few limitations to plant growth or ET. Where soils at or near the site are of poor quality, the quality can be improved and made suitable for most phytostabilization uses by adding amendments.

Water Table Elevation

The EPIC model can evaluate the effect of high-water tables. However, we set the water table depth greater than 100 feet to simulate the condition where the plants used only the precipitation stored in the 6.6 ft.-thick soil profile as their water supply. When plants are used at sites with shallow water tables, the AET may be substantially greater than estimated in this evaluation.

Table A-4. Properties of the Soil Mixture Used in All Model Estimates

Soil Property	Value
Sand content	14.2 %
Silt content	41.7 %
Clay content	44.1 %
Bulk density	1.4 gm/cc
Wilting point	0.18 ft./ft.
Field capacity	0.34 ft./ft.
Soil pH	6.8
Organic carbon	1.4 %
Cation exchange capacity	21.0 cmol/kg
Soil thickness	6.6 ft.
Hydrologic soil group	D
Number of soil layers modeled for the mixture	10

Appendix B Seasonal Water Use by Plants

This appendix contains the summary of seasonal water use by plants discussed and referenced in Section 3.4.7. The summary table and the references from *Water Use by Naturally Occurring Vegetation Including an Annotated Bibliography* edited by Eldon Johns and published by a task committee of the American Society of Civil Engineers [40].

Table B-1. Seasonal Water Use by Plants

CAUTION: The length of growing season may vary considerably.
Individual papers should be obtained and reviewed in all instances.

Common Name	Scientific Name	Consumptive Use	Reference
Arrowweed	Pluchea Sericea	96″	McDonald and Hughes, 1968
Aspen	Populus	9.9-16.5″	Tew, 1967
Aspen	Poputus	10.3-24.18″	Johnston, et at., 1969
Aspen	Poputus	18.53-24.15″	Johnston, 1970
Aspen	Populus	18.7″	Croft and Monniger, 1953
Aspen	Populus	19.2″	Brown and Thompson, 1965
Baccharis	Baccharis	31.6-52.0″	Turner and Hatpenny
Baccharis	Baccharis	56″	Gatewood, et at., 1950
Buckwheat	Fagopyrum Escutentum	3.1″	Branson, et at., 1970
Buckwheat	Fagopyrum Esculentum	24.3″	Patric, 1961
Buffaloberry		3.5-9.0″	Meyboom, 1964
Cattail	Typha	35-45″	Pratt, et at., 1985
Cattail	Typha	52.5-77″	Parshall, 1937
Cattail	Typha	60.4″	Christianson, 1970
Cattail	Typha	63.4″	Blaney, et al., 1933
Cattail	Typha	90-198″	Young and Blaney, 1942
Cattail	Typha	100″	McDonaLd and Hughes, 1968
Ceanothus	Ceanothus Crassifolius	23.6″	Patric, 1961
Chamise	Adenostoma Fasciculatum	25.5″	Patric, 1961
Chaparral		21.6-42″	Scholl, 1976
Cottonwood	Populus	40.6″	Meyboom, 1964
Cottonwood, Mix w/willow	Populus	60.0-92.7″	Muckel & Btaney, 1945, see Weeks & Sorey, 1973
Cottonwood	Populus	72″	Gatewood, et at., 1950
Creosote Bush	Larrea Tridentata	10.2″	Sanunis and Gay, 1979
Creosote Bush	Larrea Tridentata	9.25″	Evans, et at., 1981
Fir-Douglas	Pseudotsuga Menzlesii	12.0-13.7″	Johnston, et at., 1969

Common Name	Scientific Name	Consumptive Use	Reference
Fir-Douglas	Pseudotsuga Menziesii	18-20″	Fritschen, et at., 1977
Fir-General	Abies	6-9″	Bethelt, et at., 1980
Forbs and Grass Mix		17.0-29.6″	Rowe and Reimann, 1961
Forest (General)		14.5-21.0″	Leaf, 1975a
Forest (General)		16.8″	Leaf, 1975b
Foxtail	Lycopodium Clavatum	5.5″	Branson, et al., 1970
Grass		8.9″	Brown and Thompson, 1965
Grass		16.0″	Patric, 1961
Grass-Alta Fescue		19.4-29.9″	Dylla, et at., 1972
Grass-Bermuda		28.8-36.2″	Blaney, et at., 1933
Grass-Bermuda		73″	McDonald and Hughes, 1968
Grass-Blue Grama Native		2.9-17.6″	Bailey, 1940
Grass-Blue Grama Native		3.9″	Branson, et at., 1970
Grass-Blue Grama Native		5.6-10.6″	Aase, 1970
Grass-Blue Grama Native		9.75″	Reed and Dwyer, 1971
Grass-Blue Grama Native		24.0-41.0″	Parshall, 1937
Grass-Bluejoint		21.9-34.6″	Dylla, et at., 1972
Grass-Cheat	Bromus Tectorum	3″	Cline, et at., 1977
Grass –Meadow Mixed		4.8-10.2″	Wight and Hanks, 1981
Grass –Meadow Mixed		6.9-10.0″	Wight and Black, 1977
Grass –Meadow Mixed		8.9-10.0″	Wight, 1971
Grass –Meadow Mixed		13.0-24.15″	Hammat, 1920
Grass –Meadow Mixed		17.36-33.47″	USBR, 1977
Grass-Meadow Native		6.8-10.5″	Hanson, 1976
Grass-Meadow Native		23.2-27.8″	Kruse and Haise, 1974
Grass-Mix		10.08-48.36″	Houk, 1930
Grass-Mix		14.6″	Weeks and Sorey, 1973
Grass-Mix		14.7-22.6″	White, 1932
Grass-Mix		19.57-22.58″	Dylla and Muckel, 1964

Common Name	Scientific Name	Consumptive Use	Reference
Grass-Mix		20.75-28.32″	USBR, 1977
Grass-Native		5.12-19.60″	Johnston, et al., 1969
Grass-Native		9.1″	Harrison, 1983
Grass-Native		18.5-24.3″	Rich, 1952
Grass-Needle Mix		10.6″	Buckhouse and Coltharp, 1976
Grass-Needle Mix		12.2″	White and Brown, 1972
Grass-Pasture		8.4-16.1″	Rowe end Reimann, 1961
Grass-Pasture		20.6-27.2″	Ritchie, et at., 1976
Grass-Prairie		7.6"	Lauenroth and Sims, 1976
Grass-Prairie		9.4-11.9″	Pochop, et at., 1985
Grass-Prairie		10.0-36.3″	Reported in Young and Blaney, 1942
Grass-Prairie		12″	Parton, et at., 1981
Grass-Salt		6.2-21.7″	Grosz, 1972
Grass-Salt		13.2-42.1″	Young and Blaney, 1933
Grass-Salt		13.43-48.8″	Lee, 1915
Grass-Salt		16.2-39.8″	Reported in Young and Blaney, 1942
Grass-Salt		18.7-29.2″	USBR, 1973, 1979
Grass-Salt		19.1-22.4″	Dylla, et at., 1972
Grass-Salt		27.7″	Criddte, et at., 1964
Grass-Salt		33.2″	Christiansen, 1970
Grass-Sedge		41.5-60.2″	Parshall, 1937
Grass-Sugar		16.1-22.28″	Hamnat, 1920
Grass-Wheat (Bluebunch)	Agropyron Inerme	8-11″	Shown, et at., 1972
Grass-Wheat (Tall)	Agropyron Elongatum	23.6-32.2″	Dylla, et at., 1972
Grass-Wheat (Western)	Agropyron Smithii	12.3″	Branson, et at., 1970
Greasewood	Sarcobatus Vermiculatus	2.6″	Branson, et al., 1970
Greasewood	Sarcobatus Vermiculatus	3.7″	Branson, et at., 1976
Greasewood	Sarcobatus Vermiculatus	11.3″	Carman, 1986
Greasewood	Sarcobatus Vermiculatus	11.8-25.2″	White, 1932
Greasewood	Sarcobatus Vermiculatus	12.2-22.1″	Grosz, 1972

Common Name	Scientific Name	Consumptive Use	Reference
Greasewood	Sarcobatus Vermiculatus	14.5-17.5″	Robinson, 1970
Greasewood	Sarcobatus Vermiculatus	20.8-24.8″	Harr and Price, 1972
Herbeceous		14.8″	Croft and Monninger, 1953
Hydrophytes		22-24″	Eisenlohr, 1972
Hydrophytes		45″	Christianson, 1970
Kochia (Burning Bush)	Kochia Scoporia	22-26″	Weeks, et al., 1987
Mallow	Kostetetzkya Virginica	13.7-51.1″	Philipp and Gallagher, 1985
Maple-Manitoba, Boxelder	Acer Negundo	16.1-20.8″	Meyboom, 1964
Meadow-Mountain		8.5-31.1″	Borrelli, 1981
Meadow-Mountain		14.0-19.4″	Swartz, et at., 1972
Meadow-Mountain		16-20″	Burman and Pochop, 1986
Meadow-Mountain		16.5-27.6″	Pochop, et at., 1985
Meadow-Native Pasture		13.2″	Thompson, 1974
Meadow-Native Pasture		19.6-22.6″	Dylla and Muckel, 1964
Meadow-Native Pasture		38.4-38.7″	California Water Resources, 1975
Mesquite	Prosopis	14.5″	Qusahu and Evans, 1967, April-June
Mesquite	Prosopis	20″	Richardson, et at., 1979
Mesquite	Prosopis	40″	Gatewood, et at., 1950
Oak-Gambel	Quercus Ganbelii	11.39-18.64″	Johnston, et at., 1969
Oak-Gambel	Quercus Gambelii	14.8-18.8″	Tew, 1966
Oak-Scrub	Quercus Dunosa	16.3-23.4″	Rowe and Reimann, 1961, with Mahogany
Oak-Scrub	Quercus Dumosa	24.8″	Patric, 1961
Pine	Pinus	19.4″	Thompson, 1974
Pine	Pinus	36.3-47.0″	Riekerk, 1985
Pine-Coulter	Pinus Coulteri	25.1″	Patric, 1961
Pine-Ponderosa	Pinus Ponderosa	15.5″	Berndt, 1960

Common Name	Scientific Name	Consumptive Use	Reference
Pine-Scotch (Xmas trees)	Pinus Sylvestris	12.3-39.22″	Petersen and Hilt, 1985
Pinyon-Juniper		14.53-27.53″	Gifford, 1975
Poplar-Yellow	Liriodendron Tutipifera	26.2″	Luxmoore, et at., 1978
Quailbrush-Saltbush	Atriplex Lentiformis	44″	McDonald and Hughes, 1968
Rabbitbrush	Chrysothamnus	12.7″	Carman, 1986
Rabbitbrush	Chrysothamnus	12.8-26.3″	Grosz, 1972
Rabbitbrush	Chrysothamnus	19.92″	Robinson, 1970
Rabbitbrush	Chrysothamnus Greenei	2.4-4.8″	Branson, et at., 1976
Redroot-Pigweed	Amaranthus	31.7″	Parshall, 1937
Riparian Vegetation		13.2″	Schumann, 1967
Riparian Vegetation		17.1″	Ben-Asher, Jr., 1981
Riparian Vegetation		22.4″	Sammis, 1972
Rose-Wild	Rosa	20.5″	Robinson, 1970
Rush	Juncus	20.8″	Meyboom, 1964
Rush	Juncus	52.6-86.6″	Parshall, 1937
Rush-Baltic (Wire Grass)	Juncus Balticus	84.5″	Blaney, et at., 1933
Russian Olive	Elaeagnus Angustifolia	18.6-114.6″	USBR, 1973-1979
Russian Thistle	Salsola Kali	22.9-26.1″	Parshall, 1937
Sagebrush & Cheatgrass	Artemisia Tridentata	9.37″	Gutknecht, et at., 1980
Sagebrush-Big	Artemisia Tridentata	3.7-7.0″	Branson, et at., 1970
Sagebrush-Big		3.9″	Branson, et at., 1976
Sagebrush-Big		6.4-9.6″	Sturges, 1980
Sagebrush-Big		8-12″	Shown, et at., 1972
Sagebrush-Silver	Artemisia Cana	3.7″	Branson, et at., 1970
Sagebrush-Silver	Artemisia Cana	5.12-8.97″	Johnston, et at., 1969
Sagebrush-Silver	Artemisia Cana	6″	Cline, et at., 1977
Saltbush	Atriplex	2.4-3.3″	Branson, et al., 1976
Saltbush	Atriplex	25.9-53.9″	Phillip and Gallagher, 1985
Saltbush-Fourwing	Atriptex Canescens	38″	McDonald and Hughes, 1968
Saltbush-Nuttall	Atriplex Nuttatlii	1.0-1.6″	Branson, et at., 1970
Saltbush-Quailbrush	Atriptex Lentiformis	44″	McDonald and Hughes, 1968
Saltcedar	Tamarix Chinensis	14.9-29.2″	Grosz, 1972

Common Name	Scientific Name	Consumptive Use	Reference
Saltcedar	Tamarix Chinensis	15.6-56.4″	USBR, 1973, 1979
Saltcedar	Tamarix Chinensis	25-56″	Culter, et at., 1982
Saltcedar	Tamarix Chinensis	30-42″	Weeks, et at., 1987
Saltcedar	Tamarix Chinensis	32.6″	Criddle, et at., 1964
Saltcedar	Tamarix Chinensis	40-85″	VanHylckama, 1974
Saltcedar	Tamarix Chinensis	47.9-61.1″	Turner and Halpenny, 1941
Saltcedar	Tamarix Chinensis	68″	Gay and Hartman, 1982
Saltcedar	Tamarix Chinensis	69-71″	Gay, 1984
Saltcedar	Tamarix Chinensis	86″	Gatewood, et at., 1950
Saltcedar and Cottonwood	Tamarix Chinensis	20.9-29.7″	Weeks and Sorey, 1973, Cottonwood Mix
Sedge	Carex	21.8-27.3″	Dylla, et al., 1972
Sedge	Carex	76.9″	Reported in Young and Blaney, 1942
Shrub-Mixed		8.7″	Branson, et at., 1970
Snowberry	Symphoricarpos Racemosus	12.32-13.75″	Johnston, et at., 1969
Spruce	Picea	14.9″	Brown and Thonpson, 1965
Tules	Scirpus	40-221″	Reported in Young and Blaney, 1942
Tules	Scirpus	51.9″	Stearns, et at., 1939
Tules	Scirpus	62.9-63.4″	Blaney, et at., 1933
Tules	Scirpus	63.4-73.6″	Blaney, et at., 1933
Tules	Scirpus	64.68″	Houk, 1930
Willow	Salix	13.2″	Meyboom, 1964
Willow	Salix	30.5″	Reported in Young and Blaney, 1942
Willow	Salix	35.3″	Criddle, et at., 1964
Willow	Salix	35.3″	See Muckel and Blaney, 1945
Willow	Salix	36.4″	Robinson, 1970 7
Willow	Salix	47.8″	Blaney, et al., 1933
Willow-Dwarf	Salix	33.6″	Criddle, et al., 1964
Willow-Wolf	Elaeagnus Commutata	21.8″	Meyboom, 1964

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Appendix C USDA Plant Hardiness Zones

The plant hardiness zone map divides the continental United States into nine ranges of annual minimum temperature. (Zone 1 is only found in Alaska and is not shown.) Use this map to determine if annual minimum temperatures for a site fall below the tolerance of a particular plant species.

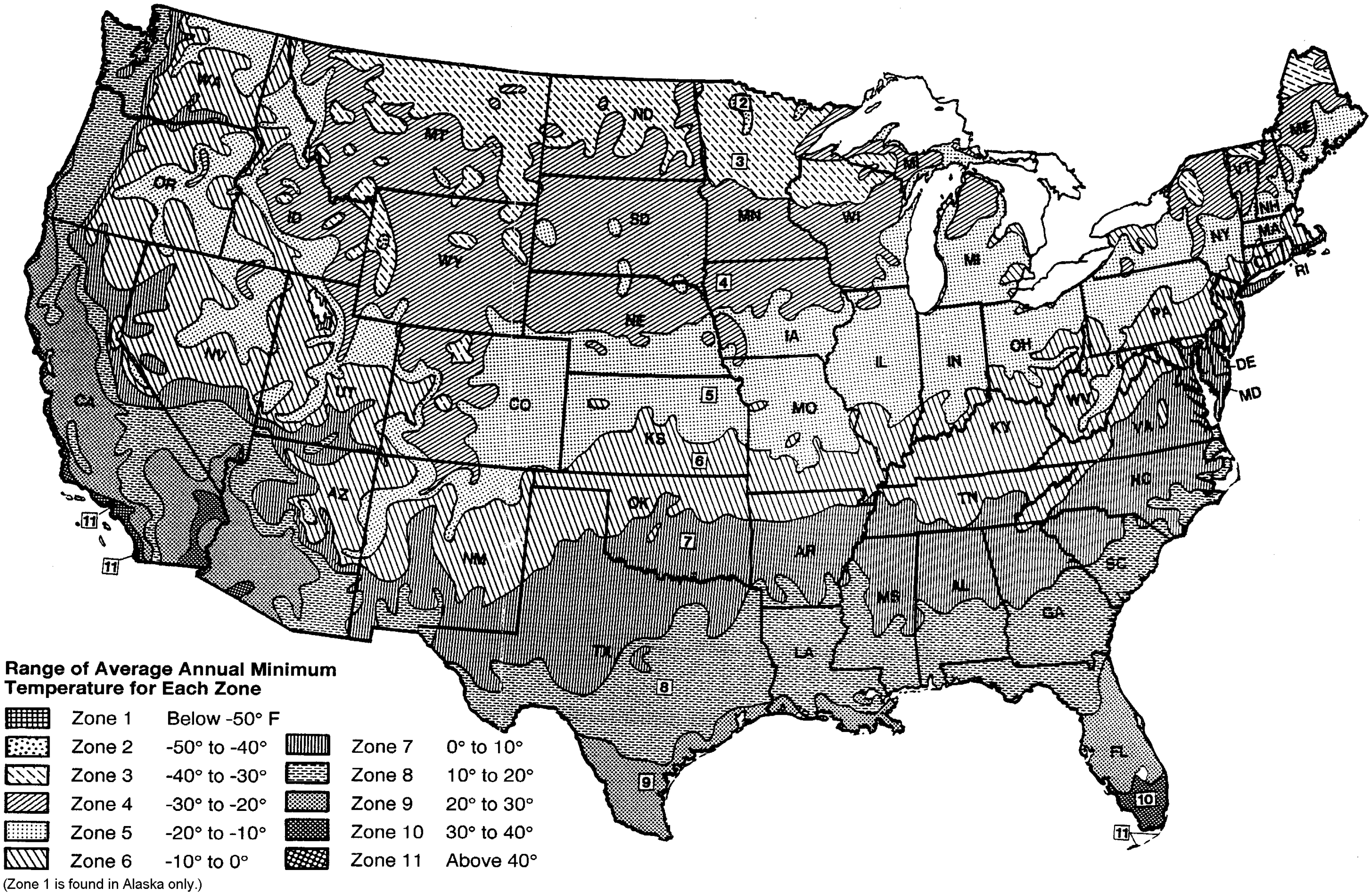

Figure D-1. USDA Plant Hardiness Zone Map
(after Alderson and Sharp [54])

Appendix D Case Studies

Phytoremediation is a relatively young discipline, particularly with respect to control of groundwater flow, and most projects are still in the early stages of establishment and initial data collection. Three case studies are presented in the following subsections to show the size and scope of actual phytostabilization projects [55, 56, 57].

Air Force Plant 4 (former Carswell AFB) – Fort Worth, Texas

This project is designed to contain and remediate a TCE plume in shallow groundwater near Air Force Plant 4 at the former location of Carswell AFB (now the Naval Air Station Fort Worth). It was initiated as part of the Environmental Security Technology Certification Program (ESTCP) and was selected as an EPA Superfund Innovative Technology Evaluation (SITE) project in 1996. Tree planting and the installation of the irrigation system was completed in April 1996.

The TCE groundwater plume is in an alluvial aquifer approximately 6 to 11 feet below ground surface (bgs) with groundwater flow to the southeast. TCE concentrations are less than 1,000 ppb with an average concentration of 610 ppb as of December 1996.

A total of 660 cottonwood trees were planted in two elongated areas perpendicular to the direction of groundwater flow. Eastern Cottonwood (*Populus deltoides*) was chosen instead of commonly used hybrid species because it is indigenous to the area and hence well suited to the local environment and should not be adversely affected by local climate extremes or disease.

Both whips and 5-gallon trees were used so comparisons can be made in the performance of each type of planting. When planted, the 5-gallon trees were approximately 7 feet tall and 1 inch in diameter; the whips were approximately 18 inches long and “about the thickness of one’s thumb”. The whips were planted so that only about 2 inches were above ground – leaving 16 inches below ground to take root. The whips and 5-gallon trees were planted in separate elongated plots running from northeast to southwest (perpendicular the flow of groundwater) with the whips upgradient of the 5-gallon trees so they would be in position to intercept the flow of groundwater first.

In addition to the newly planted trees, there is one mature cottonwood tree (70 feet tall) located on the southwest side of the site. Monitoring wells have been installed around it to enable the study of the phytoremediation capabilities of a mature tree in this system.

Monitoring wells and piezometers are located throughout the site so groundwater levels and chemistry can be monitored.

Wholesale costs of the trees (not including delivery or installation) were $8 for each 5-gallon tree and 20 cents each for the whips. Planting and landscaping cost $41,000. The complete cost for 29 monitoring wells was $200,000. Because this is a demonstration site, another $200,000 was slated for extensive site monitoring and $60,000 was slated for a fine biomass study which will determine the vertical and lateral extent of tree roots less than 2 mm in diameter.

Sixteen months after planting, the whips had grown approximately 20 feet and the 5-gallon trees experienced even faster growth. Presence of TCE in the tissue of whips in November 1996 show that they were using water from the water table after one growing season. As of the summer of 1997, test trenches were excavated that confirmed tree roots had reached the aquifer and were drawing water from the water table. However, they were not yet hydraulically controlling the TCE plume. During the summer of 1997, the largest planted trees were transpiring approximately 3.75 gallons per day. The mature tree located on the southwest edge of the site was determined to be transpiring approximately 350 gallons per day. It was noticed that transpiration rates declined during the mid-days in June indicating the trees were probably under water stress during the hottest parts of the day. Transpiration rates were also noted to vary with cloud cover – lower rates occurred on cloudy days.

The project is continuing with expanded monitoring of many parameters including those of water, soil , air and tree tissue and microbial populations.

Edgewood Area J Field Site – Aberdeen Proving Grounds, Edgewood, Maryland

This project is designed to contain and remediate a chlorinated solvent plume in shallow groundwater at the J Field site in the Edgewood area of the Aberdeen Proving Grounds in Maryland. This site was used for open pit burning of chemical agents, white phosphorous, high explosives and riot control agents. Contaminated soil has been excavated from the burn pits. Joint funding of innovative treatment technologies at the Proving Grounds is being provided by the Department of Defense (DoD) and the EPA. The EPA's Environmental Response Team (ERT) coordinated the planting. Tree planting was completed in March and April of 1996.

The plume contains several types of chlorinated solvents including 1122-TCA, TCE, PCE and TCA. Total VOC concentrations range from 20,000 ppb to 220,000 ppb. A perched groundwater zone lies between 2 to 8 feet bgs depending on the time of year. The groundwater flows to the south and southeast.

Prior to planting, a phytotoxicity study was conducted to ensure the proposed trees could grow in the contamination at the site. Nutrient levels were also tested to make sure they were adequate to support the trees. 183 hybrid poplars (*Populus trichocarpa x deltiodes* HP-510) in 4 areas totaling approximately 1 acre. They were located over the highest concentrations in the plume's leading edge . Placement of trees was also influenced by the locations of existing monitoring wells that were to be used to monitor the project.

The trees were bare-rooted and planted 2 to 6 feet bgs. Several actions were taken to promote root growth to the water table; Eight foot deep holes were augered beneath each tree to mix soil horizons and loosen the soil; Rubber tubing was installed to allow oxygen to reach the deep roots; Each tree was planted with a plastic pipe around it's upper roots; A drainage system was installed to remove rainwater from the surface.

In addition to the newly planted trees, there is one mature sweetgum tree which was left in place and will be monitored.

Both monitor wells and lysimeters have been installed on site. There are 14 monitoring wells screened from 4 to 14 feet bgs. Nine were on site originally and 5 were added in

November 1996. Two pairs of lysimeters were installed. Each pair had a lysimeter at 4 and at 8 feet bgs. They were installed at different depths because of the seasonal variability of the water table and capillary fringe. Other parameters being monitored on site include weather parameters (precipitation, temperature, humidity, wind speed and solar radiation) and tree sap flow. Sap flow measurements provide data used to estimate water usage by the trees.

Cost of the trees including installation was $80 each. Operation and maintenance is $30,000. This figure is inflated because this is a demonstration project. An additional cost specific to this site was $80,000 for clearance of unexploded ordnance during planting.

As of late 1998, approximately 10 percent of the trees had died. Causes of death included frost, deer rub (during rutting season) and insects. In May 1997, the water table beneath the trees was 2 feet lower than the levels measured in the same areas in April 1996. At the end of the second growing season (late 1998), there was a smaller but evident depression in the water table in the tenths of feet. At that time the trees were transpiring 2 to 10 gallons of water per day per tree.

Edward Sears Property – New Gretna, New Jersey

This project is designed to contain and remediate a plume of volatile organic compounds (VOCs) in groundwater at the Edward Sears property in New Gretna, New Jersey. Numerous hazardous materials were handled on this site from the mid-1960s to the early 1990’s including paints, adhesives, paint thinners and military surplus materials. Mr. Sears is no longer alive and no other responsible party for this site could be found so initial removal actions were performed by EPA Region 10’s Removal Action Branch. EPA ERT was then tasked with further investigation of the site.

The two heavily contaminated areas were excavated to 8 feet bgs and then back-filled with clean sand. The water table is approximately 9 feet below ground surface. Subsurface alluvial material varies from highly permeable sand to clay. Approximately 4 to 5 feet bgs is a highly permeable layer of sand, immediately underlying that layer is 13 feet of less permeable sand, silt and clay. Below the less permeable layer is approximately 62 feet of highly permeable sand. Most of the contamination is found in or above the less permeable layer. VOCs including TCE and PCE have been detected in the plume. TCE results from sampling before planting ranged from 0 to 390 ppb.

Substantial site preparation occurred in October and November 1996 prior to planting. The site was cleared of debris. In order to prevent infiltration of rain water into the upper root zone, a 4 inch layer of clay was placed approximately 1 foot bgs. Native soil was then replaced and the site was graded.

A total of 208 hybrid poplars (*Populus charkowiiensis x incrassata* NE 308) were planted in December 1996. At planting, the saplings were approximately 12 feet tall. 118 poplars were planted 9 feet bgs (“deep rooted”) – leaving 3 feet of the trees above ground level – in a plot approximately 0.3 acres in size. They were planted 10 feet apart north to south and 12.5 feet apart east to west. Deep rooting the trees involved several steps. First, a 12 inch diameter hole was drilled to 13 feet bgs. The hole was partially back filled with peat moss, sand, limestone and phosphate fertilizer to encourage root growth. Waxed cardboard cylinders (12 inches x 4 feet) were put in the hole to serve as barriers to root growth with the intent to direct roots down toward the water table. The cylinders settled in the holes, so a 5-gallon bucket with the bottom cut out was placed in each hole to extend the root barriers to 5 foot bgs. The trees were placed in these root barrier cylinders and the back filling was completed using clays removed from the holes while drilling.

There were 90 extra trees. They were planted approximately 3 feet apart at 3 feet bgs along the north, west and east boundaries of the site. They are expected to thin naturally over time. It is hoped that the trees will help to prevent shallow infiltration of water from offsite. They will also serve as replacements if any deep-rooted trees are lost. The entire site was also planted to grass to help control surface water.

Groundwater, soil, soil gas, plant tissue and evapotranspiration gas are to be monitored as an on-going part of the project. Also, on-site maintenance of the trees is being conducted to protect them from deer rub and poplar leaf caterpillar.

Cost of the trees (both deep and shallow rooted) including installation was $25,000 which is approximately $120 per tree. Another $15,000 was expended on the grass surface cover and one year of on-site maintenance.

Limited data is available for this project as yet, however, the trees did grow 30 inches in the first 7 months after the planting. Monitoring is continuing.

Appendix E Vendor List

Vendors

The first list is a listing of vendors of equipment that may be used in implementing a phytoremediation project. Following that is a list of four phytoremediation companies that have experience in designing and implementing phytoremediation projects.

This list of vendors is provided solely as a beginning resource to the reader. Inclusion in the list does not imply endorsement be either the Air Force or Mitretek Systems. Exclusion from the list does not imply a lack of endorsement from the Air Force or Mitretek Systems.

Table E-1. Equipment Vendor/Product Matrix

	Erosion control products	**Sap flow measurement**	**Other plant parameter measurements[1]**	**Soil moisture measurement/monitoring**	**Automatic irrigation systems**	**Climate parameter measurement/stations**	**Field tools**	**Safety equipment**	**Water quality measurement/monitoring**	**Data loggers**	**Soil/groundwater sampling**	**Water level measurement/monitoring**
Art's Manufacturing & Supply											X	
Ben Meadows Company				X		X	X	X			X	X
Campbell Scientific, Inc.			X	X		X				X		X
Caterpillar							X	X				
Coastal Environmental Systems						X				X		
Davis Instruments					X	X						
Decagon Devices, Inc.			X	X								
Dynamax, Inc.		X	X	X		X				X		
Electronic Data Solutions									X	X		X
Environmental Sensors, Inc.				X	X	X				X		
Enviro-Tech									X		X	X
Erosion Control Technologies	X											
Fountainhead Irrigation, Inc.				X	X							
Gabel Corporation				X						X		
Global Water						X			X	X		X
Hydrolab Corporation									X	X		

	Erosion control products	Sap flow measurement	Other plant parameter measurements[1]	Soil moisture measurement/monitoring	Automatic irrigation systems	Climate parameter measurement/stations	Field tools	Safety equipment	Water quality measurement/monitoring	Data loggers	Soil/groundwater sampling	Water level measurement/monitoring
In-Situ, Inc.				X					X	X		X
Irrometer Company, Inc.				X	X							
Keck Instruments, Inc.												X
Marschalk Corporation											X	X
MESA Systems, Co.		X	X	X		X				X		
MPC HydroPro Irrigation Products					X							
North American Green	X											
Onset Computer Corporation						X				X		
PP Systems		X	X									
Soil Measurement Systems				X								
Soil Sensors, Inc.				X								
Soilmoisture Equipment Corp.				X								
Spectrum Equipment International											X	
Spectrum Technologies, Inc.			X	X		X			X	X		
Synthetic Industries	X											
Telog Instruments, Inc.										X		X
Troxler Electronic Laboratories, Inc.				X								
Wescor Inc., Environmental Products				X		X			X	X		X
YSI Incorporated									X			

[1]Plant parameters include, but are not limited to: root length, stomatal and hydraulic conductance, leaf wetness, leaf area index and canopy cover.

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Table E-2. Equipment Vendor Contact Information

Art's Manufacturing & Supply 105 Harrison American Falls, Idaho 83211-1230	Ph: 800-635-7330 Fx: 208-226-7280 www.ams-samplers.com
Ben Meadows Company P. O. Box 80549 Atlanta, Georgia 30366	Ph: 800-628-2068 Fx: 800-241-6401 www.benmeadows.com
Campbell Scientific, Inc. 815 W. 1800 N. Logon, Utah 84321-1784	Ph: 435-753-2342 Fx: 435-750-9540 www.campbellsci.com
Caterpillar CAT Merchandise Catalog 3200 Rice Mine Road NE P. O. Box 2788 Tuscaloosa, Alabama 35403	Ph: 888-289-2281 Fx: 888-228-6224
Coastal Environmental Systems 1000 First Avenue South, Suite 200 Seattle, Washington 98134-1216	Ph: 800-488-8291 Fx: 206-682-5658 www.coastal.org
Davis Instruments 3465 Diablo Avenue Hayward, California 94545-2278	Ph: 800-678-3669 Fx: 510-670-0589 www.davisnet.com
Decagon Devices, Inc. 950 NE Nelson Court P. O. Box 835 Pullman, Washington 99163	Ph: 509-332-2756 Fx: 509-332-5158 www.decagon.com
Dynamax, Inc. 10808 Fallstone, Suite 350 Houston, Texas 77099	Ph: 800-727-3570 Fx: 281-564-5200 www.dynamax.com

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Electronic Data Solutions P. O. Box 31 Jerome, Idaho	Ph: 208-324-8006 Fx: 208-324-8015 www.elecdata.com
Environmental Sensors, Inc. 2759 Pasatiempo Glen Escondido, California 92025	Ph: 800-553-3818 Fx: 250-479-1412 www.envsens.com
Enviro-Tech 4851 Sunrise Drive, Suite 101 Martinez, California 94553	Ph: 800-468-8921
Erosion Control Technologies 3380 Route 22, West Unit 3A Brandburg, New Jersey 08876	Ph: 800-437-6746 Fx: 908-707-1445 www.erosioncontroltech.com
Fountainhead Irrigation, Inc. P. O. Box 2197 Walla Walla, Washington 99362	Ph: 509-529-2646 Fx: 509 522 5251 www.irrig8.com
Gabel Corporation 100-4243 Glanford Avenue Victoria, British Columbia, Canada V8Z 4B9	Ph: 604-479-6588 Fx: 604-479-1412
Global Water 11257 Coloma Road Gold River, California 95670	Ph: 800-876-1172 Fx: 916-638-3270 www.globalw.com
Hydrolab Corporation P. O. Box 50116 Austin, Texas 78763	Ph: 800-949-3766 Fx: 512-255-3106 www.hydrolab.com
In-Situ, Inc. 210 Third Street P. O. Box 1 Laramie, Wyoming 82073	Ph: 800-446-7488 Fx: 307-742-8213 www.in-situ.com

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Irrometer Company, Inc. P. O. Box 2424 Riverside California 92516-2424	Ph: 909-689-1701 Fx: 909-689-3706 www.irrometer.com
Keck Instruments, Inc. 1099 West Grand River Avenue Williamston, Michigan 48895	Ph: 800-542-5681 Fx: 517-655-1157 www.keckinc.com
Marschalk Corporation	Ph: 800-722-2800 Fx: 919-781-6470 www.marschalk.com
MESA Systems, Co. 119 Herbert Street Framingham, Massachusetts 01702	Ph: 508-820-1561 Fx: 508-875-4143
MPC HydroPro Irrigation Products 2805 West Service Road Eagan, Minnesota 55121	Ph: 800-672-3331 Fx: 612-681-8106
North American Green 14649 Highway 41 North Evansville, Indiana 47725	Ph: 800-772-2040 Fx: 812-867-0247 www.nagreen.com
Onset Computer Corporation 470 MacArthur Boulevard Bourne, Massachusetts 02532	Ph: 800-564-4377 Fx: 508-759-9100 www.onsetcomp.com
PP Systems 241 Winter Street Haverhill, Massachusetts 01830	Ph: 978-374-1064 Fx: 978-374-0972 www.ppsystems.com
Soil Measurement Systems 7090 North Oracle Road #178-170 Tuscon, Arizona 85704	Ph: 520-742-4471 Fx: 520-544-2192 www.soilmeasurement.com
Soil Sensors, Inc. 4832 Park Glen Road St. Louis Park, Minnesota 55416	Ph: 888-283-7645 Fx: 612-927-7367 www.soilsensors.com

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Soilmoisture Equipment Corp. 801 South Kellogg Avenue Goleta, California 93117	Ph: 888-964-0040 Fx: 805-683-2189 www.soilmoisture.com
Spectrum Equipment International P. O. Box 205 American Falls, Idaho 83211	Ph: 800-455-2652 Fx: 208-226-7280
Spectrum Technologies, Inc. 23839 West Andrew Road Plainfield, Illinois 60544	Ph: 800-248-8873 Fx: 815-436-4460
Synthetic Industries 309 La Fayette Road Chickamonga, Georgia 30707	Ph: 706-375-3121 Fx: www.sind.com
Telog Instruments, Inc. 830 Canning Parkway Victor, New York 14564-8940	Ph: 716-742-3000 Fx: 716-742-3006 www.telog.com
Troxler Electronic Laboratories, Inc. 3008 Cornwallis Road Research Triangle Park, North Carolina 27709	Ph: 919-549-8661 Fx: 919-549-0761 www.troxlerlabs.com
Wescor Inc., Environmental Products P. O. Box 361 Logan, Utah 84323-0361	Ph: 435-753-8311 Fx: 435-753-8177 www.wescor.com
YSI Incorporated Yellow Springs, Ohio 45387	Ph: 800-897-4151 Fx: 937-767-9353 www.YSI.com

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Phytoremediation Companies

The following is a brief list of phytoremediation companies. This is list of companies that specialize in phytoremediation projects and have worked with trees and control of groundwater flow. Phytoremediation companies that specialize in other areas, such as hyperaccumulation of metals have not been included.

Applied Natural Sciences

4129 Tonya Trail
Fairfield, OH 45011
Phone: 513-895-6061
Fax: 513-895-6062

PhytoWorks, Inc.

1400 Mill Creek Road
Gladwyne, PA 19035
Phone: 610-896-9946
Fax: 610-896-9950
www.phytoworks.com

Ecolotree, Inc.

505 East Washington Street, Suite 300
Iowa City, IA 52240
Phone: 319-358-9753
Fax: 319-358-9773
www.ecolotree.com

Verdant Technologies, Inc.

12600 8th Avenue NE
Seattle, WA 98125
Phone: 206-365-3440
Fax: 206-365-4957
www.verdanttech.com

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Appendix F Units, Conversion Coefficients

The following table of conversions was modified from Jensen et al. [6].

Length

1 micrometer (μm)
= 10^{-6} m

1 millimeter (mm)
= 10^{-1} cm
= 10^{-3} m

1 centimeter (cm)
= 10^{-2} m

1 meter (m)
= 10^{2} cm
= 3.2808 ft
= 39.370 in.

1 kilometer (km)
=10^{5} cm
=10^{3} m
= 3280.8 ft
= 0.62137 stat. Mi.

1 degree of latitude (°lat.)
=111.14 km
= 69.057 stat. Mi.

1 inch (in.)
= 25.4mm
= 2.54 cm
= 0.0254 m

1 foot (ft)
= 12 in.
= 30.48 cm
= 0.3048 m

1 statute mile (stat. Mi.)
= 5,280 ft.
= 1609.3 m
= 1.6093 km

Area [b]

1 square meter (m^2)
= 10^4 cm^2
= 1550.0 sq in.
= 10.764 sq ft

1 square foot (sq ft)
= 144 sq in.
= 0.092903 m^2

1 square mile
= 640 acres

1 acre
= 43,560 sq ft
= 4046.856 m^2
= 0.4047 ha

1 hectare (ha)
= 10^4 m^2
= 2.471 acre

Volume

1 cubic meter (m^3)
= 10^6 cm^3
= 35.315 cu ft
= 264.172 U.S. gal.
= 219.97 Brit. gal.

1 cubic inch (cu in.)
= 16.387 cm^3

1 liter (L)[a]
(1 liter originally was defined as the volume occupied by 1 kilogram of water at its temperature of maximum density, but has been redefined)
= 1000 cm^3
= 0.26417 U.S. gal.

1 cubic foot (cu ft)
= 1728 cu in.
= 7.4805 U.S. gal.
= 28.3168 L
= 0.0283168 m^3

1 acre-foot
= 1233.48 m^3
= 43,560 cu ft

1 gallon, U.S. (U.S. gal.)
= 231 cu in.
= 0.83267 Brit. gal.
= 3.78534 L
= 3.78534×10^{-3} m^3

1 million U. S. gallons
= 133,681 cu ft
= 3.0689 acre-feet

1 Imperial gallon = 1.2003 U. S. gal.

Time

1 mean solar minute (min.)
= 60s

1 mean solar day (d)
= 86,400 s
= 1440 min.
= 24 h

1 hour (h)
= 3600 s
= 60 min.

Velocity (speed)

1 meter per second ($m\ s^{-1}$)
= 3.6000 $km\ h^{-1}$
= 2.23694 $mi.\ h^{-1}$
= 3.28084 $ft\ s^{-1}$

1 mile per hour ($mi.\ h^{-1}$)
= 0.86839 knot
= 0.44704 $m\ s^{-1}$
= 1.6093 $km\ h^{-1}$

1 kilometer per hour ($km\ h^{-1}$)
= 0.27778 $m\ s^{-1}$
= 0.53959 knot
= 0.62137 $mi.\ h^{-1}$

1 foot per second ($ft\ s^{-1}$)
= 0.68182 $mi.\ h^{-1}$
= 0.3048 $m\ s^{-1}$
= 1.0973 $km\ h^{-1}$

1 knot
= 1 naut. $mi.\ h^{-1}$
= 1.15155 $mi.\ h^{-1}$
= 0.51479 $m\ s^{-1}$
= 1.85325 $km\ h^{-1}$

Mass	
1 gram (g) = 0.0022046 Ibm	1 pound avoirdupois (1 lb) = 453.59 g = 0.45359 kg
1 kilogram (kg) = 10^3 g = 2.2046 Ibm	1 short ton = 2000 Ibm = 0.892857 long ton = 0.90718 t
1 metric ton, tonne (t) = $l0^3$ kg = 2204.6 Ibm	1 long ton = 2240 Ibm = 1.12 short ton = 1.0160 t
Weight	
1 pound = 7000 grains	1 gram = 15.432 grains
Density of Water (4°C)	
1 g cm^{-3} = 62.428 lb ft^{-3} (specific wt.) = 1 t m^{-3}	1 kg m^{-3} = 10^{-3} g cm^{-3} = 10^{-3} t m^{-3}
Flowing Water	
1 second-foot = 60 cu ft min^{-1} = 448.83 U. S. gallons min^{-1} = 1.9835 acre-feet 24 h^{-1}	1 million U. S. gallons per day = 1.5472 second-feet
1 cubic foot per minute = 7.4805 U. S. gallons min^{-1}	

Pressure

1 dyne per square centimeter (dyne cm^{-2})
= 10^{-3} mb
= 10^{-6} bar
= 0.1 pascal (Pa)

1 millibar (mb)
= 103 dynes cm^{-2}
= 0.750062 mm Hg (standard)
= 0.029530 in. Hg (standard)
= 100 pascal (Pa)

1 bar (b)
= 10^6 dynes cm^{-2}
= 10^3 mb
= 10^5 N m^{-2}
= 10^5 pascal (Pa)
= 10^2 kPa

1 standard millimeter of mercury (mm Hg (standard))
= 1.333224 mb
= 0.039370 in. Hg (standard)
= 133.32 Pa

1 standard inch of mercury (in. Hg (standard))
= 0.49115 lb $in.^{-2}$
= 33.864 mb
= 25.4 mm Hg (standard)
= 3.3864 kPa
=1.1330 feet of water

1 pound per sq. inch (lb $in.^{-2}$)
= 2.0360 in. Hg (standard)
= 68.9476 mb
= 6.89476 kPa
= 2.3071 feet of water

1 standard atmosphere
= 1,013.25 mb
= 760 mm Hg (standard)
= 29.921 in. Hg (standard)
= 14.696 lb $in.^{-2}$
= 101.325 kPa
= 33.901 feet of water

1 Pa
= 1 N m^{-2}

1 foot of water
= 62.416 lb ft^{-2}

Force

1 gram force
= 980.665 dynes
= 9.80665 x 10^{-3} N

1 newton (N)
= 10^5 dynes
= kg m s^{-2}

Energy

1 erg
= 1 dyne-centimeter
= 10^{-7} joule (J)
= 2.3884 x 10^{-8} ITcal

1 joule (J)
= 10^7 ergs
= 0.23884 ITcal
= 1 N m

1 International Steam Tables calorie (ITcal)
= 4.1868 joules

Work

1 kilowatt-hour (kw h)
= 3.6 x 10^6 joules
= 3.6 megajoules (MJ)

1 British thermal unit (Btu)
(the Btu used here is defined by the relationship: 1 Btu °F^{-1} lb^{-1})
= 1 ITcal °C^{-1} g^{-1})
= 251 .996 ITcal
= 1,055.07 joules

1 foot-pound (ft-lb)
= 1.35582 joules

Power	
1 watt (W) = 1 joule s^{-1}	1 kilowatt = 10^3J s^{-1} = 1 kJ s^{-1} = 1.3405 horsepower
1 horsepower = 550 ft-lb s^{-1}	

Energy per Unit Area	
1 langley (ly) = 1 cal_{15} cm^{-2} = 4.1855 joules cm^{-2} = 0.0419 MJ/m2	1 ITcal cm^{-2} = 4.1868 joule cm^{-2} = 41 .868 kilojoules m^{-2}
1 joule cm^{-2} = 10 kilojoules m^{-2}	1 Btu ft^{-2} = 11.357 kilojoules m^{-2}

Power per Unit Area	
1 cal_{15} cm^{-2} min^{-}1 = 1 ly min^{-1} = 0.69758 kilowatts m^{-2}	1 Btu ft^{-2} min^{-1} = 0.18928 kilowatts m^{-2}

[a] The General Conference on Weights and Measures in 1964 redefined the liter to be exactly 1,000 cm^3. Hence, the cubic decimeter, expressed as 10^{-3} m^3, dm^3, or 1,000 cm^3 may be a preferred unit to avoid errors. However, for practical purposes the new and old liters are essentially the same.

[b] The unit of land area, hectare, is commonly used in the metric system, but its dimensions, 10^4 m^2, do not follow the SI guide of multiples of 10^3. The dunam = 10^3 m^2 is a more practical land unit, but it is not in common usage and its symbol may conflict with SI recommendations. The hectare with the symbol ha was derived from hecto, a multiple of 100 having the symbol h, and the "are" which is a unit of land area = 100 m^2 abbreviated "a."

Table of Metric Prefixes with symbols and orders of magnitude.

Order of Magnitude	Prefix	Symbol	Order of Magnitude	Prefix	Symbol
10^{24}	Yotta	Y	10^{-1}	deci	d
10^{21}	Zetta	Z	10^{-2}	centi	c
10^{18}	Exa	E	10^{-3}	milli	m
10^{15}	Peta	P	10^{-6}	micro	µ
10^{12}	Tera	T	10^{-9}	nano	n
10^9	Giga	G	10^{-12}	pico	p
10^6	Mega	M	10^{-15}	femto	f
10^3	Kilo	k	10^{-18}	atto	a
10^2	Hecto	h	10^{-21}	zepto	z
10^1	Deka	da	10^{-24}	yocto	y

Frequently Used Conversion Factors for Soils and Plants

From: Glossary of Soil Science Terms 1996. Soil Science Society of America [53]

Conversion Factors for SI and non-SI Units

To convert Column 1 into Column 2, multiply by	Column 1 SI Unit	Column 2 non-SI Unit	To convert Column 2 into Column 1 multiply by
	Length		
0.621	kilometer, km (10^3 m)	mile, mi	1.609
1.094	meter, m	yard, yd	0.914
3.28	meter, m	foot, ft	0.304
1.0	micrometer, µm (10^{-6} m)	micron, µ	1.0
3.94×10^{-2}	millimeter, mm (10^{-3} m)	inch, in	25.4
10	nanometer, nm (10^{-9} m)	Angstrom, Å	0.1
	Area		
2.47	hectare, ha	acre	0.405
247	square kilometer, km^2 (10^3 m)^2	acre	4.05×10^{-3}
0.386	square kilometer, km^2 (10^3 m)^2	square mile, mi^2	2.590
2.47×10^{-4}	square meter, m^2	acre	4.05×10^{3}
10.76	square meter, m^2	square foot, ft^2	9.29×10^{-2}
1.55×10^{-3}	square millimeter, mm^2 (10^{-6} m)^2	square inch, in^2	645
	Volume		
9.73×10^{-3}	cubic meter, m^3	acre-inch	102.8
35.3	cubic meter, m^3	cubic foot, ft^3	2.83×10^{-2}
6.10×10^{4}	cubic meter, m^3	cubic inch, in^3	1.64×10^{-5}
2.84×10^{-2}	liter, L (10^{-3} m^3)	bushel, bu	35.24
1.057	liter, L (10^{-3} m^3)	quart (liquid), qt	0.946
3.53×10^{-2}	liter, L (10^{-3} m^3)	cubic foot, ft^3	28.3
0.265	liter, L (10^{-3} m^3)	gallon	3.78
33.78	liter, L (10^{-3} m^3)	ounce (fluid), oz	2.96×10^{-2}
2.11	liter, L (10^{-3} m^3)	pint (fluid), pt	0.473

(continued on next page)

Conversion Factors for SI and non-SI Units - (continued)

To convert Column 1 into Column 2, multiply by	Column 1 SI Unit	Column 2 non-SI Unit	To convert Column 2 into Column 1 multiply by
	Mass		
2.20×10^{-3}	gram, g (10^{-3} kg)	pound, lb	454
3.52×10^{-2}	gram, g (10^{-3} kg)	ounce (avdp), oz	28.4
2.205	kilogram, kg	pound, lb	0.454
0.01	kilogram, kg	quintal (metric), q	100
1.10×10^{-3}	kilogram, kg	ton (2000 lb), ton	907
1.102	megagram, Mg (tonne)	ton (U.S.), ton	0.907
1.102	tonne, t	ton (U.S.), ton	0.907
	Yield and Rate		
0.893	kilogram per hectare, kg ha^{-1}	pound per acre, lb $acre^{-1}$	1.12
7.77×10^{-2}	kilogram per cubic meter, kg m^{-3}	pound per bushel, lb bu^{-1}	12.87
1.49×10^{-2}	kilogram per hectare, kg ha^{-1}	bushel per acre, 60 lb	67.19
1.59×10^{-2}	kilogram per hectare, kg ha^{-1}	bushel per acre, 56 lb	62.71
1.86×10^{-2}	kilogram per hectare, kg ha^{-1}	bushel per acre, 48 lb	53.75
0.107	liter per hectare, L ha^{-1}	gallon per acre	9.35
893	tonnes per hectare, t ha^{-1}	pound per acre, lb $acre^{-1}$	1.12×10^{-3}
893	megagram per hectare, Mg ha^{-1}	pound per acre, lb $acre^{-1}$	1.12×10^{-3}
0.446	megagram per hectare, Mg ha^{-1}	ton (2000 lb) per acre, ton $acre^{-1}$	2.24
2.24	meter per second, m s^{-1}	mile per hour	0.447
	Specific Surface		
10	square meter per kilogram, m^2 kg^{-1}	square centimeter per gram, cm^2 g^{-1}	0.1
1000	square meter per kilogram, m^2 kg^{-1}	square millimeter per gram, mm^2 g^{-1}	0.001
	Pressure		
9.90	megapascal, MPa (10^6 Pa)	atmosphere	0.101
10	megapascal, MPa (10^6 Pa)	bar	0.1
2.09×10^{-2}	pascal, Pa	pound per square foot, lb ft^{-2}	47.9
1.45×10^{-4}	pascal, Pa	pound per square inch, lb in^{-2}	6.90×10^{3}

(continued on the next page)

Conversion Factors for SI and non-SI Units - (continued)

To convert Column 1 into Column 2, multiply by	Column 1 SI Unit	Column 2 non-SI Unit	To convert Column 2 into Column 1 multiply by
	Density		
1.00	megagram per cubic meter, Mg m^{-3}	gram per cubic centimeter, g cm^{-3}	1.00
	Temperature		
1.00 (K – 273)	Kelvin, K	Celsius, °C	1.00 (°C + 273)
(9/5 °C) + 32	Celsius, °C	Fahrenheit, °F	5/9 (°F – 32)
	Energy, Work, Quantity of Heat		
9.52×10^{-4}	joule, J	British thermal unit, Btu	1.05×10^{3}
0.239	joule, J	calorie, cal	4.19
10^{7}	joule, J	erg	10-7
0.735	joule, J	foot-pound	1.36
2.387×10^{-5}	joule per square meter, J m^{-2}	calorie per square centimeter (langley)	4.19×10^{4}
10^{5}	newton, N	dyne	10^{-5}
1.43×10^{-3}	watt per square meter, W m^{-2}	calorie per square centimeter minute (irradiance), cal cm^{-2} min^{-1}	698
	Transpiration and Photosynthesis		
3.60×10^{-2}	milligram per square meter second, mg m^{-2} s^{-1}	gram per square decimeter hour, g dm^{-2} h^{-1}	27.8
5.56×10^{-3}	milligram (H_2O) per square meter second, mg m^{-2} s^{-1}	micromole (H_2O) per square centimeter second, μmol cm^{-2} s^{-1}	180
10^{-4}	milligram per square meter second, mg m^{-2} s^{-1}	milligram per square centimeter second, mg cm^{-2} s^{-1}	104
35.97	milligram per square meter second, mg m^{-2} s^{-1}	milligram per square decimeter hour, mg dm^{-2} h^{-1}	2.78×10^{-2}
	Plane Angle		
57.3	radian, rad	degrees (angle), °	1.75×10^{-2}

(continued on next page)

Conversion Factors for SI and non-SI Units - (continued)

To convert Column 1 into Column 2, multiply by	Column 1 SI Unit	Column 2 non-SI Unit	To convert Column 2 into Column 1 multiply by
	Electrical Conductivity, Electricity, and Magnetism		
10	siemen per meter, S m^{-1}	millimho per centimeter, mmho cm^{-1}	0.1
10^4	tesla, T	gauss, G	10^{-4}
	Water Measurement		
9.73×10^{-3}	cubic meter, m^3	acre-inches, acre-in	102.8
9.81×10^{-3}	cubic meter per hour, m^3 h^{-1}	cubic feet per second, ft^3 s^{-1}	101.9
4.40	cubic meter per hour, m^3 h^{-1}	U.S. gallons per minute, gal min^{-1}	0.227
8.11	hectare-meters, ha-m	acre-feet, acre-ft	0.123
97.28	hectare-meters, ha-m	acre-inches, acre-in	1.03×10^{-2}
8.1×10^{-2}	hectare-centimeters, ha-cm	acre-feet, acre-ft	12.33
	Concentrations		
1	centimole per kilogram, cmol kg^{-1} (ion exchange capacity)	milliequivalents per 100 grams, meq 100 g^{-1}	1
0.1	gram per kilogram, g kg^{-1}	percent, %	10
1	milligram per kilogram, mg kg^{-1}	parts per million, ppm	1
	Radioactivity		
2.7×10^{-11}	bequerel, Bq	curie, Ci	3.7×10^{10}
2.7×10^{-2}	bequerel per kilogram, Bq kg^{-1}	picocurie per gram, pCi g^{-1}	37
100	gray, Gy (absorbed dose)	rad, rd	0.01
100	sievert, Sv (equivalent dose)	rem (roentgen equivalent man)	0.01
	Plant Nutrient Conversion		
	Elemental	Oxide	
2.29	P	P_2O_5	0.437
1.20	K	K_2O	0.830
1.39	Ca	CaO	0.715
1.66	Mg	MgO	0.602

Appendix G Glossary

actinometer—the instrument for measuring terrestrial and solar radiation 9commonly called a pyranometer).

advection—horizontal transfer of heat energy by large-scale motions of the atmosphere.

aeration—see soil aeration.

albedo—the ratio of electromagnetic radiation reflected from a soil and crop surface to the amount incident upon it. In practice, the value is applied primarily to solar radiation.

allelopathic toxicants—Chemicals produced by other plants that kill or limit growth of roots for the plant in question.

amendment—see soil amendment.

anemometer—the instrument used to measure wind velocity.

anemometer level—the height above ground at which an anemometer is exposed.

annual plant—a plant that lives only one year or growing season (as opposed to a perennial plant that grows several years).

arid climate—generally any extremely dry climate.

bar—a unit of pressure equal to 106 dynes per cm^2, 100 kilopascals, 29.53 inches of mercury.

bulk density —see soil bulk density.

calorie—(abbreviated cal.) a unit of heat required to raise the temperature of 1 gram of water from 14.5 degrees Celsius to 15.5 degrees Celsius. The International Steam Table calorie equals 1.00032 cal_{15}.

capillary fringe—The zone of soil above a water table that is nearly saturated by capillary action.

cation exchange—the interchange between a cation in solution and another cation in the boundary layer between the solution and surface of negatively charged material such as clay or organic matter.

cation exchange capacity (CEC)—the sum of exchangeable bases plus total soil acidity at a specific pH value, usually 7.0 or 8.0. Usually expressed in meq (milliequivalents) per 100 grams of soil.

Celsius—same as centigrade temperature scale.

cemented—having a hard, brittle consistency because the particles are held together by cementing substances such as humus, $CaCO_3$, or the oxides of silicon, iron and aluminum. The hardness and brittleness persist even when wet.

chisel—to break up soil using closely spaced gangs of narrow shank-mounted tools. It may be performed at other than the normal plowing depth. Chiseling at depths > 40 cm is usually termed subsoiling.

Class A pan—the U.S. Weather Bureau evaporation pan is a cylindrical container fabricated of galvanized iron or monel metal with a depth of 10 inches and a diameter of 48 inches. The pan is placed on an open 2- x 4-inch wooden platform with the top of the pan about 41 cm (16 inches) above the soil surface. It is accurately leveled at a site that is nearly flat, well sodded, and free from obstructions. The pan is filled with water to a depth of eight inches, and periodic measurements are made of the changes of the water level with the aid of a hook gage set in the still well. When the water level drops to seven inches, the pan is refilled. Its average pan coefficient is about 0.7 for lake evaporation.

Class A pan coefficient—fraction used to estimate shallow lake evaporation from Class A pan evaporation data. Multiply Class A pan evaporation by the coefficient to obtain shallow lake evaporation. The average coefficient is 0.7, however, it varies by region.

clay—a soil separate consisting of particles <0.002 mm in equivalent diameter.

claypan—a dense, compact slowly permeable layer in the subsoil having a much higher clay content that the overlying material, from which it is separated by a sharply defined boundary. Claypans are usually hard when dry, and plastic and sticky when wet.

consumptive use—the total amount of water taken up by vegetation for transpiration or building of plant tissue, plus the unavoidable evaporation of soil moisture, snow, and intercepted precipitation associated with vegetal growth. (also see evapotranspiration.)

crop coefficient—the ratio of evapotranspiration occurring with a specific crop at a specific stage of growth to reference crop evapotranspiration at that time.

Darcy's law—the law stating that the velocity of a fluid in permeable media is directly proportional to the hydraulic gradient.

day length—the length of day from sunrise to sunset expressed in hours.

deep percolation—the drainage of soil water by gravity below the maximum effective depth of the root zone.

dew point—the temperature to which a given parcel of air must be cooled at constant pressure and at constant water vapor content until saturation occurs, or the temperature at which saturation vapor pressure of the parcel is equal to the actual vapor pressure of the contained water vapor.

duty of water—the total volume of irrigation water required to mature a particular type of crop. It includes consumptive use, evaporation, and seepage from ditches and canals, and water eventually returned to streams by percolation and surface runoff.

effective precipitation—the portion of precipitation that remains on the foliage or in the soil that is available for evapotranspiration and reduces the withdrawal of soil water by a like amount.

evaporation—the physical process by which a liquid or solid is transformed to the gaseous state, which in irrigation usually is restricted to the change of water from liquid to gas.

evapotranspiration—the combined processes by which water is transferred from the earth surface to the atmosphere; evaporation of liquid or solid water plus transpiration from plants. (also see consumptive use.)

facultative phreatophyte—a plant that may grow either as a phreatophyte or a non-phreatophyte in response to conditions at the site.

Fahrenheit temperature scale—(abbreviated F.) A temperature scale with the ice point at 32° and the boiling point of water at 212°. Conversion to the Celsius scale °C is (°F equal 1.8 °C plus 32).

field capacity— the content of water remaining in a soil 2 or 3 days after having been wetted with water and free drainage is negligible. For practical purposes, the water content when soil matric potential is –1/3 atmospheres.

forb—A broad-leaved flowering plant, as distinguished from the grasses, sedges, etc.

friable—A consistency term pertaining to the ease of crumbling of soils.

grass—Any of a family of plants with long, narrow, leaves, jointed stems, flowers in spikelets, and seelike fruit, as wheat, rye, barley, oats, sugar cane, bamboo, etc.

growing season—the period and/or number of days between the last freeze in the spring and the first frost in the fall for the freeze threshold temperature of the crop or other designated temperature threshold.

halophyte—A plant that can grow in salty or alkaline soil.

hardpan—a soil layer with physical characteristics that limit root penetration and restrict water movement.

humidity, absolute—mass of water vapor per cubic meter.

humidity, relative —the dimensionless ratio of actual vapor pressure of the air to saturation vapor pressure, commonly expressed in percentage.

humus—Total of the organic compounds in soil exclusive of undecayed plant and animal tissues and the soil biomass. The term is often used synonymously with soil organic matter.

hydraulic conductivity—the proportionality factor in the Darcy flow law, which states that the effective flow velocity is proportional to the hydraulic gradient.

hydraulic head—the total of fluid pressure head and elevation with respect to a specified datum.

hydrophyte—Any plant growing only in water or very wet earth.

hydrostatic pressure—the pressure in a fluid in equilibrium that is due solely to the weight of fluid above.

hygrometer—the instrument used to measure humidity.

insolation—(contracted from incoming solar radiation.) solar radiation received at the earth's surface.

irrigation efficiency—the ratio of the volume of water required for a specific beneficial use as compared to the volume of water delivered for this purpose. Commonly interpreted as the volume of water stored in the soil for evapotranspiration compared to the volume of water delivered for this purpose, but may be defined and used in different ways.

irrigation water requirements—the quantity of water exclusive of precipitation that is required for various beneficial uses.

Joule—the unit of energy or work done when the point of application of 1 newton is displaced a distance of 1 meter in the direction of force, 1 joule = 1 watt second.

Langley—A unit of energy per unit area commonly used in radiation measurements that is equal to 1 gram calorie per square centimeter.

latent heat—the heat released or absorbed per unit mass of water in a reversible, isobaric-isothermal change of phase.

leaching efficiency—the ratio of the average salt concentration in drainage water to an average salt concentration in the soil water of the root zone when near field capacity (also defined as the hypothetical fraction of the soil solution that has been displaced by a unit of drainage water).

leaching requirement—the fraction of water entering the soil that must pass through the root zone in order to prevent soil salinity from exceeding a specific value.

leaf area index—the area of one side of leaves per unit area of soil surface.

legume—Any of a large family of herbs, shrubs, and trees, including the peas, beans, vetches, clovers, etc., with usually compound leaves, flowers having a single carpel, an fruit the is a dry pod splitting along two sutures. Many legumes are nitrogen-fixing and often are used for forage.

loam—soil material that contains 7 to 27 percent clay, 28 to 50 percent silt and <52 percent sand.

lysimeter—a device used to measure the quantity or rate of water movement through or from a block of soil or other material, such as solid waste, or used to collect percolated water for qualitative analysis.

mesophyte—a plant that grows in a moderately moist environment.

micrometer—(abbreviated μm.) a unit of length equal to one-millionth of a meter, or one-thousandth of a millimeter.

millibar—(abbreviated mb.) a pressure unit of 0.1 kPa, and equal to onethousandth of a bar. Atmospheric pressures are commonly reported in millibars, or in kilopascals. one mb = 102 N m^{-2}.

Newton—the unit of force in the mkgs system of units; the force that gives to a mass of 1 kg an acceleration of 1 m/s^2.

nomograph—a graph having three coplanar curves, usually parallel straight lines, each graduated for a different variable so that a straight line cutting all three curves intersects the related values of each variable.

Pascal—the unit of pressure in the SI system; 1 pascal equals 1 newton per square meter.

perennial plant—a plant that normally lives three or more years (as opposed to an annual plant that grows only one year or season).

phreatophyte—a plant which uses large amounts of water and acquires water from the water table or capillary fringe.

potential evapotranspiration—the rate at which water, if available, would be removed from wet soil and plant surfaces expressed as the rate of latent heat transfer per unit area or an equivalent depth of water.

psychrometric chart—a nomograph for graphically obtaining relative humidity and dew point from wet and dry bulb thermometer readings.

pyranometer—a general name for actinometers that measure the combined intensity of incoming direct solar radiation and diffuse sky radiation.

radiation—the process by which electromagnetic radiation is propagated through free space as distinguished from conduction and convection.

radiation, extraterrestrial—solar radiation received "on top of" the earth's atmosphere.

radiation, global—the total of direct solar radiation and diffuse sky radiation received by a unit horizontal surface (essentially less than about 3 micrometers).

radiation, net—the difference of the downward and upward solar and long-wave radiation flux passing through a horizontal plane just above the ground surface.

radiation, short-wave—a term used loosely to distinguish solar and diffuse sky radiation from long-wave radiation.

radiation, solar—the total electromagnetic radiation emitted by the sun.

radiation, thermal—electromagnetic radiation with a wavelength greater than 0.8 micrometers. (for convenience, long-wave radiation is normally considered to include all wavelengths greater than solar radiation or essentially 3 micrometers).

reed—a tall grass with hollow jointed stalks, especially one of the genera *Phragmites* or *Arundo*

saline soil—a nonalkali soil containing soluble salts in such quantities that they interfere with the growth of most plants.

sand—unconsolidated granular mineral material ranging from 0.05 to 2 mm in diameter.

saturated air—moist air in a state of equilibrium with a plane surface of pure water or ice at the same temperature and pressure; i.e., air whose vapor pressure is the saturation vapor pressure and whose relative humidity is 100%.

saturation deficit—(also called vapor pressure deficit.) the difference between the actual vapor pressure and the saturation vapor pressure at the existing temperature.

saturation vapor pressure—the partial pressure of water vapor in the atmosphere when the air is saturated (see saturated air).

sedge—any of various plants of the family *Cyperaceae*, resembling grasses, but having solid stems.

shrub—a woody perennial plant differing from a tree by its low stature and by generally producing several basal shoots instead of a single bole.

silt (silt soil)—soil material that contains 80% or more silt and < 12% clay.

soil aeration—The process by which air in the soil is replenished by air from the atmosphere. In a well-aerated soil, the air in the soil is similar in composition to the atmosphere above the soil. Poorly aerated soils usually contain a much higher percentage of carbon dioxide and a correspondingly lower percentage of oxygen. The rate of aeration depends largely on the volume, size and continuity of pores in the soil.

soil amendment—Any material—such as lime, gypsum, sawdust, or synthetic conditioners—that is worked into the soil to make it more productive. The term is used most commonly for added materials other than fertilizer.

soil bulk density—the mass of dry soil per unit bulk volume. It's value is expressed as Mg/m^3 or gm/cm^3. Where units are expressed in the metric system and water is the reference, it is often expressed as a dimensionless value.

soil solution—the aqueous liquid phase of the soil and its solutes.

soil water tension—(also called matric or capillary potential.) the work that must be done per unit quantity of pure water to transport it from free water at the same elevation to soil water.

soil water—water present in the soil pores (also called soil moisture, which includes water vapor).

solar constant—the rate at which solar radiation is received outside the earth's atmosphere on a surface normal to the incident radiation.

specific heat—the heat capacity of a system per unit mass.

stoma—A microscopic opening in the epidermis of plants, surrounded by guard cells and serving for gaseous exchange.

tilth—The physical condition of soil as related to its ease of tillage, fitness as a seedbed, and its impedance to seedling emergence and root penetration.

transpiration—the process by which water in plants is transferred as water vapor to the atmosphere.

vapor pressure—the partial pressure of water vapor in the atmosphere.

vapor pressure deficit—(also called saturation deficit.) the difference between the actual vapor pressure and the saturation vapor pressure at the existing temperature.

water content—in soil mechanics, the ratio, expressed as a percentage, of the weight of water in a given soil mass to the weight of solid particles. In soil science, the amount of water lost from the soil after drying it to constant weight at 105°C, expressed either as the weight of water per unit weight of dry soil or as the volume of water per unit bulk volume of soil.

wet bulb temperature—the temperature an air parcel would have if cooled adiabatically to saturation at constant pressure by evaporation of water into it with all latent heat being supplied by the parcel.

wilting point—the water content at which soil water is no longer available to plants. For practical purposes, the water content when soil matric potential is approximately 15 atmospheres.

xerophyte—A plant structurally adapted to growing under very dry or desert conditions, often having greatly reduced leaf surfaces for avoiding water loss.

zero plane displacement—an empirically determined constant introduced into the logarithmic wind velocity profile to extend its applicability to very rough surfaces or to take into account the displacement of a profile above a dense crop.

An excellent source for additional definitions of terms related to soil and agriculture is the *Glossary of Soil Science Terms, 1996* published by the Soil Science Society of America [53].

Appendix H Acronyms

bgs	below ground surface
CEC	cation exchange capacity
DoD	Department of Defense
EPA	Environmental Protection Agency
ERT	EPA Environmental Response Team
ESTCP	Environmental Security Technology Certification Program
ET	evapotranspiration
K	hydraulic conductivity
NATO	North Atlantic Treaty Organization
NPK	nitrogen, phosphorus and potassium
PET	potential evapotranspiration
ppb	parts per billion
ROD	Record of Decision
SITE	Superfund Innovative Technology Evaluation
TCE	trichloroethylene
USDA	U.S. Department of Agriculture
VOC	volatile organic compound