Vegetated Landfill Covers and Phytostabilization—The Potential for Evapotranspiration-Based Remediation at Air Force Bases

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Vegetated Landfill Covers and Phytostabilization— The Potential for Evapotranspiration-Based Remediation at Air Force Bases

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Executive Summary

Two new and promising technologies use plants for environmental remediation. Vegetated landfill covers and phytoremediation methods control or remediate contamination by mechanisms that are in turn governed by natural evaporation and the transpiration of plants. Vegetated landfill covers minimize infiltration of precipitation into landfills. Phytostabilization – a sub-field of phytoremediation - uses plants to control water in the vadose zone and/or alter local groundwater flow patterns. During phytoremediation, plants move large amounts of water from the soil to the atmosphere, and they may accumulate, transfer, or destroy some contaminants found in the vadose zone or shallow groundwater.

To use plants successfully in environmental remediation, it is necessary to understand the requirements for plant growth and to estimate the probable performance of plants at a particular site. This document provides an initial assessment of the probability for successful use of plants in vegetated landfill covers or in phytostabilization systems within the continental United States.

Evapotranspiration (ET) is the sum of transpiration by the plant and evaporation from the soil surface. Potential ET (PET) is the amount of water that would return to the atmosphere if abundant, freely transpiring plant leaves are available and the water supply to the plants is abundant and unrestricted. PET is the maximum amount of water that plant systems can transfer back to the atmosphere. While plant performance may be limited by several factors, the climatic factors that control PET present the largest potential limitation to the use of plants in remediation. These climatic factors should be carefully considered during the first step of evaluating the possibility of using plants in remediation systems.

We estimated the PET ratio (annual PET/annual precipitation) and classified 60 Air Force bases as affording *good*, *fair*, or *marginal* opportunities for using plants as part of the environmental remediation approach. The results are presented below:

Opportunity	**PET Ratio**	**Number of Bases**
Good	PET Ratio 1.5	42
Fair	1.2 PET Ratio < 1.5	14
Marginal	PET Ratio < 1.2	4

Climatic factors are favorable for the effective use of ET landfill covers or phytostabilization at most Air Force installations in the continental United States. Both ET landfill covers and phytostabilization have the potential to improve remediation effectiveness, reduce costs and maintenance, and improve the appearance of remedial actions at most Air Force bases.

Introduction

Controlling water is often the key to controlling and remediating contaminated Air Force sites because many contaminants are either soluble in or moved by water. Plants are assuming an ever-increasing role in remediating contamination at Air Force bases. Plants move large amounts of water from the soil to the atmosphere. They may also accumulate, transfer, or destroy contaminants found in the vadose zone or shallow groundwater. To use plants successfully, it is necessary to understand the requirements for plant growth and to estimate the probable performance of plants at a particular site. Robust plant growth most completely achieves remediation goals.

Many factors may limit plant growth, which in turn may limit the effectiveness of plants in environmental cleanup systems. Evapotranspiration (ET) is the sum of transpiration by the plant and evaporation from the soil surface. ET is often the largest controlling factor in the use of plants in remediation. It is also a primary factor that should be carefully considered before spending money on design and installation of remediation systems that use plants. ET may control plant effectiveness in at least two ways:

- Limited water supply may reduce ET, and consequently plant growth, thus limiting remediation effectiveness for some plants.
- Limited ET may not remove enough water from the vadose zone to perform the desired remediation function.

Potential ET (PET) is the amount of water that would return to the atmosphere if abundant, freely transpiring plant leaves are available and the water supply to the plants is abundant and unrestricted. PET is limited by the amount of energy available to evaporate water. Actual ET (AET) by a plant system is almost always less than PET and is reduced by factors that limit plant growth. These factors include water supply, incident solar radiation, humidity, air temperature, wind, dormant seasons, immaturity of the plants, dry soil layers, plant type, plant disease, insect attack, soil fertility, and soil physical properties. Climatic factors from this group are collectively the largest potential limitation for plant growth and they control PET.

This document contains the results of an assessment of the ability of plants to successfully control water movement in the vadose zone and in shallow groundwater or to remove contaminants from soil and groundwater. This assessment is based on PET estimates for 60 Air Force bases within the United States.

Cost and Potential Savings

ET landfill covers typically cost about half as much to build as conventional barrier-type landfill covers and have low future maintenance costs (Hauser et al., 1999a; and Gill et al., 1999). They have the potential to reduce landfill cover construction costs to the Air Force by $500 million (Hauser et al., 1999a).

Because the field of phytoremediation is new, there are few cost and performance data. There is evidence that phytoremediation can clean up a contaminated site more effectively and with substantially lower cost than conventional methods. Schnoor (1997) presents comparative costs for remediation in the rhizosphere:

Type of Treatment	Range of costs $/Ton
Phytoremediation	$10–35
In Situ Bioremediation	$50–150
Soil Venting	$20–220
Indirect Thermal	$120–300
Soil Washing	$80–200
Solidification/Stabilization	$240–340
Solvent Extraction	$360–440
Incineration	$200–1,500

How Plants Are Used for Remediation

There are several ways in which plants may be used to remediate contaminated sites. Plants may be used to control the water balance in vegetated landfill covers (Weand et al., 1999). Plants are also the basis for phytoremediation, which is divided into sub-fields including: phytostabilization (Hauser et al., 1999b), phytoextraction, rhizofiltration, phytodegradation, rhizodegradation, or phytovolatilization (U.S. EPA, 1999; and Pivetz, 2001). This document focuses primarily on the use of plants in vegetated landfill covers and for phytostabilization, although it may be useful for other plant applications.

Evapotranspiration (ET) Landfill Covers

ET landfill covers use vegetation to work with the forces of nature rather than attempting to control them. ET covers are simply a layer of fertile soil covered by native grasses. They contain no barrier layers (Figure 1). ET covers use two natural processes to control infiltration into the waste: the soil acts as a water reservoir, and natural evaporation from the soil plus plant transpiration empties the soil water reservoir before it can infiltrate into the waste to generate leachate. In an ET cover, vegetation should remove water from the soil quickly after precipitation to restore the soil water reservoir capacity for the next precipitation event. Both potential and actual ET (AET) are important design criteria because they determine the effectiveness of the ET landfill cover. The PET is the maximum amount of water that plants can remove, while the AET estimate indicates how plants may actually perform in the environment of the site. ET landfill covers are inexpensive, practical, and easily maintained biological systems that will remain effective over extended periods of time—perhaps centuries—at low cost.

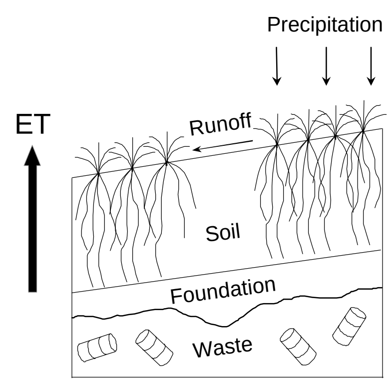

Figure 1. ET Landfill Cover

At many sites, ET covers can meet the requirements for landfill covers by (1) controlling infiltration into the waste and (2) isolating the waste and preventing contact with receptors. Gas control may be incorporated into ET covers where needed. ET landfill covers typically cost about half as much to build as conventional barrier-type landfill covers and have low maintenance costs over time.

The concept and principles of ET landfill covers were previously verified and are more completely described in papers available from the Air Force Center for Environmental Excellence, Technology Transfer Division (AFCEE/ERT) and on their web site.[1] The papers available from AFCEE/ERT include Weand et al. (1999), Hauser et al. (1999a), Boyer et al. (1999), Gill et al. (1999), and Hauser et al. (2000).

Phytostabilization

Phytostabilization is the use of plants to immobilize contaminants in the soil or to control groundwater movement. Mechanisms for phytostabilization include absorption and accumulation by roots, precipitation of chemicals within the root zone, and control of water movement in shallow groundwater by extraction with plants (use of plants in lieu of or in support of extraction wells or physical barriers).

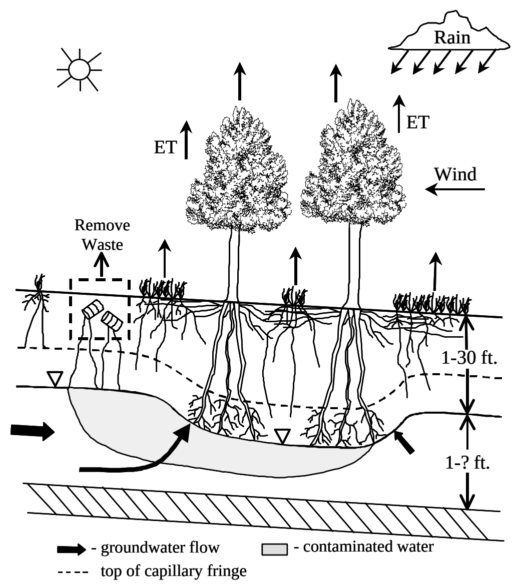

Figure 2. Principles of Phytoremediation

This document focuses on phytostabilization as it is used to remove groundwater from the capillary fringe at a rate sufficient to stabilize movement of near-surface groundwater (Figure 2). Phytostabilization is more completely described in a draft protocol (Hauser et al., 1999b) that is available from the AFCEE/ERT and on their web site.[1] PET is the upper limit of ET for the site and estimates the best-expected performance of phytostabilization systems.

Phytoremediation

Phytoremediation is the direct use of living plants for in situ remediation of contaminated soil, sludges, sediments, and groundwater through contaminant removal, degradation, or containment (Figure 2). 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 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. EPA, 1999).

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

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[1] http://www.afcee.brooks.af.mil/er/ert/erthome.htm

the appropriate sub-field of phytoremediation for a particular site. PET may or may not be a major factor in determining effectiveness of phytoremediation methods, such as extraction or degradation of contaminants.

Factors To Be Considered

Water Balance

The water balance is an accounting of all water entering and leaving the site—a mass balance. It is used to understand the pathways of water movement at a site. Elements of the water balance for a site are displayed in Figure 3.

Based on the principle of mass conservation, the water balance for a site is as follows:

Precipitation + Irrigation = ET + Runoff + Change in Stored Soil Water + Lateral Movement + Deep Percolation + Capillary Rise + Change in Groundwater Storage

The source for infiltration is both precipitation and irrigation, if applied. ET moves the majority of the incoming water back to the atmosphere. Depending on the amount of shade produced, plants may control the amount of evaporation from the soil surface, as well as the amount of transpiration. Therefore, growing plants are major controllers of the amount of ET. Plant residue may also affect total ET from a site during dormant seasons by covering and insulating the soil.

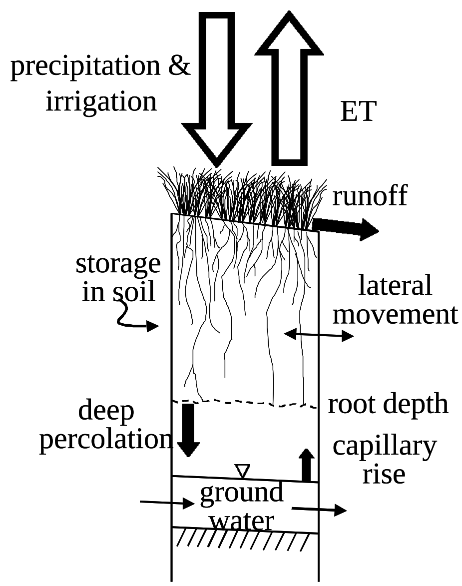

Figure 3. Water Balance at a Site

At many sites, the second largest loss of water is by surface runoff. Change in stored soil water, lateral movement, deep percolation, capillary rise, and change in groundwater storage must be entered into the equation with the appropriate algebraic sign. Site conditions frequently allow the assumption that lateral movement in the vadose zone is zero.

By analyzing each of these processes, it is possible to develop a water balance that may be used to evaluate and design landfill covers or phytoremediation systems. The principles of water balance analysis are described in recent texts (American Society of Civil Engineers, 1996; Koerner and Daniel, 1997; McAneny et al., 1985; McBean et al., 1995; Weand et al., 1999; and Gill et al., 1999).

Although each water balance element must be evaluated for design at a specific site, this document concentrates on ET because it provides the largest pathway for water movement. If ET is marginal at a site, then additional evaluation is required; if it is too small, then total dependence on plants may be inappropriate for the site. However, if ET is adequate, plants have the potential to achieve the desired goals. Knowledge about ET permits a planner to make an informed decision regarding whether ET landfill covers or phytostabilization methods merit further consideration at a particular site.

Factors that Limit or Change ET

AET at a site is normally less than PET because numerous factors—such as water stress, nutrient deficiency, and hydrologic factors—act to reduce ET. For example, a tree growing in an asphalt-covered parking lot may grow satisfactorily if the asphalt allows 25 percent of precipitation to infiltrate to the soil, however, if only 5 percent infiltrates, the tree may require irrigation. Hydrologic factors that control the amount of water actually removed from a contaminated site by ET include surface runoff, plant vigor, and area of soil surface available for plant production.

Procedure for PET Estimation

Base Selection

The sites for PET estimates included major Air Force bases from all climatic regions of the continental United States. Sites were chosen to ensure representation for both seacoasts, as well as hot and cold regions. Where two or more bases were in close proximity—for example, San Antonio with 4 bases—one base was chosen to represent the group. Another factor used in site selection was availability of adequate quality climate data. We selected 60 Air Force sites for PET estimates; Figure 4 displays their geographic distribution.

Figure 4. Location of 60 PET Sites

EPIC Model

We used the Environmental Policy Integrated Climate (EPIC) model to estimate PET and AET at each site. EPIC[2] and its earlier versions (Sharpley and Williams, 1990a; and Williams et al., 1990) meet the requirements for ET estimation. The EPIC model is a comprehensive model that has been extensively tested for plant growth and water balance estimates (Nicks et al., 1990; Cole and Lyles, 1990; Sharpley et al., 1990; Smith et al., 1990a and 1990b; Favis-Mortlock and Smith, 1990; Steiner et al., 1990; Cooley et al., 1990; Kiniry et al., 1990; and Sharpley and Williams, 1990b). Estimates of water movement below the root zone (deep percolation) are of particular concern when designing an ET cover. Meisinger et al. (1991) and Chung et al. (1999) evaluated the performance of the EPIC model for deep percolation and found that it satisfactorily estimated water flow below the plant root depth. The EPIC model is in use by the U.S. Department of Agriculture throughout the United States.

ET Estimation

Table 1 displays the source of climatic data, the plant cover modeled, and the ET method used for each base. We used The Priestly-Taylor ET estimation method east of

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

100° W longitude, and the Hargreaves method for bases west of that line. The Penman-Monteith ET estimation method is the most accurate of 20 methods tested by Jensen et al., 1990 (see also Hauser et al., 1999b). However, the Penman-Monteith method requires a complete climate data set, including daily wind run and relative humidity. Daily precipitation and maximum and minimum air temperatures were available for all bases; however, wind and humidity are time-consuming and expensive to collect for the large number of bases included in this evaluation. The Priestly-Taylor and Hargreaves methods produce acceptable accuracy for the selected regions and do not require wind and humidity data (Jensen et al., 1990, Tables 7.18 and 7.19). We used The EPIC model to create 100-year average annual estimates of PET, AET, and number of plant-stress days.

The value of PET for each site is controlled almost exclusively by the climate. Because we used appropriate, site-specific climate data, our estimates for PET are also appropriate for the site. The value of AET, however, is strongly influenced not only by climate but also by the plant and soil properties evaluated in the model.

Climate Data

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

Plant Cover

The plant cover was modeled as a monoculture of grass that is adapted to the region and climate of each base (Table 1). Each grass has the potential to root to two meters into the soil and to extract water from that depth. Because we used a monoculture, the amount of AET estimated is smaller than would be expected with a diverse plant cover. For example, Switch grass is a warm-season grass and was used in the Southeastern area of the country; it grows and uses water primarily during the warm months. In an ET landfill cover, a good plant-cover design would include several cool-season grasses and forbs in addition to warm-season grasses. Where both warm- and cool-season plants are grown, the total annual AET will be substantially more than for a monoculture consisting of a warm-season grass (Switch grass in this example).

Soil Data

The same soil was used in each model estimate (see Table 2 for a list of soil properties). The soil described is a mixture of the top 3.3 ft. of the Pullman silty clay loam soil found in the Southern Great Plains. It is a fertile soil with good water-holding capacity. Since this report focuses on defining the climatic limitations on plant growth, the soil properties used for the estimates present few limitations to plant growth or ET. Where soils at or near the site are of poor quality, the quality can be improved and made suitable for most phytoremediation uses by adding amendments. However, if available soils have inadequate water-holding properties, the ET cover may not be an appropriate choice in a humid or sub-humid region (Gill et al., 1999; and Weand et al., 1999).

Water Table Elevation

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

Results and Discussion

Data

Table 3 presents the average annual values of precipitation, PET, AET, and number of plant-stress days per year due to water and temperature; the results were computed by the EPIC model for a 100-year period. The table also reflects the difference between PET and AET, as well as the ratio of PET to precipitation.

The numbers for plant-stress days per year shown in Table 3 are minimum values. EPIC counts the number of days per year when water stress is the most limiting stress on plant growth. It also counts the number of days per year when temperature—either high or low—is the most limiting stress on plant growth. More than one plant stress may occur on any given day, but only one will be counted by EPIC as the most limiting stress.

It is important to note that the values for AET are minimum values. In the arid climates of George, Holloman, and Nellis AFBs, AET is limited by precipitation, and the ratio of AET to precipitation is one. The input to the EPIC model required water use from precipitation only. However, if trees were used to control shallow groundwater, the AET for trees at bases in arid, semi-arid, and sub-humid climates could be substantially greater than the annual precipitation. In these estimates, AET cannot be greater than precipitation because the water supply to the grass was limited to precipitation only.

At each of the bases, the AET amount displayed in Table 3 is the likely minimum value because of the specifications entered into EPIC. If plants were growing in both warm and cool seasons or if some of the plants were drawing water from a shallow water table, then the AET could be substantially greater than shown in Table 3.

PET Ratio

Figure 5 displays the annual values of the PET ratio. The PET ratio is greater than one for almost all of the country. At some sites in the eastern United States, site-specific analysis will be required to determine whether plant-based remediation is suitable.

In small areas along the Gulf coast, in northern New England, and in the snow belt in the Great Lakes region, PET may limit the use of ET landfill covers. In these same regions, phytostabilization in support of groundwater control may be restricted to use as a supplement to an extraction-well system. However, only five of the 60 bases examined had PET ratios less than or equal to 1.2, as shown in Table 3.

Where PET is small, design of ET landfill covers may require use of clay soils (not barrier layers) on or near the surface to increase surface runoff. Where PET is small, phytostabilization may be beneficial in two scenarios: (1) trees or other plants could supplement extraction wells, and (2) trees could stabilize groundwater without wells if the local recharge to the groundwater were reduced by buildings, parking lots, or other surfaces with diversion of runoff water outside the recharge area. Where the PET ratio is small, robust plant growth is normally relatively easy to achieve because the precipitation is adequate to meet plant needs.

Number of Water-Stress Days

Figure 6 shows the number of days per year when water stress was the greatest limiting factor for grass growth in the continental United States, as estimated by the EPIC model. Plant-growth limitation by water occurs when the soil is dry. On a day with water stress, an ET landfill cover, for instance, would contain little water in the soil water reservoir; therefore, it could easily hold substantial rainfall.

Phreatophytes and other plants preferentially use water held in soil layers near the surface. They use water most rapidly from the water table and deep soil layers when the plants are under water stress caused by dry surface soils. Therefore, on the days when EPIC indicated that water stress was the most limiting factor to plant growth, conditions were good for plants to consume significant amounts of groundwater.

The data shown in Figure 6 indicate that both ET landfill covers and phytostabilization have potential application for most of the United States. The number of days of plant stress caused by water is small for the Gulf Coast because of frequent and heavy rainfall originating in the nearby Gulf of Mexico. The coldest regions of the Northeast and the snow belt near the Great Lakes are also limited because of the short growing season and accumulations of snow that result in few days of water stress. These bases should employ an inexpensive site-specific design to verify a particular application to the base.

Plant stress due to limited soil water has the potential to kill plants. Therefore, sites with large numbers of days per year with plant stress should employ drought-tolerant plants.

The PET–AET Difference

Table 3 lists the differences between PET and AET for all of the bases. Theoretically, the PET–AET difference could be transpired by phreatophytes from groundwater. In actual practice, there are limiting factors that will substantially reduce the amount actually transpired. However, these data indicate that phytostabilization has good probability for success at most Air Force bases. Only two bases—Keesler and Loring—have PET–AET differences of less than 20 inches per year. An inexpensive site evaluation is appropriate for all bases that have small PET–AET values but may otherwise appear suitable for use of plants in remediation.

Data Interpretation

Sixty Air Force Bases

The PET values are basic estimates by the model; these values are controlled by climate input data. The choice of input data for soil or plant parameters has little influence on PET. However, the value of either stress days or AET displayed in Table 3 is influenced by the soil and plant input data. A more accurate estimate of AET at a site requires model input data based on specific knowledge of the site (which was not available for this general study). The PET analysis contained in this document is most appropriately applied to answer the initial question of whether ET landfill covers or phytostabilization are worthy of further consideration for a particular site. The number of stress days due to water and the AET estimates for 60 bases are presented as supporting data.

After calculating the PET ratios for the 60 bases, they were sorted into three groups based upon their PET ratios. The three groups were defined according to the appropriateness for use of ET landfill covers or phytostabilization at a site. The three classifications of opportunity are defined as follows:

- **Good—**High probability for success using plants for remediation.
- **Fair—**Successful application is likely, but may require site-specific analysis.
- **Marginal—**Prospects for successful use are limited and would require considerable site-specific design effort.

The number of bases falling in each group is shown below:

Opportunity	PET Ratio	Number of Bases
Good	PET Ratio 1.5	42
Fair	1.2 PET Ratio < 1.5	14
Marginal	PET Ratio < 1.2	4

Other Air Force Installations

In order to assist readers, the PET estimates for 49 additional Air Force Installations are included in Table 4. Six installations were very near to sites for which we estimated PET and have similar climates. PET estimates from Figure 5 are also provided for an additional 43 installations; conservative estimates were recorded from Figure 5 because local conditions may influence the true value of PET.

Conclusions

This assessment was limited to climatic factors because they present potential major limitations to the use of either ET landfill covers or phytostabilization. However, before choosing either, it is also important to consider additional factors, such as characteristics of available soils and availability of appropriate plants.

Climatic factors do not limit application of ET landfill covers or phytostabilization at most major Air Force bases. When used appropriately, both ET landfill covers and phytostabilization have the potential to improve remediation and significantly reduce short- and long-term costs at most Air Force bases.

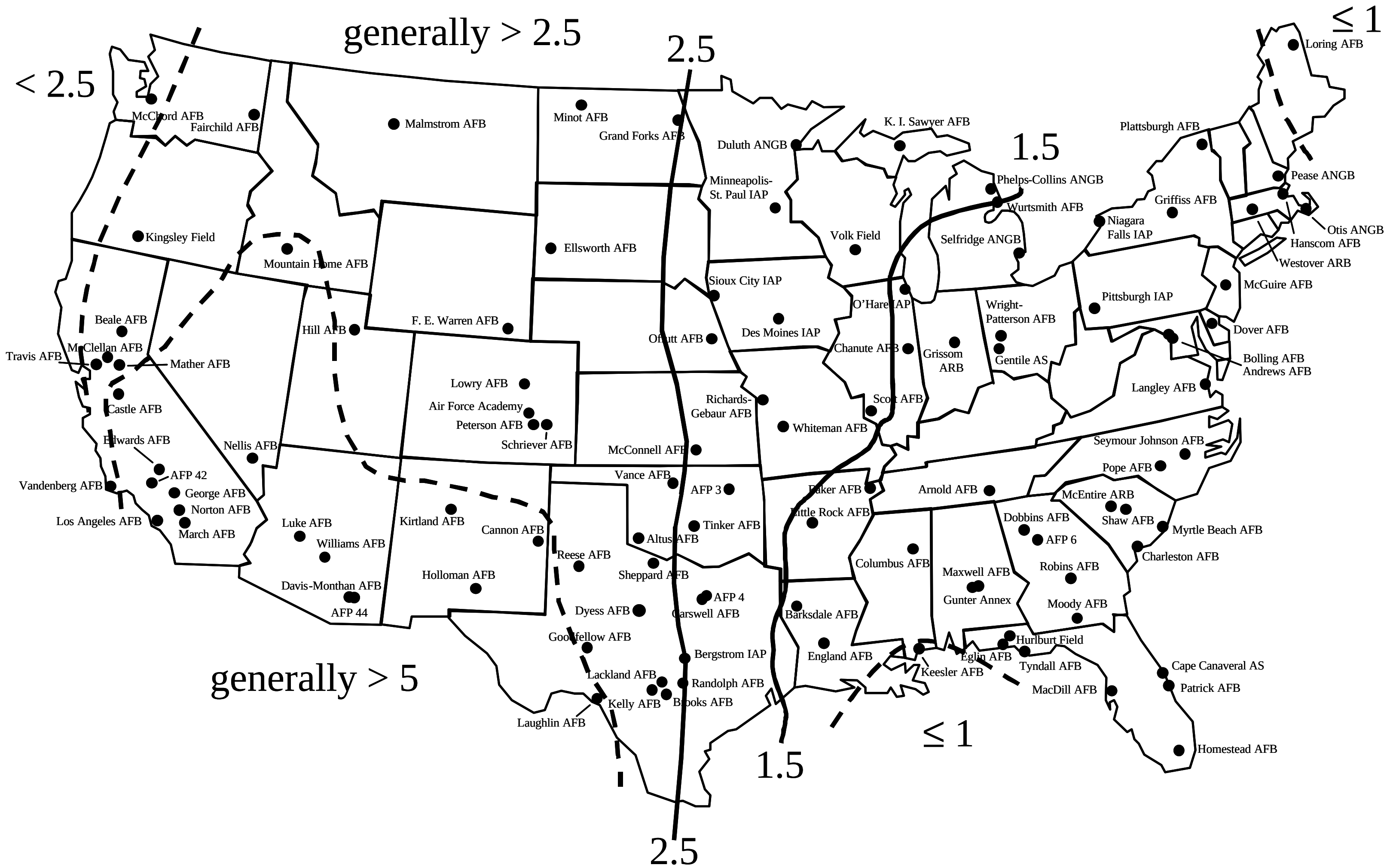

Figure 5. The Ratio of Annual Values of PET/Precipitation for the Continental United States*

*See Tables 1 and 3 for a list of the bases individually evaluated. Dashed lines are approximations.

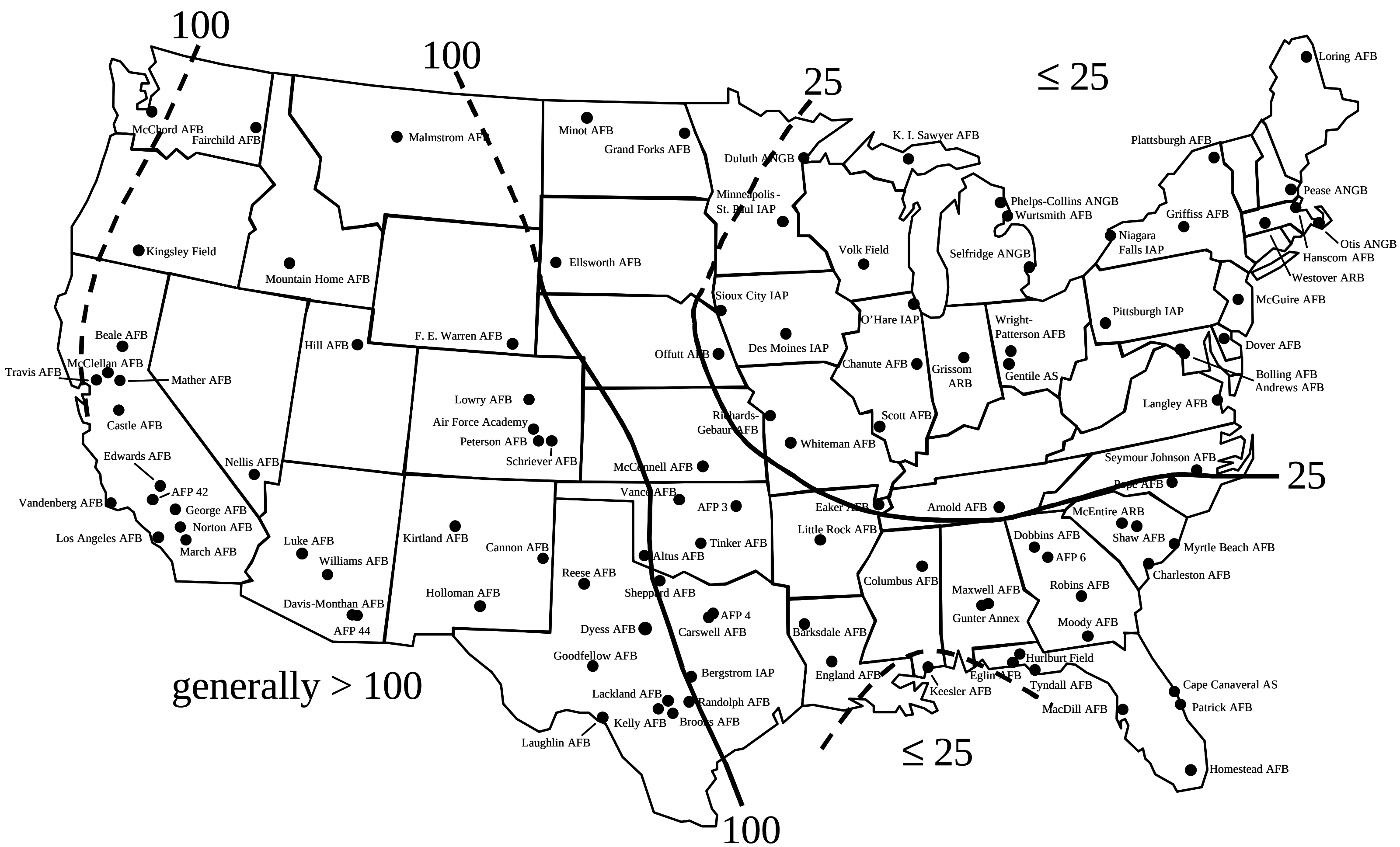

Figure 6. Number of Days per Year When Water Stress Was the Greatest Limiting Factor for Grass Growth in the United States*

*See Tables 1 and 3 for a list of the bases individually evaluated. Dashed lines are approximations.

Table 1. Air Force Bases, Arranged by Region, for which ET was Calculated, the Climate Data Source, Plant Cover, and the ET Method Used in Model Estimates.

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

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

Table 2. Properties of the Soil Mixture Used in All Model Estimates

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

Table 3. Annual Values of PET, AET, and Number of Days per Year of Plant Stress Estimated With the EPIC Model for 60 Air Force Bases in the Continental United States.

Base	State	100-Year Mean			Plant Stress Days Due To:		PET-AET	PET[4] Ratio
		PRCP[1]	PET[2]	AET[3]				
		Inches	Inches	Inches	Water	Temp.	Inches	
Air Force Academy	CO	12.8	68	12	130	180	56	5.3
Altus AFB	OK	24.6	75	23	110	190	52	3.1
Arnold AFB	TN	54.2	59	38	20	240	21	1.1
Barksdale AFB	LA	46.1	70	39	60	190	30	1.5
Beale AFB	CA	26.5	81	22	120	60	58	3.0
Bolling AFB	DC	37.2	57	29	<10	150	28	1.5
Brooks AFB	TX	28.7	78	27	120	150	51	2.7
Cannon AFB	NM	15.0	83	15	160	140	68	5.5
Castle AFB	CA	12.6	84	12	200	50	72	6.7
Chanute AFB	IL	34.8	50	26	10	170	24	1.4
Charleston AFB	SC	48.3	67	43	30	210	24	1.4
Columbus AFB	MS	54.1	66	42	40	200	24	1.2
Davis-Monthan AFB	AZ	11.5	95	11	220	60	83	8.2
Dover AFB	DE	37.4	53	28	<10	160	26	1.4
Dyess AFB	TX	23.1	77	22	120	170	55	3.3
Ellsworth AFB	SD	19.5	59	19	90	200	40	3.0
Fairchild AFB	WA	16.5	52	14	90	210	38	3.2
George AFB	CA	5.3	92	5	210	120	87	17.5
Goodfellow AFB	TX	18.2	84	18	170	100	67	4.6
Grand Forks AFB	ND	19.1	48	17	70	180	31	2.5
Hill AFB	UT	19.9	63	18	100	200	45	3.2
Holloman AFB	NM	10.7	91	11	190	110	80	8.5
Homestead AFB	FL	63.3	81	53	70	50	28	1.3
Keesler AFB	MS	69.3	62	49	<10	180	14	0.9
Kirtland AFB	NM	8.8	78	9	180	140	69	8.8
Langley AFB	VA	41.3	60	32	<10	130	29	1.5
Laughlin AFB	TX	16.9	87	16	190	60	71	5.2
Little Rock AFB	AR	49.8	64	39	50	210	26	1.3
Loring AFB	ME	36.8	39	21	20	210	18	1.0
Lowry AFB	CO	12.8	68	12	130	180	55	5.3
Luke AFB	AZ	7.7	108	8	250	70	100	14.1
MacDill AFB	FL	52.4	80	46	90	80	34	1.5
Malmstrom AFB	MT	15.4	51	14	100	210	37	3.3
Maxwell AFB	AL	51.5	70	43	50	190	27	1.4
McChord AFB	WA	40.9	53	29	40	150	24	1.3
McClellan AFB	CA	17.3	79	16	170	50	63	4.6
McConnell AFB	KS	29.3	70	27	70	230	42	2.4
McGuire AFB	NJ	46.4	50	28	<10	160	22	1.1
Minot AFB	ND	15.7	52	15	70	240	38	3.3

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

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

Table 4. Annual Values of Precipitation, and PET Ratio for 109 Air Force Installations in the Continental United States (data sorted by state)

Installation	State	Lat.[1] Deg.	Long.[2] Deg.	Precip.[3] Inches	PET[4] RATIO	Estimated[5] from
Gunter Annex	AL	32.4	86.3	52	> 1.0	Figure 5
Maxwell AFB	AL	32.4	86.4	51.5	1.4	Calculated
Eaker AFB	AR	36.0	90.0	50	>= 1.0	Figure 5
Little Rock AFB	AR	34.9	92.2	49.8	1.3	Calculated
AFP 44 - Tucson	AZ	32.2	110.9	12	> 5.0	Figure 5
Davis-Monthan AFB	AZ	32.2	110.9	11.5	8.2	Calculated
Luke AFB	AZ	33.5	112.4	7.7	14.1	Calculated
Williams AFB	AZ	33.6	112.2	8	> 5.0	Figure 5
AFP 42 - Palmdale	CA	34.6	118.1	8	> 5.0	Figure 5
Beale AFB	CA	39.1	121.4	26.5	3.0	Calculated
Castle AFB	CA	37.4	121.4	12.6	6.7	Calculated
Edwards AFB	CA	34.9	117.9	8	> 5.0	Figure 5
George AFB	CA	34.5	117.3	5.3	17.5	Calculated
Los Angeles AFB	CA	33.9	118.4	14	> 2.5?	Figure 5
March AFB	CA	33.9	117.3	8	> 5.0	Figure 5
Mather AFB	CA	38.5	121.4	17	4.6	*Calc. Near*
McClellan AFB	CA	38.7	121.4	17.3	4.6	Calculated
Norton AFB	CA	34.2	117.3	16	> 5.0	Figure 5
Travis AFB	CA	38.3	121.9	28.8	2.8	Calculated
Vandenberg AFB	CA	34.7	120.6	14.4	4.5	Calculated
Air Force Academy	CO	39.0	104.9	12.8	5.3	Calculated
Lowry AFB	CO	39.7	104.9	12.8	5.3	Calculated
Peterson AFB	CO	38.8	104.7	15	5.3	*Calc. Near*
Schriever AFB	CO	38.8	104.5	15	> 2.5	Figure 5
Bolling AFB	DC	39.0	77.0	37.2	1.5	Calculated
Dover AFB	DE	39.1	75.5	37.4	1.4	Calculated
Cape Canaveral AS	FL	28.5	80.6	45	>= 1.0	Figure 5
Eglin AFB	FL	30.6	86.6	64	>= 1.0	Figure 5
Homestead AFB	FL	25.5	80.4	63.3	1.3	Calculated
Hurlburt Field	FL	30.5	86.5	65	>= 1.0	Figure 5
MacDill AFB	FL	27.8	83.5	52.4	1.5	Calculated

Installation	State	Lat.[1] Deg.	Long.[2] Deg.	Precip.[3] Inches	PET[4] RATIO	Estimated[5] from
Patrick AFB	FL	28.2	80.6	52.3	1.5	Calculated
Tyndall AFB	FL	30.2	85.6	55.4	1.3	Calculated
AFP 6 - Marietta	GA	33.9	84.5	54	>= 1.0	Figure 5
Dobbins ARB	GA	33.9	84.5	54	>= 1.0	Figure 5
Moody AFB	GA	31.0	83.2	48.0	1.5	Calculated
Robins AFB	GA	32.6	83.6	45.1	1.6	Calculated
Des Moines IA	IA	41.5	93.7	33	> 1.5	Figure 5
Sioux City IA	IA	42.4	96.4	26	> 1.5	Figure 5
Mountain Home AFB	ID	43.1	115.9	7.7	9.6	Calculated
Chanute AFB	IL	40.3	88.2	34.8	1.4	Calculated
O'Hare IAP	IL	41.8	88.0	34	>= 1.0	Figure 5
Scott AFB	IL	38.5	89.9	32.5	1.9	Calculated
Grissom ARB	IN	40.6	86.2	39	> 1.0	Figure 5
McConnell AFB	KS	38.6	97.3	29.3	2.4	Calculated
Barksdale AFB	LA	32.5	93.6	46.1	1.5	Calculated
England AFB	LA	31.3	92.5	58	>=1.0	Figure 5
Hanscom AFB	MA	42.5	71.3	45	>= 1.0	Figure 5
Otis ANGB	MA	41.7	70.5	46	>=1.0?	Figure 5
Westover ARB	MA	42.2	72.6	44	>= 1.0	Figure 5
Andrews AFB	MD	38.8	76.8	37	1.5	*Calc. Near*
Loring AFB	ME	46.9	67.9	36.8	1.0	Calculated
K. I. Sawyer AFB	MI	47.3	88.3	37	>= 1.0	Figure 5
Phelps-Collins ANGB	MI	45.1	83.5	29	>= 1.5	Figure 5
Selfridge ANGB	MI	42.6	82.8	30	>= 1.0	Figure 5
Wurtsmith AFB	MI	44.5	83.4	28.3	1.5	Calculated
Duluth ANGB	MN	46.8	92.2	31	> 1.5	Figure 5
Minn-St Paul IAP	MN	44.9	93.2	27	> 1.5	Figure 5

Installation	State	Lat.[1] Deg.	Long.[2] Deg.	Precip.[3] Inches	PET[4] RATIO	Estimated[5] from
Richards-Gebaur AFB	MO	38.8	94.1	39	> 1.5	Figure 5
Whiteman AFB	MO	38.7	93.6	33.9	1.8	Calculated
Columbus AFB	MS	33.6	88.4	54.1	1.2	Calculated
Keesler AFB	MS	30.4	88.9	69.3	0.9	Calculated
Malmstrom AFB	MT	47.5	111.2	15.4	3.3	Calculated
Pope AFB	NC	79.0	35.2	48.0	1.3	Calculated
Seymour Johnson AFB	NC	35.3	78.0	47.7	1.3	Calculated
Grand Forks AFB	ND	47.9	97.4	19.1	2.5	Calculated
Minot AFB	ND	48.4	101.3	15.7	3.3	Calculated
Offutt AFB	NE	42.1	95.9	30.9	1.8	Calculated
Pease ANGB	NH	70.8	43.8	43	>=1.0?	Figure 5
McGuire AFB	NJ	40.0	74.6	46.4	1.1	Calculated
Cannon AFB	NM	34.4	103.3	15.0	5.5	Calculated
Holloman AFB	NM	32.8	106.1	10.7	8.5	Calculated
Kirtland AFB	NM	35.0	106.6	8.8	8.8	Calculated
Nellis AFB	NV	36.2	115.0	4.1	21.5	Calculated
Griffis AFB	NY	43.3	75.5	46	> 1.0	Figure 5
Niagara Falls IAP	NY	43.1	78.9	39	>= 1.0	Figure 5
Plattsburgh AFB	NY	45.8	73.4	32.5	1.4	Calculated
Gentile AS	OH	39.8	84.2	39	>= 1.0	Figure 5
Wright-Patterson AFB	OH	39.8	84.1	39.1	1.4	Calculated
AFP 3 - Tulsa	OK	36.2	95.9	39	>= 1.5	Figure 5
Altus AFB	OK	34.7	99.3	24.6	3.1	Calculated
Tinker AFB	OK	35.4	97.4	31.9	2.2	Calculated
Vance AFB	OK	36.4	97.9	25.9	2.8	Calculated
Kingsley Field	OR	42.1	121.7	13	>=2.5	Figure 5

Installation	State	Lat.[1] Deg.	Long.[2] Deg.	Precip.[3] Inches	PET[4] RATIO	Estimated[5] from
Pittsburgh IA ARS	PA	40.5	80.2	34	>= 1.0	Figure 5
Charleston AFB	SC	32.8	80.0	48.3	1.4	Calculated
McEntire AFB	SC	34.0	81.0	48	>= 1.0	Figure 5
Myrtle Beach AFB	SC	33.7	78.9	50	>= 1.0	Figure 5
Shaw AFB	SC	34.0	80.5	46.8	1.4	Calculated
Ellsworth AFB	SD	44.1	103.1	19.5	3.0	Calculated
Arnold AFB	TN	35.4	86.1	54.2	1.1	Calculated
AFP 4 - Ft Worth	TX	32.8	97.3	32	>= 1.5	Figure 5
Bergstrom AFB	TX	30.3	97.8	32	2.5	Figure 5
Brooks AFB	TX	29.3	98.4	28.7	2.7	Calculated
Carswell AFB	TX	32.8	97.3	32	> 1.5	Figure 5
Dyess AFB	TX	32.4	99.8	23.1	3.3	Calculated
Goodfellow AFB	TX	31.4	100.4	18.2	4.6	Calculated
Kelly AFB	TX	29.4	98.6	29	2.7	*Calc. Near*
Lackland AFB	TX	29.4	98.6	29	2.7	*Calc. Near*
Laughlin AFB	TX	29.4	100.8	16.9	5.2	Calculated
Randolph AFB	TX	29.5	98.3	29	2.7	*Calc. Near*
Reese AFB	TX	33.6	101.9	18.8	4.4	Calculated
Sheppard AFB	TX	34.0	98.5	28.5	2.7	Calculated
Hill AFB	UT	41.1	112.0	19.9	3.2	Calculated
Langley AFB	VA	37.1	76.3	41.3	1.5	Calculated
Fairchild AFB	WA	47.6	117.7	16.5	3.2	Calculated
McChord AFB	WA	47.1	122.5	40.9	1.3	Calculated
Volk Field	WI	43.9	90.3	32	> 1.5	Figure 5
F. E. Warren AFB	WY	41.2	105.9	13	> 2.5	Figure 5

[1] Lat–North Latitude

[2] Long–West Longitude

[3] Precip–Average annual precipitation from database used for PET estimates or from Hauser et al. (1999b).

[4] PET Ratio–Ratio of annual PET/annual precipitation.

[5] Estimated from–PET Ratio derived from an estimate for the site, interpolated from Figure 5, or calculated at a nearby base with similar climate.

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