Draft Protocol for Controlling Contaminated Groundwater by Phytostabilization

November 5, 1999

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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1 Introduction

The Air Force is responsible for a large number of sites that contain water-soluble contamination in the vadose zone or in the ground water. The contamination at many of these sites is confined by natural conditions to a relatively shallow depth of the earth's crust (0 to 30 feet maximum, depending upon site characteristics). The contaminants are usually moving in water both within the vadose zone and shallow ground water. In addition, the contaminants are often naturally biodegrading, but the rate of degradation and retardation is not sufficient to prevent continued migration into uncontaminated areas, thereby resulting in ongoing environmental concerns.

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

Many shallow groundwater bodies are thin, contain a limited amount of water, and have low hydraulic conductivity (referred to as the "K" value in this report). As a result, water may move slowly and well yields may be very small.

Several methods are currently employed to remediate shallow groundwater bodies, including: soil vapor extraction, bioventing, biodegradation, flow barriers, in situ passive treatment walls, groundwater removal for treatment by horizontal and vertical wells and drains. The currently used methods rely on relatively homogeneous subsurface conditions and high hydraulic conductivity. The currently used methods are costly. The widely used groundwater capture methods may fail because of low well yields, subsurface heterogeneity, failure to capture all (or even most) of the groundwater body, 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 new concepts that utilize growing plants are known collectively as phytoremediation. One or more phytoremediation methods may have promise as a means to remediate shallow groundwater bodies. There are numerous definitions of the field of phytoremediation and its sub-fields. This protocol follows the definitions found in a recent United States Environmental Protection Agency (EPA) publication (U. S. Environmental Protection Agency, 1999) which are restated and summarized below.

1.1 Phytoremediation Definitions

"Phytoremediation is 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." (U. S. Environmental Protection Agency, 1999).

Phytoremediation has been investigated extensively by research and small-scale demonstrations, but there are few full-scale applications. Further development of the sub-fields is likely to lead to wider use of phytoremediation.

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 to remediate different sites. The contaminant and local conditions determine the appropriate sub-field of phytoremediation for a particular site.

The definitions below generally follow those used in U. S. Environmental Protection Agency, (1999), and are used 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 certain 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 or a combination of these plants is selected and planted at a site based on the type of metals present and other site conditions. The plants are 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. While the ash or compost derived from the plant material must be properly disposed of, its volume should be 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 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, then incinerated, composted to recycle the contaminants, or otherwise disposed of in a protective manner.
- **Phytodegradation**, also called phytotransformation, is the breakdown of contaminants taken up by plants through metabolic processes within the plant, or the breakdown of contaminants external to the plant through the effect of compounds (such as 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 the natural substances released into the soil by plant roots—sugars, alcohols, and acids—containing organic carbon. The organic carbon provides food for soil microorganisms that may biodegrade contaminants as they consume the plant root exudates.
- **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.

1.2 Focus

The focus of this protocol is phytostabilization. It is further 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 a replacement for, or supplement to, 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.

This protocol is written as a “draft” document for the following reasons:

- 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.
- Because the Air Force is currently designing and conducting field tests, an interim protocol is needed.

This protocol is intended to provide the Air Force with the basic framework for phytostabilization and to assist the Air Force in designing and optimizing field tests.

1.3 Contents and Use of This Protocol

This protocol contains six sections that include the definition of the term phytostabilization, a discussion of the technology required for planning and implementation, preliminary site screening, system design and plant establishment, operation and maintenance of the system, documentation, verification of performance and project completion. It also contains extensive references and appendices.

If used for project planning and implementation, the entire document will be of use, but will require emphasis on 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. Preliminary evaluation will make extensive use of section 4 with less emphasis on the remainder of the protocol.

2 Phytostabilization

This protocol is intended to explain known principles that are required for success in using phytostabilization to withdraw sufficient groundwater to control the lateral movement of contaminants in the shallow groundwater. 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. Figure 1 demonstrates the concept with a cross-section through a phytostabilization site.

2.1 Assumptions and Goals

Cleanup goals for a dissolved phase contaminant plume are not likely to be achieved if the source of the contamination is not remediated or contained. Similarly to any site remediation effort, phytostabilization requires that the source of the contaminant be removed,

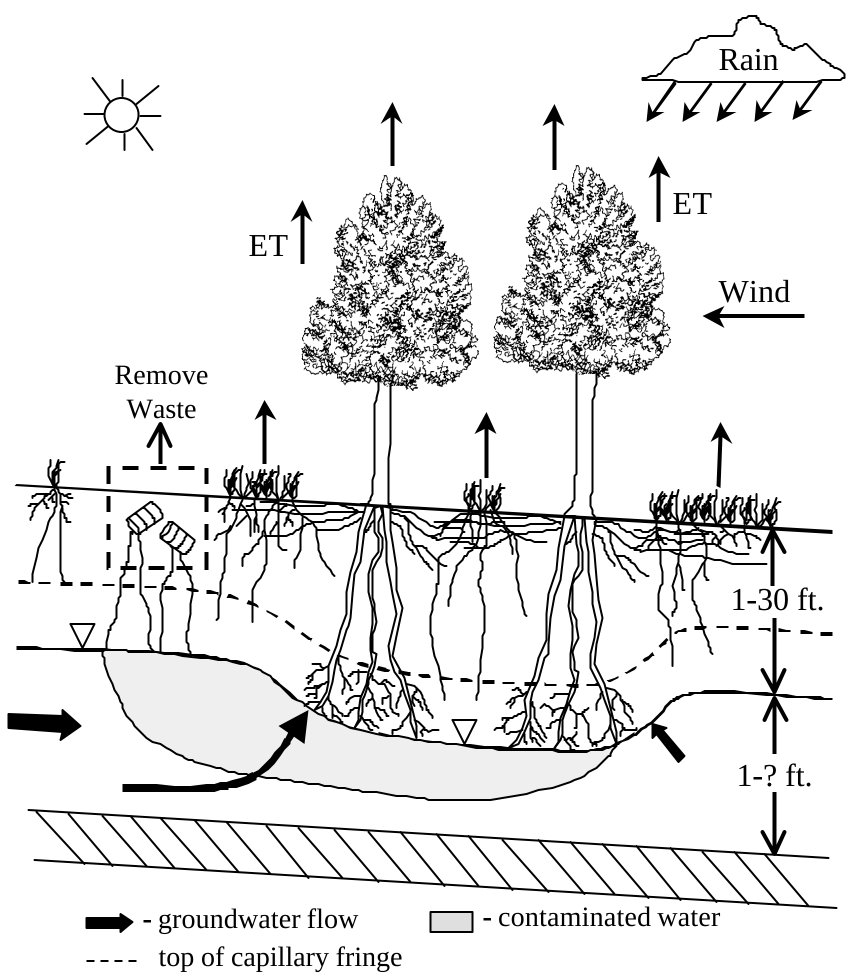

Figure 1. Cross-section through a Phytostabilization Site

controlled or remediated in such a way that no additional contaminant will be introduced into the environment. For example, the source may be physically removed or be cut off from the environment by in-ground treatment walls.

The goal of a phytostabilization effort is to stabilize a contaminated plume and to assist in complete remediation at the site.

2.2 Benefits, Cost-Effectiveness and Disadvantages

Phytostabilization relies on growing trees or other plants, thus it is an aesthetically pleasing, solar-energy driven, passive technique that can be used to clean up sites with shallow groundwater containing low to moderate concentrations of contamination. It requires minimal maintenance. The method is relatively unproven in full-scale remediation efforts, however, some tests suggest that phytostabilization may produce substantial cost savings. At some appropriate sites (see section 4.1.1) phytostabilization may completely replace traditional pump-and-treat systems. At sites where complete year round containment of contaminant movement in the ground water by phytostabilization is not possible, it may be feasible to shut off the pump and treat systems throughout the growing season and consequently save considerable operating and maintenance costs or speed up remediation of the site. 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.

Phytostabilization has the following disadvantages:

- Water removal is reduced during winter which may allow contaminated water to migrate away from the capture zone
- Complete year round containment of contaminant movement in the groundwater 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.

2.3 Requirements for Successful Implementation of Phytostabilization

Requirements for successful use 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.
- 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. However, implementation of field scale phytostabilization projects may reveal additional requirements for success or suggest modification of the requirements listed above.

3 Technology for Planning and Implementation

Several areas of technology are required for successful use of phytostabilization to remediate contaminated sites. This section includes discussion of hydrogeologic, climatic, evapotranspiration, plant, and soil technology that should be used to plan and implement a phytostabilization project.

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; however, they are usually stunted and 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 cannot remediate poor soil conditions within a century. Sharratt et al. (1998) studied the Wadsworth wagon trail in Minnesota more than 100 years after it was abandoned. The trail has been covered with native grasses continuously since abandonment in 1871. 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. This section provides the basic requirements that should form the foundation for successful planning of phytostabilization at all sites, including those that are less favorable.

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 soils at the site, plant disease and insect control, water supply and plant nutrients are optimized for plant growth. Therefore, the active practice of agricultural engineering and application of principles used in production agriculture 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 from 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 10 feet deep should generally be amenable to phytostabilization. On the other hand, where the soil above the water table is loose and sandy, the maximum depth may be 30 feet or more.

There are reports that tree roots can penetrate to great depths; for example, Rendig and Taylor (1989) state that mesquite roots have been found as deep as 174 feet. 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 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; it 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 used by phreatophytes (defined in section 3.3.1) from the water table 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 (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.

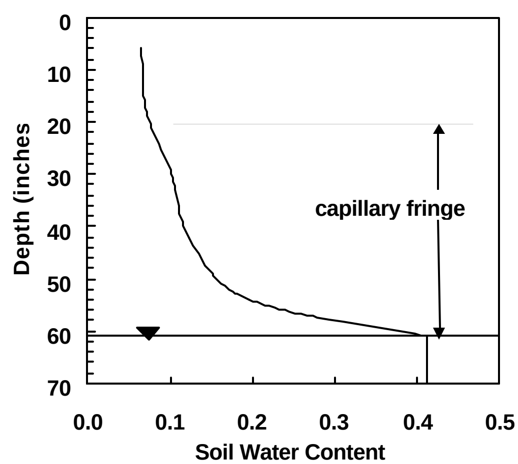

Figure 2. The capillary fringe above the water table in sandy subsoil with sandy loam topsoil (Benz et al., 1984)

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 K value and the hydraulic gradient determine the rate of movement (velocity) of water 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 (1986) provides details regarding aquifer properties and estimates 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 (formation of low vertical K value) to minimize water flow into aquifers located below the uppermost aquifer. At some sites, the lower aquifers are under sufficient pressure to cause flow to move upward into the upper aquifer. If upward flow is reasonably expected to continue during the remediation period, then the upper aquifer may be considered isolated, even though the K values 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 K value 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 but 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 influence rate of movement. Soluble contaminants may, for practical purposes, move nearly as fast as the water, however, less soluble contaminants or those adsorbed by the aquifer 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 may have a toxic effect on the plants grown to remove water from the aquifer and result in a reduction to both growth rate and transpiration. If toxicity may be an issue, plants that are tolerant to the contaminant or natural dissolved solids should be selected for use. Data showing the response of plants to many contaminants is unavailable (more data may be published as phytoremediation systems become more widely used). However, 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.

3.2 Climate

Climatic factors are important in assessing the potential value of phytostabilization at a site, design of the system and assessment of results. In order to assess 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 are unavailable for the site, remotely measured precipitation values may be used, however, the accuracy of estimates for the site decreases with increasing distance of measurement away from the site.

During periods with significant precipitation, but low potential evaporation the phytostabilization system may not remove enough water to control groundwater unless there was significant residual drawdown from an earlier period. Figure 3 shows the distribution of monthly precipitation for several locations within the continental United States. In the southeastern US, 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.

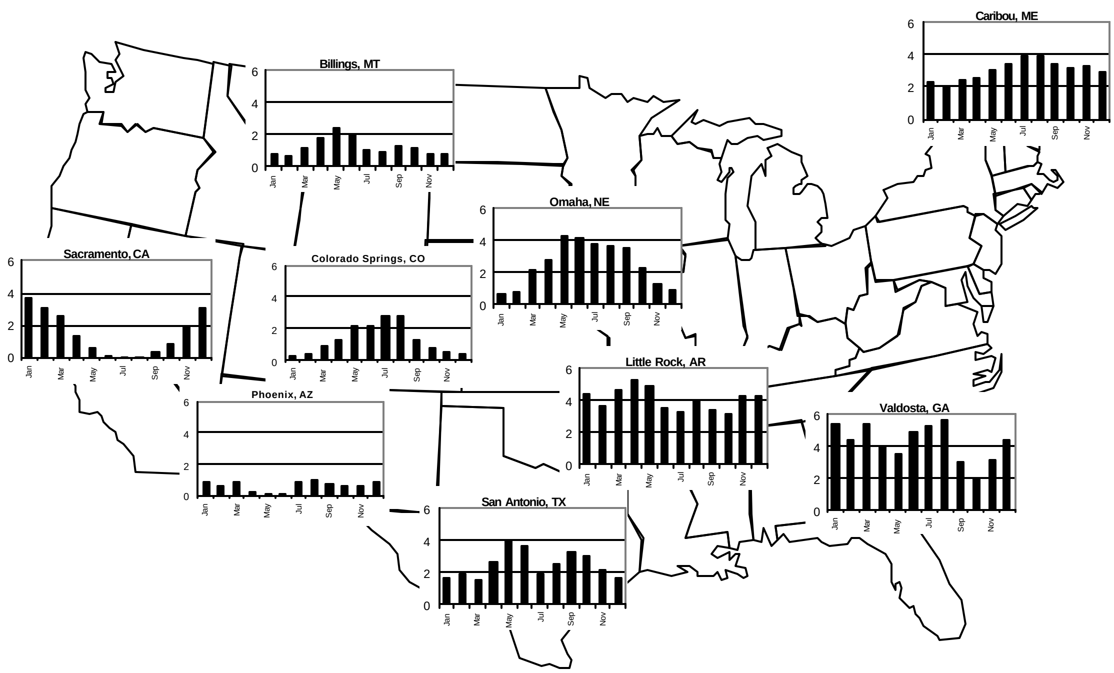

Figure 3. Distribution of monthly precipitation within the continental United States.

Also, while it is true that conditions will vary throughout the US, 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 at Norton and March AFBs, located near San Bernadino and Riverside, California respectively. The pan evaporation at Norton and March AFBs is the same, 70 inches per year; however, precipitation is 16 and 8 inches respectively. This is a two-fold difference in precipitation within 14 miles. There is only a small elevation difference between these two sites; however, they are near the mountain ranges of Southern California, so topography has a strong influence on climate. This illustrates the need to use site specific data in the western United States.

3.3 Evapotranspiration

The ET process is the evaporation of water from (1) the soil surface or (2) from plants, primarily the stomata in plant leaves. Evaporation of water requires heat input to the system. The rate of evaporation is proportional to the rate of heat or energy input to the system.

Potential ET (PET) is the maximum ET that can result from a set of climatic conditions, but actual ET may be less than the potential amount. Soil factors, available water supply, plant selection, disease, insects and stage of plant growth may reduce ET for a particular time period. The magnitude of PET is useful in preliminary planning to identify the maximum possible performance of phytostabilization and serves as the basis for estimates of actual ET.

ET may be measured directly at the site or estimated from other measured parameters. Direct measurement at the site will normally be impractical due to the high cost; the alternative is to estimate potential ET from climatic measurements. 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 discuss methods for estimating ET; however, a complete discussion of the physics of the ET process is beyond the scope of this protocol. This protocol contains basic equation sets needed to estimate reference ET by six methods. The resulting reference ET amounts may be used to estimate PET. The reference Jensen et al. (1990) contains more than one equation for some variables, each using different "metric" units. Complete equation sets for a particular method are scattered throughout the book and they are difficult to assemble. The equations required for each method are assembled together in this protocol with a consistent set of "metric" units. The reader is referred to the complete handbook compiled by a committee of the American Society of Civil Engineers (Jensen et al., 1990) for additional information.

3.3.1 Basic Physics of ET

The primary source of energy for the ET system is solar energy; however, advected energy may be an important source of heat. Advected energy is heat energy carried laterally by the wind; 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.

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 received at the surface.

3.3.2 Potential ET (PET)

There are numerous methods that may be used to estimate PET for a site. Jensen et al. (1990) discussed and tested 20 methods for estimating reference (potential) ET. They tested the methods against experimentally measured lysimeter and climate data from 11 sites. Elevation at the sites ranged from 30 m below sea level to 2774 m above sea level. Latitudes ranged from 38° S at Aspendale, Australia, to near the equator at Yangambi, Zaire, to 56° N at Copenhagen, Denmark. Their book contains 17 pages of pertinent references and is the result of years of effort by a dozen of the world’s leading ET research scientists and engineers.

Jensen et al. (1990) found that the Penman-Monteith method was the most accurate; however, it also requires the greatest amount of input data and solution of several equations to estimate ET. Other methods that are discussed in this protocol require fewer measured input data but produce acceptable accuracy if used appropriately.

The data, coefficients, and constants required to estimate PET are discussed below and with the methods. This protocol contains the same symbols and definitions as ASCE Handbook 70 by Jensen et al. (1990) (HB 70) to simplify further research by the reader. In addition, it uses a consistent set of metric units. The methods, symbols, coefficients, and constants are defined where used and in the glossary in Appendix H.

Jensen et al. (1990) state *"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 impossible 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 against the worldwide measurements of ET at 11 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 protocol contains six methods for estimating PET; they were selected from the group of 20 ET estimation methods contained in HB 70. These six methods are believed to be most appropriate for use in phytostabilization estimates of PET:

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

Table 1 contains a list of the measured data that are required for each of the methods discussed here, along with estimates of the method's accuracy. Most of the methods require additional coefficients that may be estimated from these data and universal constants. Each method, its coefficients, and use of its equations are discussed in Appendix A.

The Penman-Monteith method is the most accurate of all of the 20 methods tested and of the six chosen for inclusion in this protocol (see Table 1). It also requires more equations and calculations than the others and the greatest number of measured daily input data. It is most accurate when used on an hourly basis and the values summed to obtain daily values of ET (Jensen et al., 1990); however, it may be used on a daily basis. When used on an hourly basis, it requires input data measured and recorded on an hourly basis. 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 remaining five methods require only daily values of input data.

The Penman (1963) method was the foundation for the Penman-Monteith and not surprisingly produces accurate estimates (see Table 1). However, it also requires the maximum amount of daily data and is less accurate than the Penman-Monteith method.

Table 1. Data required by 6 methods for estimating reference ET (PET), standard error of estimate for each method and seasonal ET estimate as percent of lysimeter measurement (information selected from HB 70, Jensen et al., 1990).

Required Data		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[1]
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[2]	MJ m^{-2} d^{-1}	X	X	X			
Standard error of estimate for ET estimates at **Arid** locations, mm/day		0.4	0.6	**1.8**[3]	0.6	0.9	0.9
Standard error of estimate for ET estimates at **Humid** locations, mm/day		0.3	0.6	0.6	0.8	0.8	0.9
Seasonal ET estimate as *percentage* of lysimeter measurement, **Arid** locations.		*99*	*98*	***73***	*106*	*88*	*91*
Seasonal ET estimate as *percentage* of lysimeter measurement, **Humid** locations.		*104*	*114*	*97*	***122***	*82*	***125***

1. TE = estimate from table or equation.
2. May be calculated, but this reduces accuracy of ET estimate.
3. Bold, underlined numbers show large differences from lysimeter measured values.

The remaining four methods discussed here, require fewer data, but produce acceptable results, table 1. Some of them are acceptable in either a humid or arid climate, but not both.

An arid climate is defined in HB 70 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 the tests reported in HB 70. So for purposes of phytostabilization design and evaluation within the continental United States, an arid climate may be assumed for most locations west of 104^{O} longitude (western border of North and South Dakota). Some locations in humid, cool, coastal locations on the West Coast are exceptions. 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 Penman-Monteith method is most accurate when used on an *hourly* basis; the others are best used on a *daily* basis. If a method is used on an hourly basis, ET is estimated for each hour of the day and the amount summed for the day; if used on a daily basis, ET is estimated directly for each day. 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.
- Jensen et al. (1990) state, “*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.

Jensen et al. (1990) recommend minimum time periods 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.

The *Environmental Policy Integrated Climate (EPIC)* model (personal communication from Williams, J. R) and its earlier versions called “Erosion/Productivity Impact Calculator” (Sharpley and Williams, 1990a and Williams et al., 1990) estimates PET under either dryland or irrigated conditions for cultivated crops and for some trees. The EPIC model is a comprehensive model that was extensively tested for ET and water balance estimates, including sites with significant accumulation of snow in winter (Nicks et al., 1990, Cole and Lyles, 1990, Sharpley et al., 1990, Smith et al., 1990a, Favis-Mortlock and Smith, 1990, Steiner et al., 1990, Cooley et al., 1990, Smith et al., 1990b, Kiniry et al., 1990 and Sharpley and Williams, 1990b).

The EPIC model estimates ET from measured climatic data or from estimates made by a thoroughly tested stochastic climate generator. The EPIC model contains equations for the Penman-Monteith, Penman, Priestly-Taylor, and Hargreaves methods for estimating PET. It is a robust model that may be used in estimating ET for phytostabilization sites where a complete set of climate data are available or for the site where little or no data exist.

There are 14 other estimating methods that were not selected for inclusion in this protocol although some of them might be useful. The reasons for not including each method are stated below:

- The **Thornthwaite** method was developed for the valleys of the east central United States; however, it seldom fits conditions found in other locations. Jensen et al. (1990) state *“Because the Thornthwaite equation has validity only in areas that have climates similar to that in east-central USA...it has been one of the most misused empirical equations in arid and semiarid irrigated areas.”*
- 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.

3.3.3 Actual ET

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 for only part of the time (Campbell, 1977). The actual ET rate at a phytostabilization site may often be less and seldom greater than the estimated PET. The PET estimates are useful because they provide the planner with an upper bound for expected results. However, it is often desirable to make an estimate of 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. Soil evaporation rate drops below the potential rate when the soil surface dries.
- **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 less than the potential rate (Ritchie, 1972).
- **Stage of plant growth.** When perennial plants are dormant—early in spring when growing plant parts are small or in fall as plants senesce—the actual rate of ET is less than the potential amount.
- **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 rate of root growth and reduce 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 oxygen diffusion rate and thus root growth. Reduced root growth may significantly reduce actual ET rate.

- **Soil temperature.** If soil temperatures are less than or greater than the optimum for root growth, roots may grow too slowly to explore the soil mass fully, thus reducing the ET rate below the potential rate (Rendig and Taylor, 1989).

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 that case, roots may proliferate at depth, and the actual ET rate may be relatively high but less than the potential amount. The EPIC computer model computes limiting factors and estimates actual ET under either dryland or irrigated conditions for grasses, for cultivated crops, and for some trees (personal communication from Williams; J. R and Sharpley and Williams, 1990a; and Williams et al., 1990).

3.4 Plants

Successful phytostabilization of groundwater requires use of plants that grow robustly under the conditions at the site. They must be able to remove large amounts of soil water at depth; they are required to tolerate the contaminant chemicals found at the site.

3.4.1 Criteria for Potentially Useful Plants

Plants used at phytostabilization sites 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
- Grow rapidly to maximize interception of solar radiation
- Grow robustly in the presence of site contaminants
- Not be attractive to birds (on Air Force bases)
- Transpire water over a long growing season

Plants that meet the requirements will often be phreatophytes. Phreatophytes are plants that are capable of using water from the water table or its capillary fringe (i.e., saltgrass, alfalfa cottonwood, or willow). The plants that may be used at a particular site include trees, perennial grasses, forage plants, sedges, and reeds.

3.4.2 Trees

Trees have advantages when used 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; however, other trees may be useful in some situations. Because water use by deciduous trees is small after the leaves drop, evergreen trees may have an advantage in some climates. 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 cultivated trees. General rooting patterns of cultivated trees will provide guidance regarding the irrigation required to produce large phreatophyte trees and large aboveground biomass—a requirement for phytostabilization success.

Deciduous fruit trees normally have most of their root mass in the top 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 (Uriu and Magness, 1967).

Citrus trees are mesophytes and indigenous to the humid tropics but 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 (Hilgeman and Reuther, 1967).

While the trees chosen for a phytostabilization site may have different rooting patterns and water requirements than the cultivated trees discussed above, the data shown provide an indication of 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 aeration status and microbial activity are closest to optimum; thus, they will also consume available water from the uppermost layers before using water held in the soil at depth.

The rooting potential of trees considered for use should be examined on a case-by-case basis. Trees used for phytostabilization should have the potential to extend roots deep into the soil. Some trees have potential to develop very extensive root systems. Rendig and Taylor (1989) summarized plant root data that show that mesquite (*Prosopis glandulosa*) may extend roots as deep as 174 feet. Gile et al. (1997) studied mesquite on the Jornada Experimental Range near Las Cruces, NM. They found that mesquite trees that were only 2 feet tall produced one root that was 72 feet long and that numerous roots descended to a depth of several feet, then grew upward to within 2 inches of the soil surface. They found that a mesquite tree growing in a playa that was periodically flooded had one root that extended to a depth of 18 feet. In all cases, they found that cemented soil layers stopped the downward penetration of roots.

Heitschmidt et al. (1988) 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 horizon. They state that the results of their work support 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 8 inches, upward for 12 inches, then downward again all within a horizontal distance of 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 6.5 feet. A mature honey mesquite tree had a LAI of only 1.1.

Farrington et al. (1996) studied water uptake by jarrah (*Eucalyptus marginata*) trees in Australia and found that eucalyptus could extract water from groundwater down to a depth of 46 feet in deep sands. They also summarized other Australian work that demonstrated the following:

- River red gums (*Eucalyptus camaldulensis*) used groundwater in summer.
- Roots of jarrah (*Eucalyptus marginata*) can extend to a depth of 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."*

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. Dickmann and Stuart (1983) summarized important cultural and other facts regarding this genus. They state that 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. They have a predisposition to hybridize naturally or through controlled crossing.

Dickmann and Stuart (1983) also state that populus will perform at their full potential only on the best soils and in the best climate. 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:

- Deep medium-textured soil (greater than 3 feet deep)
- Large amounts of plant nutrients
- Ample soil aeration
- Soil pH between 5.5 and 7.5
- No hardpans, gravel, or other obstructions to root growth
- Ample rainfall and/or a water table at 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 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; thus it 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 profile. If the groundwater is less than 10 feet deep, the grasses may 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. In addition, it has been successfully grown where it derives its primary water supply from a shallow aquifer. Alfalfa possesses many of the desirable plant traits required for phytostabilization.

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 reduce contaminant concentrations in the water.

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

Grass, sedges, reeds and alfalfa may be suitable plants for phytostabilization sites. 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 may be successfully used at a site in the clear zone of a runway or an area where trees may attract unwanted birds.

3.4.4 Root Environment and 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 in the system and their requirements. Rendig and Taylor (1989) state that plant roots serve many complex functions:

- 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 also 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 0.8 inches per day, however, during most of the time 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. Rendig and Taylor (1989) discuss factors that may limit root growth, including:

- Low or high soil pH
- Chemical toxicity (H, Al, Be, Cd, Pb, Cu, Cr, Fe, Hg, and Zn)
- Allelopathic toxicants
- 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 usually 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 salts may 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 in the root respiration process and its 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 exercise more control of 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. 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, and values above 1.7 Mg/m^3 may effectively prevent root growth (Eavis, 1972; Monteith and Banath, 1965; Taylor et al., 1966; Jones, 1983; Timlin et al., 1998 and Gameda et al., 1985). Particle size distribution in the soil interacts with soil density to control root growth. Roots often grow better in sandy soils. Jones (1983) demonstrated that plant root growth is reduced at soil bulk density greater than 1.5 Mg/m^3 for most soils, and reduced to less than 0.2 optimum root growth for all soils containing more than 30% silt plus clay and having bulk density greater than 1.6 Mg/m^3. Grossman et al. (1992) summarized 18 laboratory studies and found that root growth was only 0.2 of optimum for soil bulk density greater then 1.45 Mg/m^3 except for 3 soils in which root growth was restricted at soil bulk density of 1.3 Mg/m^3. It is often suggested that soil freezing and thawing may amend compacted soils, however, Sharatt et al. (1998) present 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. Although some phreatophytes obtain oxygen for root activity through aboveground plant parts and transfer it downward inside the root (for example Cypress trees); most plants used for phytostabilization require oxygen in the soil. 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. Most plants are stressed if the air-filled pore space in the soil is less than 10 percent although 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 to the roots.

Air-filled porosity in the soil is important because each root requires air and oxygen and because during rain or irrigation these pores become channels for water and air to move rapidly through the soil. Soil pore space includes both large and very small pores. Small pores contribute little to the movement of air; however, much of the 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. An adverse impact of soil compaction is the reduction of large pore spaces. Sandy soils tend to have large pore spaces, while clay soils often contain more total pore space, but it is contained in small 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 threat from contaminants in the groundwater should be evaluated.

Maas (1986) and Rhoades and Loveday (1990) present the tolerance to saline irrigation water exhibited by many cultivated crops, nut, and fruit trees. Figure 4 presents Maas (1986) divisions for classifying crop tolerance to saline irrigation water. They defined salinity of irrigation water by its electrical conductivity (EC). 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 grasses that are salt-tolerant, including barley, wheat, Bermuda grass, desert saltgrass, and others.

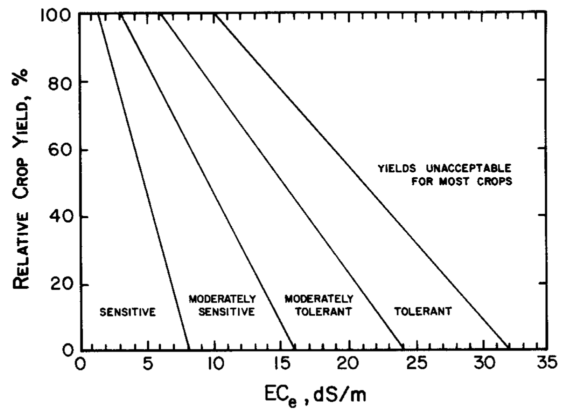

Figure 4. Divisions for classifying crop tolerance to salinity based on electrical conductivity (Maas, 1986)

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.

Because trees may not cover all of the ground during their first years of growth, a suitable grass may be planted between the rows to consume more water than 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

Equations for PET are presented elsewhere in this protocol. It is important to understand that plants growing on an actual site will transpire at the potential rate for only part of the time.

Claims are sometimes made that trees consume more water than grass or other plants. A single plant of any kind growing in a desert and having an ample supply of water in its root zone may transpire more water than calculated based on the solar energy falling on the plant. In a desert environment, the wind is heated by the exposed hot, barren soil and rock. The advected energy carried to the plant by the hot, dry wind will increase ET rate. Because trees are larger than other plants and have a large evaporating surface, this effect may be larger for isolated trees than for other isolated plants during short periods of extreme conditions. There is little advected energy at night and none on calm days, thus producing little or no increase in ET. Advected energy has a smaller effect as the area of similar vegetation increases. It has little effect when the plants suffer water or other stress that significantly reduces ET; this condition may apply during a significant part of every year. Therefore, there is the possibility for excess water use by isolated trees, but the actual difference between isolated grass and trees may be relatively small. Many plants have significant ET potential and trees should not be presumed to be the best choice at every site.

When trees are small, they can not 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.

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 and 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.

Hilgeman and Reuther (1967) reported water use by orange trees in Arizona and California (see Table 2). These data from producing orchards show that some trees may not consume large amounts of water even in hot dry climates. 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, (1990) state *"information on estimated orchard ET is scant."*

Table 2. 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

Hilgeman and Reuther, 1967

Blad and Rosenberg (1974) reported that in eastern Nebraska, alfalfa, a tap-rooted crop used 20 to 25 percent more water from a water table at 3 to 5 feet depth than native grasses. Wallender et al. (1979) found that cotton—a tap-rooted crop—consumed only 14 inches of water (60 percent of total water use) from a water table at 7.5 feet below the surface during one crop year in California.

Benz et al., 1984 reported the effect of water table depth on water use by alfalfa from shallow water tables in North Dakota. Water use from the water table aquifer varied from zero to 57 percent of total water use depending on treatment. Figure 5 shows the effect of water table depth on water use from the aquifer by alfalfa with either light or heavy irrigation.

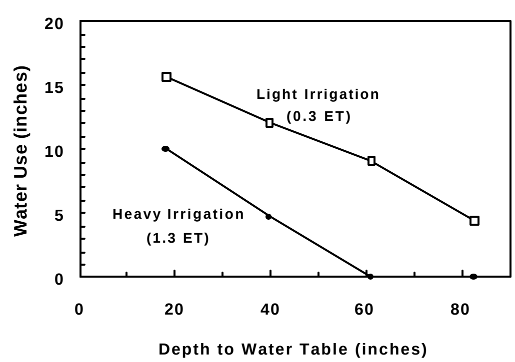

Figure 5. Growing season water use from the water table aquifer by irrigated alfalfa in North Dakota (Benz et al., 1984).

Tovey (1963) measured the water use of alfalfa grown in lysimeters with three constant water table elevations at Reno, NV. He filled the lysimeters with disturbed, coarse-, medium- and fine-textured soils. The water tables were static at 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 6 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 2 and 8 feet. Tovey (1963) stated that there was good root development in the lysimeters and that alfalfa roots extended below the water table into the saturated zone.

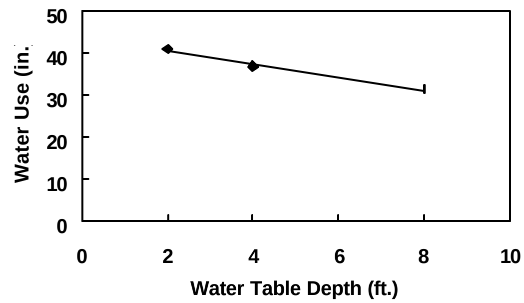

Figure 6. Annual water use from the water table aquifer by alfalfa with no irrigation, Reno, NV, (Tovey, 1963).

There are few data available on water consumption by trees from water table aquifers. Johns (ed.) (1989) 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. They reported data derived from three field experiments. While there are differences in water use between sites because of elevation and climate, the trends are clear. Where the water table was at 4 feet in a desert environment, saltcedar consumed more than 6.5 feet of groundwater per year, but where the water table was at 9 feet, it consumed less than half that amount.

Fletcher and Elmendorf (1955) summarized information on phreatophytes that consume large amounts of water on river flood plains and other areas of high water tables in the western USA. Gay (1986) and Weaver et al. (1986) measured water used by phreatophytes in New Mexico and Arizona. Table 3 summarizes their data showing groundwater consumption and the depth to the water table from which plants are known to draw water or the measured depth to water where ET was measured.

The actual water consumption from the water table appears to be less than the expected PET at all sites. It is therefore, important to understand the limiting factors to water consumption from the water table.

Table 3. Annual Water Use from the Groundwater and Potential or Actual Depth to Water Table Reached by Roots for Phreatophytes in the Western United States

Species	Water Use (inches/year)	Water Table Depth (feet)
Mesquite (*Prosopis juliflora*)[1]	-----	40 - 100
Cottonwood (*Populus spp*.)[1]	-----	10 - 20
Saltgrass (*Distichlis spicata*)[1]	13 - 49	6 - 12
Willows (*Salix spp.*)[1]	30 - 35	-----
Sedges and Reeds[1]	77	-----
Tules and Cattails[1]	90 - 120	-----
Mixed brush, Utah[1]	38 - 47 (4 Months)	-----
Mixed brush, Gila River, AZ[1]	30	-----
Saltcedar *(Tamarix chiniensis)*, Pecos River, NM[2]	23 - 34	3.3 - 12[5]
Kochia *(Kochia scoparia)*, Alkali sacaton grass *(Sporobolus aeroides)*, Desert seepweed *(Suaeda spp.)* and Russian thistle *(Salsoa kali)*, Pecos River, NM[2]	22 - 26	12[5]
Saltcedar *(Tamarix chiniensis)*, Lower Colorado River, AZ[3]	(Growing season - Mar 23 - Nov. 11) AET[4] = 68 *(PET[4] = 97)*	10.8[5]

[1]Fletcher and Elmendorf (1955)
[2]Weaver et al. (1986)
[3]Gay (1986)
[4]PET = potential ET and AET = actual ET
[5]Actual depth to water table, not potential.

The actual water consumption from water table aquifers appears to be less than the expected PET at all sites. It is, therefore, important to understand the limiting factors to water consumption from the water table.

There is a wide variability in the amount of water consumed from the water table aquifer. 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.

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 adequate amounts of plant nutrients to sustain growth. (Excess nutrients may contaminate the aquifer.).

3.5 Soils

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 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 7. Soils that contain sufficient cation exchange capacity to hold adequate plant nutrients and provide a good root growth environment will include sandy loam, loam, and silt loam. Sandy clay soils tend to have high soil strength. A desirable soil will probably contain at least 20 percent or more sand.

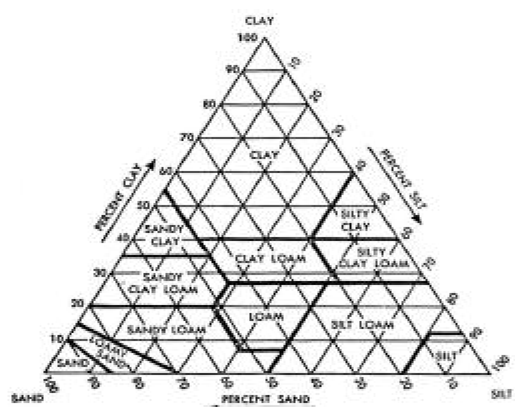

Figure 7. USDA Textural Classification of Soils

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. 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 17 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. It should be noted that addition of organic material, other than peat, to improve soil structure or soil tilth may not be worth the expense.

Where the soil contains hard or dense layers, the soil should be modified: boreholes to the water table should be drilled and backfilled with desirable soil 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. Some phreatophytes can grow with little or no oxygen in the soil; however, most plants will perform better if the soil contains adequate oxygen. Soil below the water table normally contains too little oxygen to support robust root growth except by phreatophytes; however, 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 third nutrient in total demand 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 normally found in adequate amounts in many soils.

The soil should be free of harmful constituents such as manmade chemicals, oil, and natural salts. The 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, and other problems.

3.5.2 Soil Properties at Remediation Sites

Most Air Force bases were built on highly fertile soils because the large areas of level land that are required for runways are usually associated with fertile soil. 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 Hillel (1998).

4 Preliminary Site Screening

Because any remediation activity is expensive, it is desirable to conduct a preliminary site screening to determine whether phytostabilization may be appropriate for the site and if it is worthwhile to pursue more complete and more expensive evaluations. Site screening may make two kinds of errors:

- Selection of the technology when it is *not* the most suitable choice
- Rejection of the technology when it *is* the most suitable choice

The goal of this section is to assist the reader in making the correct preliminary choice quickly and at low cost and to reduce the risk of decision-making error. A decision to accept phytostabilization technology should then be confirmed by a more complete investigation.

The preliminary site screening should be undertaken with existing information. Most contaminated Air Force sites have been evaluated, and substantial factual information is available. It will be rare that new investigations are required during this stage of phytostabilization technology evaluation for Air Force bases.

4.1 Preliminary Technical Evaluation

The following sections discuss factors that should be considered during a preliminary evaluation including climate, ET, growing season, depth to groundwater, soils, and site-specific factors. These factors are also important to a complete evaluation; however, they will be discussed and used here as appropriate for a preliminary evaluation. Keep in mind that a more detailed evaluation is required to produce the data needed for the final design of a phytostabilization system.

4.1.1 Climatic Variables

There are several climatic variables that affect the performance of phytostabilization systems; however, two factors provide enough information for preliminary considerations, they are precipitation and evaporation. While specific site conditions will affect the efficacy of the technology, in general, phytostabilization is probably appropriate for use in areas where annual evaporation exceeds annual precipitation.

As mentioned in Section 3, PET is the maximum possible evapotranspiration rate as controlled by climate only. This report presents an approximation to PET that is useful in preliminary screening; it is based on weather bureau data from the Class-A pan. The Class-A pan is a standard and widely used apparatus for measuring evaporation from open water and the data are available for many locations in the United States. The Class-A pan is a metal vessel, 4 feet in diameter and 10 inches deep that contains water. Daily measurements of water level allow estimates of daily evaporation rates when precipitation is accounted for (Veihmeyer, 1964).

Total annual evaporation from a shallow lake may serve as an approximation to the annual value of PET. Kohler, et al (1959) state that annual Class-A pan evaporation provides an estimate of annual evaporation from a shallow lake after it is adjusted by a coefficient between 0.60 and 0.81. They derived the coefficients and published maps of the United

States that show the pan coefficient as percent. Maps of the continental United States showing precipitation, Class-A pan coefficient, and Class-A pan evaporation are included in Appendix C at the end of this report. The pan evaporation data more closely approximate shallow lake evaporation in cool and humid climates than in hot or dry climates (Veihmeyer, 1964); therefore, pan coefficients are larger for the northern and coastal areas of the country and smaller for hot and dry regions.

It is clear that phytostabilization technology is more likely to succeed where the annual lake evaporation exceeds annual precipitation than where it is less. The ratio was defined and estimated as follows:

Ratio = annual lake evaporation/annual precipitation

The ratio serves as a useful screening indicator because locations where the ratio is greater than one are favorable to success for phytostabilization technology. The ratio is only an approximation to the quotient of PET/precipitation; therefore, at sites where the ratio is less than one, further evaluation of the possible use of phytostabilization is appropriate as discussed below.

Appendix B contains a table of selected Air Force installations containing the Class-A pan evaporation, pan coefficient, and annual precipitation, as well as the corresponding ratio. Figure 8 shows the location of the Air Force installations listed in Appendix B. For locations not in the table, the ratio may be derived from data read from the maps in Appendix C.

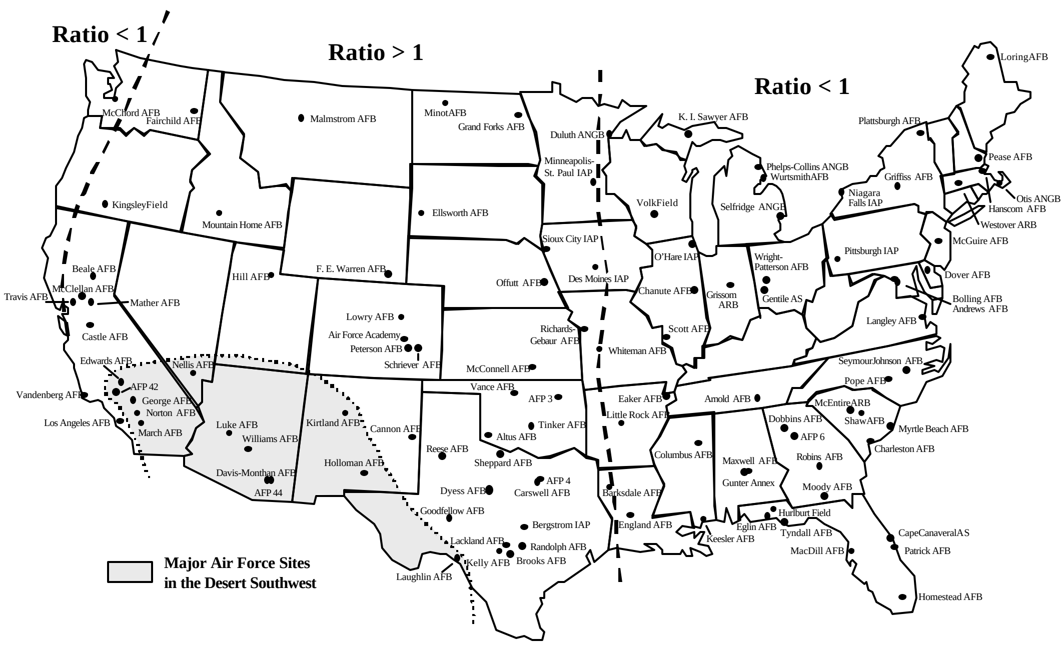

Figure 8. Location of Air Force installations listed in Appendix B and areas with ratios of annual lake evaporation/annual precipitation greater or less than one.

Dashed lines on Figure 8 delineate the regions where the ratio is less than one or greater than one. This figure should be used as a general guide only. Other available data should be considered before making a final determination, as discussed below.

***Ratio >1*:** The ratio is greater than one in the Great Plains and most of the western United States. Sites located in this region will very likely be appropriate for phytostabilization, and a phytostabilization system should have the potential to lower the water table in this region.

***Ratio <1*:** Where the ratio is less then one it is less obvious that phytostabilization technology is appropriate. However, site-specific conditions may still allow the successful use of this technology, as described below:

- Infiltration of precipitation to groundwater may be limited by soils that cause significant surface runoff or infiltration may be reduced at the site by covering the ground with plastic sheets.
- The recharge zone for the site area may be partially covered by buildings or parking lots.
- Lake evaporation may not accurately estimate PET because of site specific anomalies, i.e. mountains.
- A more accurate estimate of site specific PET and precipitation may indicate that the site remains a candidate for phytostabilization.

As stated above, lake evaporation is an approximation to PET. Potential ET was estimated by the EPIC model using the Priestly-Talor equation for F. E. Warren AFB, WY, and Robbins AFB, GA. The quotient of annual PET/precipitation was estimated for each year of a 100-year period. These bases are located in eastern Wyoming and in Georgia; they are dry and wet sites respectively. Figure 9 shows the probability distribution of the quotient of annual PET/Precipitation for each base. The mean value of the quotient PET/Precipitation at F. E. Warren AFB was 4.0; therefore it was larger than the ratio which was 3.1 (Appendix B). This confirms that it is safe to assume that a ratio greater than one at F. E. Warren indicates probable success for phytostabilization.

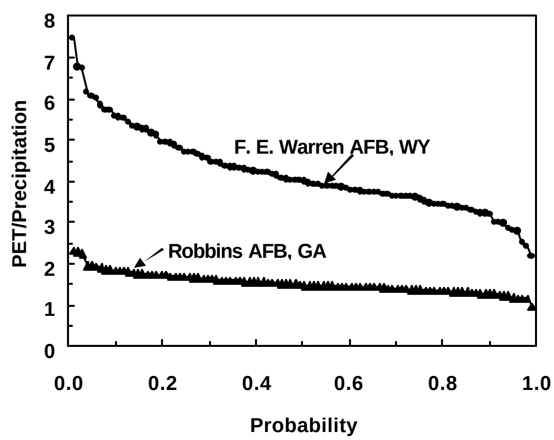

Figure 9. Probability distribution for the quotient of annual PET/Precipitation in WY and GA. PET was estimated for each year of a 100-year period by EPIC using the Priestly-Taylor equation.

At Robbins AFB the ratio was 1.0, indicating some doubt that phytostabilization is an appropriate technology at that site. However, the mean value of the quotient PET/Precipitation at Robbins AFB was 1.5 (figure 9); therefore phytostabilization appears to be an appropriate technology

These data show that the ratio was less than the quotient PET/Precipitation in both a dry and wet climate and that the PET/Precipitation quotient was greater than 1.0 at both sites.

Therefore, phytostabilization is likely to succeed at both sites even though the value of the ratio was only 1.0 at the wet site.

***Desert (ratio >4)*:** While evaporation-to-precipitation ratios greater than one are desirable, care must be used at locations where the ratio exceeds four. At these locations, hardy plants may be required to withstand the dry conditions (See Section 3.4). For example, George AFB, CA, Nellis AFB, NV, and Laughlin AFB, TX, each have ratios greater than 4.0; however, annual precipitation at these locations is 6, 4, and 18 inches respectively. At George AFB and Nellis AFB, phytostabilization vegetation must be capable of obtaining almost all water required for plant maintenance from the groundwater or else irrigation is required. At Laughlin AFB, little or no irrigation may be required after plant establishment. Phytostabilization should work very well at these locations; however, plant selection and establishment are important issues at each site.

4.1.2 Plant Hardiness Zones and Length of Growing Season

Appendix D contains a plant hardiness zone map of the United States and indicates annual minimum air temperatures for each zone. Appendix D will allow quick determination of whether a particular plant species is adapted to the site.

The length of the growing season is an important parameter because deciduous trees and other plants consume little water when dormant. Length of the growing season may be estimated as the time between the last spring frost (32 deg. F) and the first fall frost. 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 may select evergreen species for the site; however, they may or may not control the water table during winter because their rate of water use may be small during the cold months.

4.1.3 Depth to Groundwater

Section three 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 preliminary screening. Simple rules of thumb that may be used if more accurate criteria are not available include -- **If other phytostabilization criteria are met and groundwater depth is:**

- **Less than 10 feet** -- phytostabilization is likely to be effective
- **Between 10 and 20 feet** -- the amount of water consumed from groundwater by each plant will be reduced below the amount consumed from shallower water tables aquifers
- **Between 20 and 30 feet** -- severe reductions of water consumption from a water table aquifer
- **Deeper than 30 feet** -- special analysis is required that may be beyond the scope of preliminary site screening.

4.1.4 Soils

During preliminary screening, all of the available data that describe the surface soils, soil material in the vadose zone and the uppermost aquifer should be assembled and evaluated.

Data on the soil at the site as it may have existed before creation of 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.

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 because, if they exist, they must be modified to assure success of the phytostabilization effort. In addition, chemical spills, soil compaction or 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.

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 bulk density of 1.6. Soil bulk density less than 1.45 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 .

4.1.5 Site Factors

Factors peculiar to the site may be important. The following factors should be considered during preliminary site screening:

- Use or non-use of the uppermost aquifer for domestic, livestock, or irrigation water
- Nearby springs and connection to streams or other surface 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

4.2 Site Objectives

The objectives for remediation of the site should be clearly defined before a complete technical evaluation is attempted regarding the possible use of phytostabilization. The questions posed below regarding site objectives should be answered to the extent of available information for the site during the preliminary evaluation.

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, its 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 have all parties involved in the decision making process from the beginning.

Questions that should be answered before establishing the objectives for site remediation by phytostabilization include:

- What remediation systems exist at the site now?
- Is hydraulic control of groundwater required or desirable?
- Is the climate suitable for phytostabilization?
- Are the soils suitable for phytostabilization?
- Is the hydrogeology suitable for phytostabilization?
- Does phytostabilization make sense?
- Is there support for implementing and monitoring new technology?

5 Design and Establishment

This section on design and establishment discusses important issues that are peculiar to phytostabilization remediation technology; however, it is not a complete design or establishment guide. The reader is presumed to have access to standard remediation design expertise.

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 only effective in containing and remediating the dissolved phase plume. In order to achieve cleanup goals in the groundwater, it is necessary to eliminate the contaminant loading to the groundwater from the source. Source remediation, whether by *in situ* treatment, through excavation or by containment, is required for a successful phytostabilization project.

5.1 Plant Selection and 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; thus, infiltration of rainwater to the water table is limited and trees must draw their water supply from the groundwater. A grass cover will be particularly effective before the tree canopy closes and shades the entire ground surface. After the tree canopy closes, the low-growing vegetation will probably die because of inadequate sunlight, which is not a problem because by that time it is no longer needed.

Grass, sedges, forbs, and forage plants like alfalfa may be used alone or in combination with trees.

5.2 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 is discussed elsewhere in this protocol.

5.3 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.

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. Because ET must be estimated from climatic data, section three contains a detailed explanation of useful ET estimation methods.

Soil water content and soil water potentials 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 can not be justified. It is more practical to evaluate groundwater flow and assume some small fraction of precipitation that may be added to the groundwater or, in some cases, estimate water flow through the vadose zone 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 Irrigation System

Irrigation will be required at all sites to establish 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 will require sprinkler irrigation. Flood irrigation is a poor choice because it is likely to cause excessive losses by deep percolation to the water table; thus increasing the amount of water that must be withdrawn from the aquifer to achieve containment.

For most applications, a timer-controlled drip irrigation system should 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 will provide more precise application of water but it is less reliable than timer-controlled systems.

Plants can 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.

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 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. 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 determine if they are healthy and growing well. If leaves are present healthy trees should have no visible discoloration of leaves, 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.

5.5.1 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.

Because they are difficult to establish from seed and they are normally widely spaced, trees are normally transplanted as growing plants. They may be small, bare-rooted seedlings or trees up to 15 feet high that were grown in containers. Small trees less than 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.

5.5.2 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; however, they may often 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 below. Review Section 3.3.4 Root Environment and Requirements for Good Root Growth, for more extensive discussion of these and other conditions for good root growth (and therefore robust plant growth).

Excellent sources for methods to test soils for suitability at phytostabilization sites are three publications from the Soil Science Society of America, they are Klute (ed.) (1986), Weaver et al. (editors) (1994) and Sparks et al. (editors) (1996).

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.

Table 4. 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.

Gravel or rock material is often found in disturbed soils and 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, 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, they may require additional irrigation, fertilizer, and other treatment.

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 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 to a depth of 18 to 36 inches on 12-inch centers between the tree rows or over the entire surface if only surface vegetation is to be planted. 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.

5.5.3 Air Inlet Wells

Inadequate aeration at depth may slow or prevent root growth. Air inlet wells made of perforated pipes may be installed 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 within the vadose zone, but they are inexpensive and provide access deep into the profile if problems develop in the future.

5.5.4 Irrigation

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 the planting operation and should be copiously irrigated immediately after planting.

5.5.5 Fertilization

It is important that plants have access to adequate nutrients during establishment. Slow-release fertilizer is 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 fertilizer is available in pellets that will release the nutrients over a period of one year that will support the tree during the important initial growing season.

6 Operation and Maintenance

The purpose of a phytostabilization system is to lower the groundwater sufficiently to stop lateral movement of contaminated water. Accordingly, performance 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 or in research. Monitoring during operation requires measuring fewer parameters and data than are needed for scientific research on basic principles and natural laws. Monitoring of the system should include collection of only the data needed to assess performance of the phytostabilization system. A person familiar with the system, its parts, and the requirements should visit 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 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 possible if the rate of inflow of groundwater to the site is less than the rate of withdrawal by the vegetation during the day; this phenomenon may be used to the advantage of the assessment program.

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 normally less than that induced by phreatophytes. Continuous measurement of water-table elevation both under and remote from the tree rows 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.

If the possibility exists for reduction of contaminants in the groundwater as a result of root growth of vegetation at the site or by natural attenuation, then groundwater quality should be measured. The sampling and analysis should be performed annually or as required to determine the change in concentration of contaminants in the aquifer.

6.1.2 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 terms involved are precipitation, groundwater flow and actual ET. Precipitation should be measured at the site. Because it is too costly, ET should not be measured at the site; however, actual ET may be estimated from PET that is in turn derived from measured climate data. Groundwater flow (Driscoll, 1986) may be approximated by a simple model with hand calculations or if the site is complex, may require complex calculations that are best accomplished by a computer model.

During operation of the system, its performance should be monitored by a minimum of two 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. Some sites may require more than two monitor wells. The monitor well data should be tied to a complete evaluation of water table elevation for all monitor wells in the area; all monitor wells should be measured at the beginning and end of the growing season.

6.1.3 Soil Water

Soil water content and soil water potentials 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.

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 Groundwater Level

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 monitor 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 extend far enough out to define the zone of influence of the system.

6.2.2 Climate Parameters

Irrigation of trees or other plants during establishment requires knowledge of daily or weekly water use, which may be estimated from PET which, in turn, 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 effectiveness of alfalfa, grass or other plants may be estimated as a fraction of PET. 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. If accurate estimates of daily potential ET are required then soil heat flux is 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 approximating 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.

6.2.3 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 measure water use by 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 monthly and for each irrigation season.

6.2.4 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 about the 12-inch depth and deep in the soil profile but above the capillary fringe (e.g., 6 to 8 feet 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.

6.2.5 Minimum Site Measurements

Table 5 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. All of the site-specific parameters are required for all sites. Daily measurements of precipitation are required for all sites. The other climate parameters may be selected to satisfy the PET method that will be used

Arid Sites—PET Estimate

The Hargreaves method provides acceptable accuracy for estimating PET at arid sites; however, it is not recommended for humid sites (see Section 3.3.2). At arid sites, the minimum climate parameters required for using the Hargreaves method are daily values of maximum and minimum air temperature. However, recording of only the minimum data will preclude using more accurate PET methods to evaluate performance.

Humid sites - PET estimate

The Priestly-Taylor method provides acceptable accuracy for estimating PET at humid sites; however, it is not recommended for arid sites (section 3.3.2). The minimum climate parameters required for using the Priestly-Taylor method include all climate parameters shown in table 5 except wind. Soil heat flux may be calculated (Appendix A) and will produce small errors in daily estimates of PET. Annual values of soil heat flux are near zero; therefore, if annual PET is desired the soil heat flux may be assumed to be zero, thus calculated values are acceptable for use in equations for PET used in annual evaluations. Because soil heat flux is somewhat difficult and expensive to measure, it should be measured at phytostabilization sites only if highly accurate estimates of PET are required.

Relative humidity is relatively easy and inexpensive to measure in the field if other parameters are already being measured and recorded. Therefore, relative humidity should be included in the list of parameters to measure in the field.

Because modern climatic stations may function unattended for days or weeks, the equipment is available from many vendors and it is relatively inexpensive in relation to total costs for a phytostabilization system, it is recommended that all of the climate parameters except soil heat flux be measured at all sites.

Table 5. Parameters that Should Be Measured and Recorded at a Phytostabilization Site
(Bold Parameters are the Minimum for the Penman-Montieth Method for Estimating PET)

Parameter	Purpose	Recording Frequency
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 at a minimum of 2 wells Beginning and End of growing season for well field.
Soil water condition, electrical resistivity or other	Plant water requirement, performance assessment	4 times per day
Water use by trees (sap flow gage)	Performance assessment (measure 2 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

6.3 Maintenance

Maintenance after establishment is just as important for a phytostabilization site as it is for any mechanical remediation system. The plants and other parts of the system will require regular monitoring and maintenance; indeed 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 expensive emergency 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.

6.3.1 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 bimonthly inspection 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 what actions might be taken to prevent or ameliorate 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. Measure plant height, density, and LAI as required for other plants such as alfalfa.

6.3.2 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 adequate in most soils. It is advisable to consult local experts and/or test the soil for plant nutrient status. Some forms of nitrogen are highly soluble, thus highly mobile, and can become contaminants in water. Phosphorus is normally bound to soil clay or soil organic matter. However, if phosphorus is applied as fertilizer on the soil surface, rainfall may remove significant amounts in surface runoff and may create contamination issues. 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 well worth the extra cost.

6.3.3 Tree Pruning and Plant Harvest

The purpose of a tree planting for phytostabilization is to maximize water consumption from an aquifer. High rates of water consumption require large above ground biomass. Tree pruning should, therefore, be kept to the minimum amount required to allow access to the site; it 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 harvest to maintain healthy plants. This issue should be carefully studied during planning and design.

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 and 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.

7 Project Completion

Project completion should be planned as part of the overall project-planning process. There may be issues that could cause significant costs during project completion; these issues should be evaluated with all other aspects of project planning and cost estimates.

7.1 Defining the Ending Point

The closure of a phytostabilization site will be 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 should be possible to model 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, it 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 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 acceptably met. Once the cleanup goals have been attained, the site should be formally closed with the regulatory oversight entity.

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 above ground 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 is no disposal issue. If contamination is discovered in the plant material, regulatory disposal procedures must be followed.

7.3 Contaminant Storage in Roots

No significant amount of volatile organic materials should accumulate or remain in the roots of the phytostabilization plants at the end of the remediation process. If there was significant metal contamination in the plume, some plant and metal combinations may result in elevated concentrations of metals retained in roots. These metals may form stable compounds within the organic matrix of the roots and thus may not leach out of the soil and recontaminate the groundwater. However, if significant metals were present in the groundwater plume, then 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 some limited confirmatory sampling of roots and surrounding soils should be undertaken to ensure worker safety.

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Appendix A

Calculating PET

This Appendix contains the equations, coefficients and constant values that may be used to estimate potential evapotranspiration using the 6 methods discussed in section 3.3.2. The methods shown here and in section 3.3.2 were taken from the Civil Engineering Handbook number 70 (Jensen et al. (1990). The methods in HB 70 were designed to estimate ET from "reference crop" conditions, which are defined as well watered grass or alfalfa that is transpiring at maximum rate for the climate. The estimates of ET made by these methods are good estimates of PET. No similar methods were found for trees or forest.

Handbook 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. In addition, HB 70 presents extensive tests of each method it presents against measured values of ET along with evaluations of the accuracy of each method. Because the physics of water evaporation are complex, HB 70 contains numerous methods, equations and systems of units. This protocol contains a unified set of methods, equations and units taken from HB 70. They provide the user a unified set of methods that may be used in 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 check equations and coefficients contained herein against the original references (shown in Jensen et al, 1990) or the equations and definitions contained in HB-70 (Jensen et al, 1990).

Appendix A is divided into three sections:

- Section A-1: methods used to calculate potential evapotranspiration
- Section A-2: secondary equations necessary to calculate input values required by the methods
- Section A-3: summary list of the symbols used in the first two sections

Each method is presented in the order it was discussed in Section 3.3.2. They are 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 coefficients are used in more than one ET method. The appropriate equations and explanations for these commonly used coefficients are listed separately in alphabetical order. They are alphabetized by name rather than symbol.

In order to make it possible for the user to go to the original source for further information, the equation numbers from HB 70 have been used verbatim in this report. Where equation numbers were not used in the original text, the page number is given here. They are not presented in numerical order. The units of measurement are displayed to the right of each equation and are followed by the equation number.

Please note the following:

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.

Appendix A-1

PET 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.

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[1] (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}

[1] 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.

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[2] (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.

[2] 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.

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[3] (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:

$\boldsymbol{x}$ = calibration coefficient

$\boldsymbol{x}$ = 1.26 for humid or wet climates
$\boldsymbol{x}$ = 1.7 for arid and semi-arid climates

[3] 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.

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

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

RH_m = mean relative humidity, percent
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.

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

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

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:

C_T = temperature coefficient

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

where

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

and

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

T_x = intercept of the temperature axis

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

z = elevation, m
e_2^0 = saturated vapor pressure at mean maximum temperature, kPa
e_1^0 = saturated vapor pressure at mean minimum temperature, kPa

Notes:

The above saturated vapor pressure values (***e_2^0***, ***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.

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 $\boldsymbol{\lambda}$ (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.)

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

Appendix A-2

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 <u>Air density</u>

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

where $\boldsymbol{z}$ = elevation, m

***P* ¾ <u>Atmospheric pressure at elevation *z* (estimated)</u>**

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

where $\boldsymbol{z}$ = elevation, m

r_a ¾ <u>Diffusion resistance of air layer</u>

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

where $\boldsymbol{z_w}$ = height of wind speed measurement, cm
$\boldsymbol{z_p}$ = height of humidity and temperature measurements, cm
$\boldsymbol{u_z}$ = mean wind speed at height $\boldsymbol{z_w}$, m s^{-1}

$\boldsymbol{z_{om}}$ = roughness length for momentum transfer

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

$\boldsymbol{z_{ov}}$ = roughness length for vapor transfer

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

$\boldsymbol{d}$ = zero plane displacement of wind profile

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

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

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

R

R_A ¾ <u>Radiation, extraterrestrial</u>

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

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

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

$\boldsymbol{d}$ = Declination

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

$\boldsymbol{d_r}$ = Relative distance of the Earth from the sun

$$d_r = 1 + 0.033\cos\left(2pJ/365\right) \qquad \text{unitless} \qquad [7.30]$$

$\boldsymbol{w_s}$ = Sunset hour angle

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

1 degree = 0.0175 rad
1 radian = 57.296°

<u>Notes</u>:

To calculate monthly values of $\boldsymbol{R_A}$, use values of $\boldsymbol{J}$ 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 $\boldsymbol{R_A}$ can be obtained by dividing by the latent heat of vaporization ($\boldsymbol{l}$). If $\boldsymbol{R_A}$ is in units of MJ m^{-2} d^{-1}, divide by $\boldsymbol{l}$ 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 <u>Radiation, net</u>**

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

$$R_{bo} = \left(a_1 + b_1\sqrt{e_d^0}\right)\left(4.903\times10^{-9}\right)\left(T_x^4 + T_n^4\right)/2 \qquad \text{MJ m}^{-2}\ \text{d}^{-1} \qquad [3.17]$$

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

RH¾ 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:

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

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:

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

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:

$$RH_m = (RH_n + RH_x)/2 \qquad \text{percent}$$

e^0 ¾ Saturation vapor pressure

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

where $\boldsymbol{T}$ = mean temperature, °C

Notes:

This equation is used in several methods to calculate saturation vapor pressure at various temperatures. If the method requires $\boldsymbol{e^0}$ at dew-point, use the mean dew-point temperature; if the method requires $\boldsymbol{e^0}$ 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.

α ¾ <u>Short-wave reflectance coefficient or albedo</u>

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 <u>Slope of the saturation vapor pressure – temperature curve</u>

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

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

G_i ¾ <u>Soil heat flux for time period *i*</u>

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

<u>Notes</u>:

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 <u>Vapor pressure deficit</u>

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

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

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

Appendix A-3

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 B

Estimates of Shallow Lake Evaporation and the Ratio of Shallow Lake Evaporation to Precipitation from Pan Evaporation and Precipitation Data for Selected Air Force Installations (Average Annual Values)

The following data is provided to assist in the preliminary screening of a site.

Latitude and longitude are provided so that the values may be used in calculating site specific estimates of ET using equations presented earlier in this report (Section 3.3.2 and Appendix A).

The Class A pan evaporation and Class A pan coefficient data were obtained by reading values from the maps located in Appendix C. The Class A pan is the standard apparatus used by the United States Weather Service to measure evaporation rates. However, since measurements made with the Class A pan consistently exceed the true evaporation rate, the value has to be multiplied by the coefficient to arrive at a reasonable estimate of shallow lake evaporation.

The ratio of evaporation to precipitation was calculated for selected sites as described in Section 4.1.1.

Installation	State	Lat.[1]	Long.[2]	Precip.[3]	Pan Evap.[4]	Coef.[5]	Evap.[6]	Ratio[7]
		Deg.	Deg.	Inches	Inches	---	Inches	---
Gunter Annex	AL	32.4	86.3	52	58	0.76	44	0.8
Maxwell AFB	AL	32.4	86.4	52	58	0.76	44	0.8
AFP 44 - Tucson	AZ	32.2	110.9	12	95	0.69	66	5.6
Davis-Monthan AFB	AZ	32.2	110.9	12	95	0.69	66	5.6
Luke AFB	AZ	33.5	112.4	8	105	0.68	71	9.2
Williams AFB	AZ	33.6	112.2	8	105	0.68	71	8.9
Eaker AFB	AR	36.0	90.0	50	53	0.75	40	0.8
Little Rock AFB	AR	34.9	92.2	49	58	0.74	43	0.9
AFP 42 - Palmdale	CA	34.6	118.1	8	80	0.73	58	7.3
Beale AFB	CA	39.1	121.4	20	68	0.74	50	2.5
Castle AFB	CA	37.4	121.4	11	85	0.74	63	5.7
Edwards AFB	CA	34.9	117.9	8	110	0.70	77	9.6
George AFB	CA	34.5	117.3	6	110	0.68	75	12.5
Los Angeles AFB	CA	33.9	118.4	14	61	0.76	46	3.2
March AFB	CA	33.9	117.3	8	70	0.72	50	6.3
Mather AFB	CA	38.5	121.4	17	70	0.74	52	3.0
McClellan AFB	CA	38.7	121.4	21	70	0.74	52	2.5
Norton AFB	CA	34.2	117.3	16	70	0.70	49	3.1
Travis AFB	CA	38.3	121.9	18	65	0.76	49	2.7
Vandenberg AFB	CA	34.7	120.6	14	57	0.79	45	3.2
Air Force Academy	CO	39.0	104.9	16	65	0.70	46	2.9
Lowry AFB	CO	39.7	104.9	15	58	0.70	41	2.7
Peterson AFB	CO	38.8	104.7	15	58	0.70	41	2.7
Schriever AFB	CO	38.8	104.5	15	58	0.70	41	2.7
Dover AFB	DE	39.1	75.5	44	46	0.77	35	0.8

Installation	State	Lat.[1]	Long.[2]	Precip.[3]	Pan Evap.[4]	Coef.[5]	Evap.[6]	Ratio[7]
		Deg.	Deg.	Inches	Inches	---	Inches	---
Cape Canaveral AS	FL	28.5	80.6	45	60	0.77	46	1.0
Eglin AFB	FL	30.6	86.6	64	62	0.77	48	0.7
Homestead AFB	FL	25.5	80.4	62	65	0.77	50	0.8
Hurlburt Field	FL	30.5	86.5	65	60	0.77	46	0.7
MacDill AFB	FL	27.8	83.5	50	65	0.77	50	1.0
Patrick AFB	FL	28.2	80.6	47	60	0.77	46	1.0
Tyndall AFB	FL	30.2	85.6	55	62	0.77	48	0.9
AFP 6 - Marietta	GA	33.9	84.5	54	54	0.75	41	0.7
Dobbins ARB	GA	33.9	84.5	54	54	0.75	41	0.7
Moody AFB	GA	31.0	83.2	50	59	0.75	44	0.9
Robins AFB	GA	32.6	83.6	45	58	0.75	44	1.0
Mountain Home AFB	ID	43.1	115.9	10	51	0.73	37	3.7
Chanute AFB	IL	40.3	88.2	36	41	0.77	32	0.9
O'Hare IAP	IL	41.8	88.0	34	39	0.77	30	0.9
Scott AFB	IL	38.5	89.9	39	47	0.76	36	0.9
Grissom ARB	IN	40.6	86.2	39	42	0.77	32	0.8
Des Moines IA	IA	41.5	93.7	33	50	0.74	37	1.1
Sioux City IA	IA	42.4	96.4	26	53	0.71	38	1.4
McConnell AFB	KS	38.6	97.3	33	80	0.70	56	1.7
Barksdale AFB	LA	32.5	93.6	47	65	0.73	48	1.0
England AFB	LA	31.3	92.5	58	65	0.75	49	0.8
Loring AFB	ME	46.9	67.9	37	25	0.80	20	0.5
Andrews AFB	MD	38.8	76.8	45	47	0.76	36	0.8
Hanscom AFB	MA	42.5	71.3	45	33	0.77	25	0.6
Otis ANGB	MA	41.7	70.5	46	34	0.77	26	0.6
Westover ARB	MA	42.2	72.6	44	35	0.76	27	0.6
K. I. Sawyer AFB	MI	47.3	88.3	37	32	0.80	26	0.7
Phelps-Collins ANGB	MI	45.1	83.5	29	33	0.78	26	0.9
Selfridge ANGB	MI	42.6	82.8	30	40	0.75	30	1.0
Wurtsmith AFB	MI	44.5	83.4	31	33	0.78	26	0.8
Duluth ANGB	MN	46.8	92.2	31	32	0.77	25	0.8
Minn-St Paul IAP	MN	44.9	93.2	27	41	0.74	30	1.1
Columbus AFB	MS	33.6	88.4	56	56	0.76	43	0.8
Keesler AFB	MS	30.4	88.9	62	63	0.77	49	0.8
Richards-Gebaur AFB	MO	38.8	94.1	39	60	0.73	44	1.1
Whiteman AFB	MO	38.7	93.6	40	55	0.73	40	1.0
Malmstrom AFB	MT	47.5	111.2	15	50	0.70	35	2.3
Offutt AFB	NE	42.1	95.9	30	57	0.72	41	1.4
Nellis AFB	NV	36.2	115.0	4	110	0.66	73	17.4
Pease AFB	NH	70.8	43.8	43	33	0.77	25	0.6
McGuire AFB	NJ	40.0	74.6	44	43	0.76	33	0.7
Cannon AFB	NM	34.4	103.3	18	102	0.68	69	3.9
Holloman AFB	NM	32.8	106.1	12	100	0.68	68	5.7
Kirtland AFB	NM	35.0	106.6	9	90	0.69	62	7.2
Griffis AFB	NY	43.3	75.5	46	35	0.76	27	0.6
Niagara Falls IAP	NY	43.1	78.9	39	34	0.77	26	0.7
Plattsburgh AFB	NY	45.8	73.4	32	32	0.77	25	0.8
Pope AFB	NC	79.0	35.2	46	55	0.75	41	0.9

Installation	State	Lat.[1]	Long.[2]	Precip.[3]	Pan Evap.[4]	Coef.[5]	Evap.[6]	Ratio[7]
		Deg.	Deg.	Inches	Inches	---	Inches	---
Seymour-Johnson AFB	NC	35.3	78.0	50	55	0.76	42	0.8
Grand Forks AFB	ND	47.9	97.4	18	35	0.76	27	1.4
Minot AFB	ND	48.4	101.3	16	45	0.74	33	2.0
Gentile AS	OH	39.8	84.2	39	44	0.76	33	0.9
Wright-Patterson AFB	OH	39.8	84.1	38	44	0.76	33	0.9
AFP 3 - Tulsa	OK	36.2	95.9	39	75	0.71	53	1.4
Altus AFB	OK	34.7	99.3	26	94	0.69	65	2.5
Tinker AFB	OK	35.4	97.4	33	85	0.70	60	1.8
Vance AFB	OK	36.4	97.9	28	85	0.70	60	2.1
Kingsley Field	OR	42.1	121.7	13	55	0.74	41	3.1
Pittsburgh IA ARS	PA	40.5	80.2	34	39	0.75	29	0.9
Charleston AFB	SC	32.8	80.0	48	56	0.77	43	0.9
McEntire ARB	SC	34.0	81.0	48	56	0.75	42	0.9
Myrtle Beach AFB	SC	33.7	78.9	50	55	0.77	42	0.8
Shaw AFB	SC	34.0	80.5	48	56	0.76	43	0.9
Ellsworth AFB	SD	44.1	103.1	16	57	0.70	40	2.5
Arnold AFB	TN	35.4	86.1	56	50	0.75	38	0.7
AFP 4 - Ft Worth	TX	32.8	97.3	32	80	0.70	56	1.8
Bergstrom AFB	TX	30.3	97.8	32	78	0.70	55	1.7
Brooks AFB	TX	29.3	98.4	30	81	0.70	57	1.9
Carswell AFB	TX	32.8	97.3	32	80	0.70	56	1.8
Dyess AFB	TX	32.4	99.8	24	97	0.69	67	2.8
Goodfellow AFB	TX	31.4	100.4	20	103	0.68	70	3.5
Kelly AFB	TX	29.4	98.6	30	81	0.70	57	1.9
Lackland AFB	TX	29.4	98.6	30	81	0.70	57	1.9
Laughlin AFB	TX	29.4	100.8	18	110	0.68	75	4.2
Randolph AFB	TX	29.5	98.3	30	81	0.70	57	1.9
Reese AFB	TX	33.6	101.9	18	115	0.68	78	4.3
Sheppard AFB	TX	34.0	98.5	26	94	0.70	66	2.5
Hill AFB	UT	41.1	112.0	22	50	0.71	36	1.6
Langley AFB	VA	37.1	76.3	45	51	0.77	39	0.9
Fairchild AFB	WA	47.6	117.7	16	53	0.71	38	2.4
McChord AFB	WA	47.1	122.5	37	31	0.75	23	0.6
Volk Field	WI	43.9	90.3	32	39	0.76	30	0.9
F. E. Warren AFB	WY	41.2	105.9	13	58	0.70	41	3.1
Bolling AFB	DC	39.0	77.0	39	47	0.76	36	0.9

1. Lat. = North Latitude
2. Long. = West Longitude
3. Precip. = Average annual precipitation.
4. Pan Evap. = Average annual Class A pan evaporation. Pan evaporation was estimated for each site from the map in Appendix C by Kohler et al, 1959.
5. Coeff. = Pan coefficient for converting pan evaporation to shallow lake evaporation. Pan coefficient was estimated for each site from the map in Appendix C by Kohler et al, 1959.
6. Evap. = Estimated annual shallow lake evaporation (Pan Evap. X Coeff.).
7. Ratio = Ratio of average annual shallow lake evaporation/average annual precipitation (Evap./Precip).

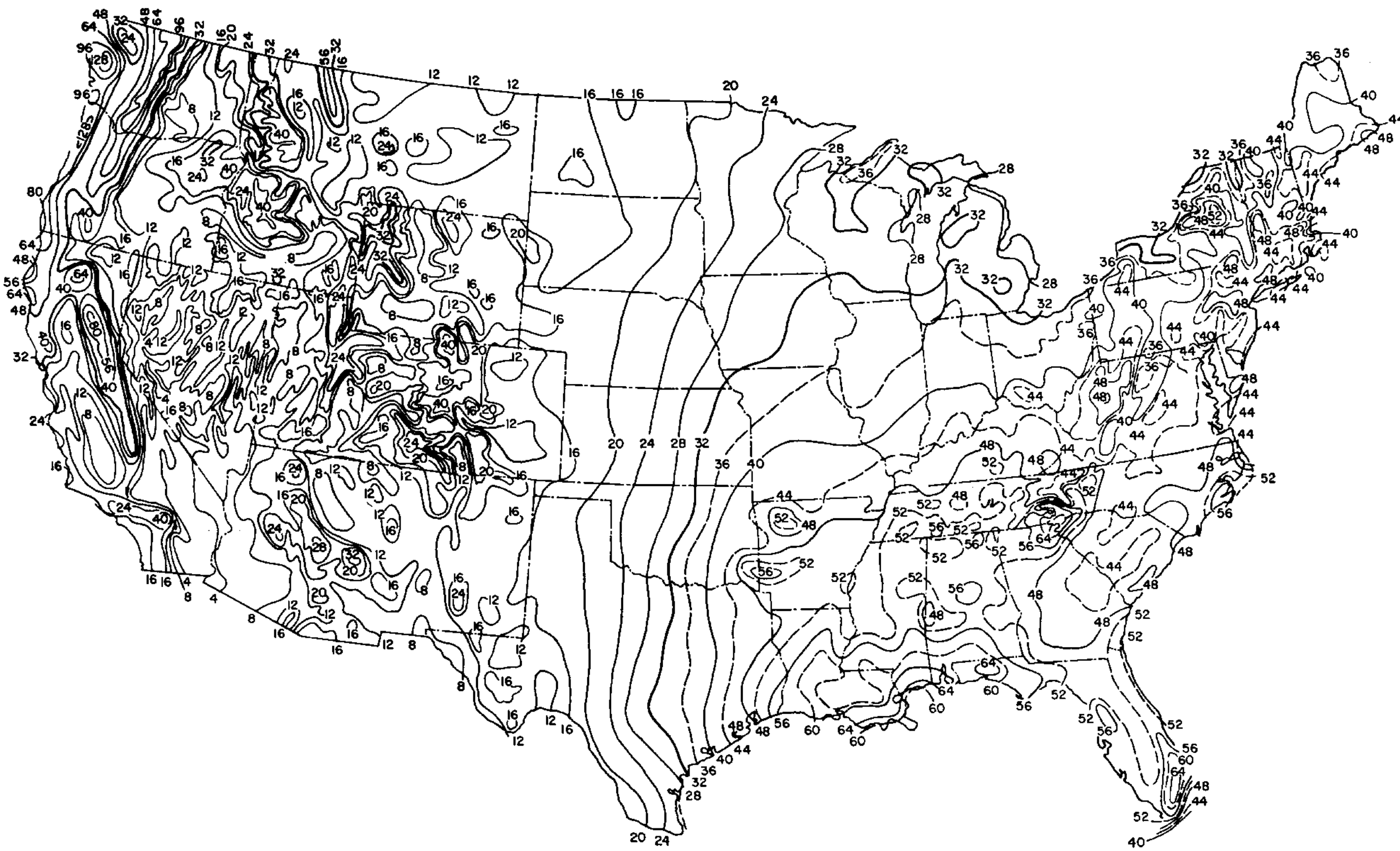
Appendix C

Precipitation, Class A Pan Evaporation and Class A Pan Coefficient Maps for the Continental United States

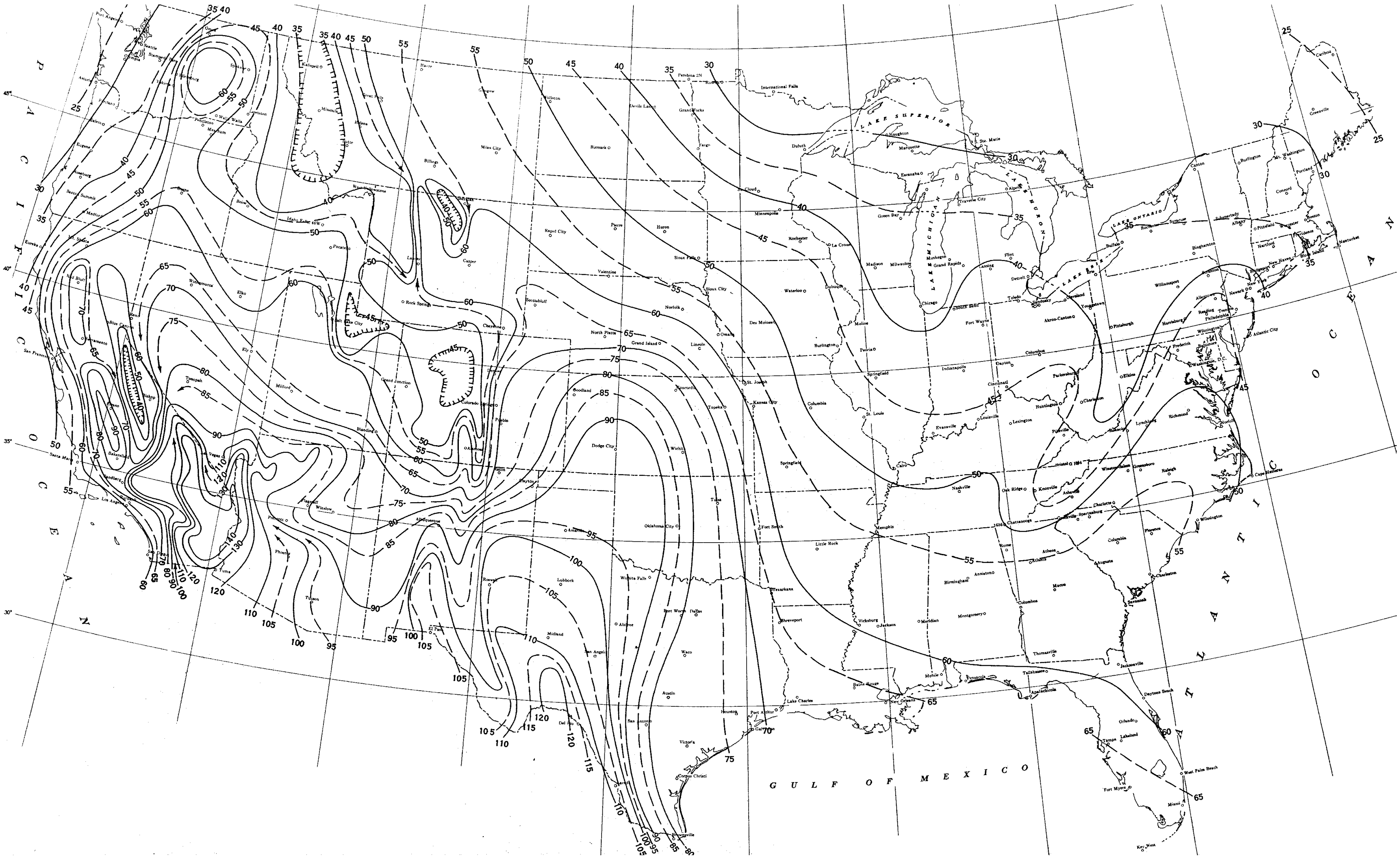
To estimate average annual precipitation for a location, read the value from the precipitation map – interpolating between contour lines where necessary.

To obtain an estimate of average annual evaporation from a shallow lake, read the values of Class A pan evaporation and Class A pan coefficient from the evaporation and coefficient maps respectively – interpolating between contour lines were necessary. Then use the following equation to calculate the estimated lake evaporation. Because the map shows the coefficient values as percentages rather than fractions (e.g. 70 rather than 0.70) the result must be divided by 100.

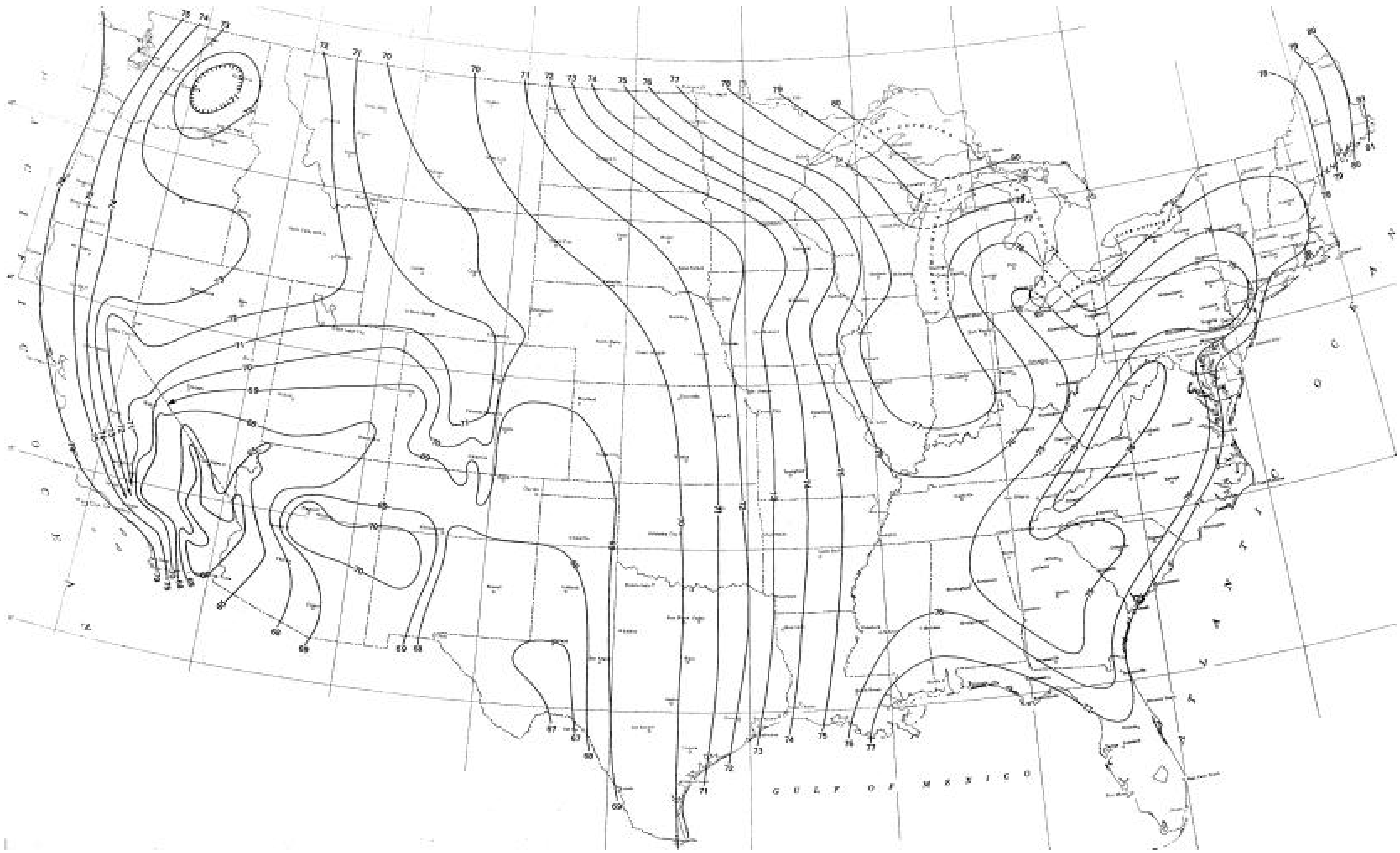
Shallow Lake Evap = (Class A pan evap * Class A pan coefficient)/100



Average Annual Precipitation, inches (Gilman, 1964)



Average Annual Class A Pan Evaporation, inches (Kohler et al, 1959)

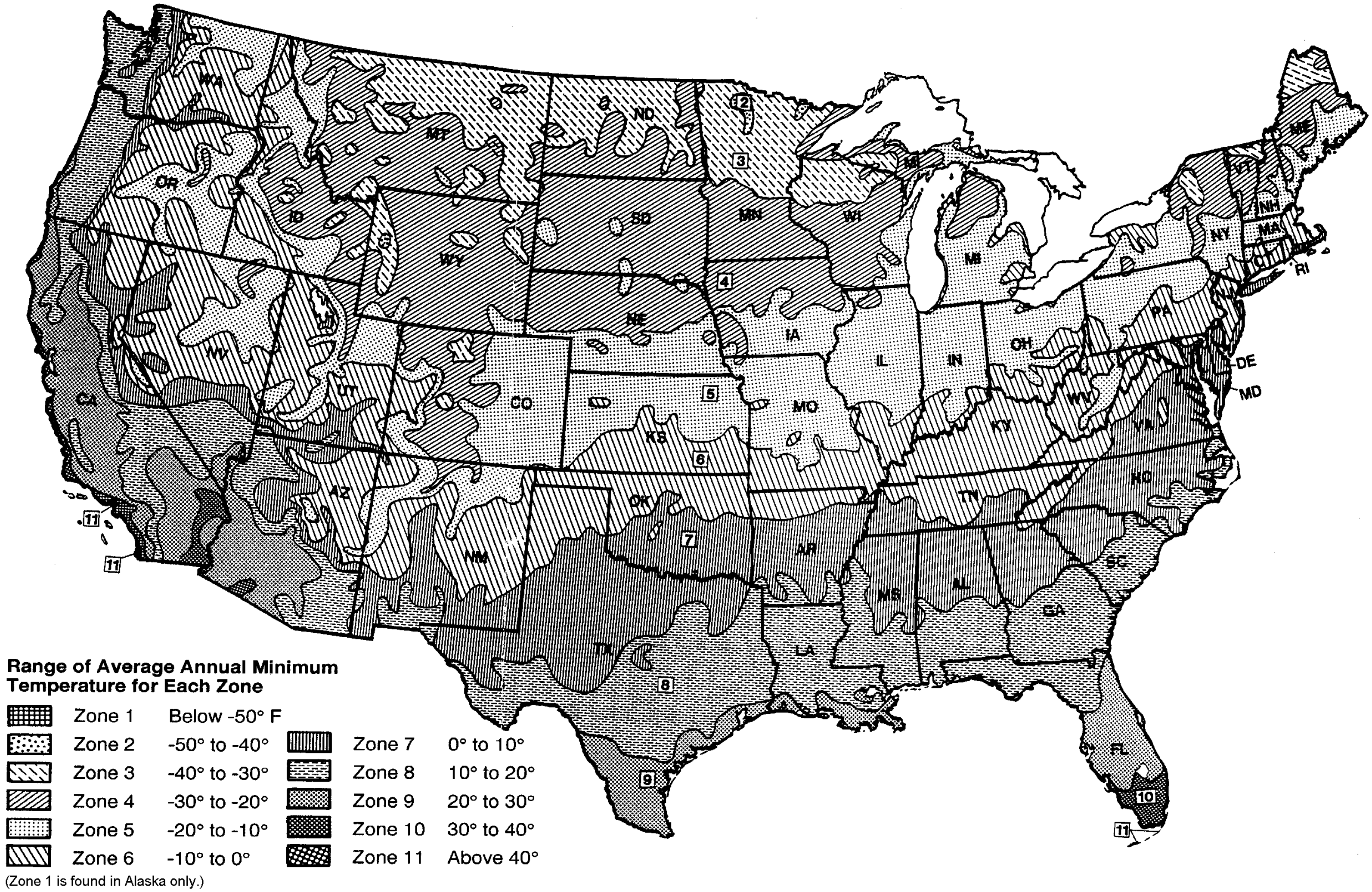


Class A Pan Coefficient, percent (Kohler et al, 1959)

Appendix D

USDA Plant Hardiness Zone Map

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.



USDA Plant Hardiness Zone Map (after Alderson and Sharp, 1995)

Appendix E

Case Studies

The following information has been summarized from three documents, they are Chappell, 1998, Environmental Quality Management, Inc., 1998 and NATO, 1998. Since phytoremediation is a relatively young discipline, particularly with respect to control of groundwater flow, most projects are still in the early stages of establishment and initial data collection. Parts of the referenced material for each case were presented in each of the references shown above.

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 cost 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 F

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.

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		
In-Situ, Inc.				X					X	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**
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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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

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.

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 G

Units, Conversion Coefficients

The following table of conversions was modified from Jensen et al, 1990.

Length	
1 micrometer (µm) = 10^{-6} m	1 degree of latitude (°lat.) =111.14 km = 69.057 stat. Mi.
1 millimeter (mm) = 10^{-1} cm = 10^{-3} m	1 inch (in.) = 25.4mm = 2.54 cm = 0.0254 m
1 centimeter (cm) = 10^{-2} m	1 foot (ft) = 12 in. = 30.48 cm = 0.3048 m
1 meter (m) = 10^{2} cm = 3.2808 ft = 39.370 in.	1 statute mile (stat. Mi.) = 5,280 ft. = 1609.3 m = 1.6093 km
1 kilometer (km) =10^{5} cm =10^{3} m = 3280.8 ft = 0.62137 stat. Mi.	

Area [b]	
1 square meter (m^2) = 10^4 cm^2 = 1550.0 sq in. = 10.764 sq ft	1 acre = 43,560 sq ft = 4046.856 m^2 = 0.4047 ha
1 square foot (sq ft) = 144 sq in. = 0.092903 m^2	1 hectare (ha) = 10^4 m^2 = 2.471 acre
1 square mile = 640 acres	

Volume

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

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

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

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

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

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

1 Imperial gallon = 1.2003 U. S. gal.

Time

1 mean solar minute (min.)
= 60s

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

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

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

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

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

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

Mass	
1 gram (g) = 0.0022046 lbm	1 pound avoirdupois (1 lb) = 453.59 g = 0.45359 kg
1 kilogram (kg) = 10^3 g = 2.2046 lbm	1 short ton = 2000 lbm = 0.892857 long ton = 0.90718 t
1 metric ton, tonne (t) = 10^3 kg = 2204.6 lbm	1 long ton = 2240 lbm = 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 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 millibar (mb)
= 103 dynes cm^{-2}
= 0.750062 mm Hg (standard)
= 0.029530 in. Hg (standard)
= 100 pascal (Pa)

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

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

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, 677 South Segoe Road, Madison, WI

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, $\mu mol\ cm^{-2}\ s^{-1}$	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 H

Glossary

actinometer—the instrument for measuring terrestrial and solar radiation.

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.

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—a shallow zone of soil above a water table that is nearly saturated by capillary action in the smaller pore spaces.

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.

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.

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.

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.

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.

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.

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.

zero plane displacement—an empirically determined constant introduced into the logarithmic 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.

Appendix I

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