# ANALYZING PLANT ROOT – CAPILLARY FRINGE INTERACTIONS FOR IMPROVED GROUNDWATER MANAGEMENT

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# ABSTRACT

The plant wilting point is generally believed to occur at a matric potential value of -1500 kPa for all plant species in all environments. In this study, I strive to illustrate how varied the plant wilting point can actually be and to show how using a constant value for all species may be a source of error. Matric potential values are determined through the use of the van Genuchten soil water characteristic curves, where each soil has its own curve. Additionally, the maximum depth of the groundwater table was studied. The maximum depth was determined based on the rooting depth of the plant species and the height of the capillary fringe water at the plant wilting point. Since no acceptable calculation for capillary fringe height at plant wilting could be found in the literature, my own technique is presented here. It involves the use of the capillary height equation presented by El-Kadi and Ling, which was taken as the maximum height of the capillary fringe in a soil. Then, a relationship between the volumetric water content at the plant wilting point and the capillary fringe height was developed and employed. Summing the rooting depth and the capillary fringe height resulted in the maximum depth of the groundwater table.

Data was collected through a literature review and was categorized based on twelve soil types, four ecoregions, and three vegetation classes. These categories allowed me to identify patterns within subsets of data points. Based on these patterns, guidance tables for managing the groundwater table depth are presented.

# BIOGRAPHICAL SKETCH

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# CHAPTER 1: INTRODUCTION

The Fourth Assessment Report from the IPCC stated that three primary factors of climate change will affect freshwater resources through their impacts on the hydrologic cycle: higher temperatures, rising sea levels, and increased precipitation variability [1]. One component of the hydrologic cycle that has not been thoroughly investigated with the onset of climate change is groundwater [1-4]. Some studies have shown that groundwater levels are correlated with precipitation more than with temperature [1], and increased variability in precipitation can affect groundwater levels. In a study of a Belgian aquifer, a climate change model demonstrated that the groundwater level would decrease over time [5]. In the study of the Grand Forks aquifer, variations in river-stage elevation in the basin were shown to have a more significant effect on groundwater levels than variations in recharge, though both river-stage variations and recharge variations were products of climate change scenarios [3]. Hsu, et al. [6] conducted a study in Taiwan showing that the groundwater level will drop by 3m before 2022 based on a linear regression model of precipitation. While these studies demonstrate the likelihood of groundwater levels dropping in the future, the relationship between groundwater levels and climate change is still quite unclear. In fact, human influences seriously impact groundwater availability both directly through overdraft and indirectly through land use that reduce infiltration. Given the limited extent of data on groundwater table dynamics, it will be difficult to distinguish between human and climate influences on groundwater levels [7].

Additionally, the human pressures on groundwater resources are expected to increase, both due to increasing population demands and also due to the decreasing reliability of other freshwater sources [1]. Many regions currently overdraft from their groundwater supplies in order to meet demand, thereby lowering the groundwater table. This overdraft is having serious impacts on surface ecosystems. It is becoming recognized that groundwater overdraft is not a sustainable practice, especially considering the variable climate of the future.

Regions that are affected by these factors will need to analyze their options for managing groundwater levels. As Green et al. [8] point out, “human systems of resource management and governmental policies must be considered” (pg 531) in order to effectively maintain the groundwater resource. The literature provides several methodologies and management strategies for general [9] and specific issues [4]. Harou and Lund [10] provide suggestions on how to stop overdrafts. Most of these recommendations are focused on sustained management to meet human needs, and do not usually consider the simultaneous impacts on natural ecosystems.

Although invisible, groundwater is essential to both terrestrial and aquatic ecosystems in several ways. In one study of the American southwest [11], four impacts of groundwater overdraft were reported: “reduction of streamflow and lake levels, reduction or elimination of vegetation, land subsidence, [and] seawater intrusion” (pg 397). Discharging groundwater contributes to baseflow in all streams, and therefore can be a major component of streamflow. Groundwater helps maintain saturated soil water that is key to wetland health and functioning. Beneath the soils, there are endemic, obligate groundwater communities of organisms, including microscopic and cavedwelling [12]. Groundwater prevents surface subsidence [13]. Finally, groundwater is actually the saturated downward end of a gradient in soil moisture that wicks upward, thereby contributing to surface soil water availability for all plants.

Perhaps the most overlooked of this list are the potential impacts of declining groundwater levels on surface plant communities, both natural and crops. When precipitation has been lacking, the surface soils sequentially dry out to deeper and deeper depths. Plants cannot rely on soil water storage and must instead turn to deeper soil layers or go to groundwater itself if they have the mechanism to do so. Jasper, et al. [14] mention the connection between the groundwater table and the rooting zone. They also discuss that "soil moisture deficit is often the most important stress factor for vegetation" (pg 551). With climate change, varying precipitation and increased evapotranspiration will lead to less reliable soil water storage, which can have grave impacts on plant life.

Periods of drought are of particular concern to plant communities. Here, a drought is defined as any prolonged period of time where a dearth of precipitation allows for the top soil to dry out. In this way, the top soil is then unable to supply plants with the water they need to survive. Veihmeyer and Hendrickson [15] agreed with this outcome when they said that soil moisture becomes a constraint on plant viability when water is not supplied to the roots at an adequate rate. Plants must be able to access enough groundwater in order to sustain life during drought periods. As Naumburg, et al. [16] pointed out: "It is widely recognized that a decrease in groundwater depth can be detrimental to vegetation if the change separates roots from their water source" (pg 727). Now, considering the impacts of climate change, it may become more challenging for plants to access groundwater.

Unlike natural ecosystems, crops receive supplemental irrigation waters to maintain high yields. However, in a water-stressed world, it will be vital for farmers to be wary of their use of water and understand how much water stress their crops can resist. Veihmeyer and Hendrickson studied the growth of many different crop trees in a variety of water-stressed soils. They have documented that insufficient water decreases the growth rate of fruit [17]. These lower growth rates in turn led to smaller fruit by volume, which is a fundamental quality of crop value. Davis [18] noticed similar issues in his study of corn. It has been estimated that irrigation accounts for

70% of all water use worldwide [19]. However, where irrigation resources are limited, plant dependence on soil moisture, and access to groundwater supplies between rainfalls, will be very important. It will be necessary to ensure groundwater levels do not drop below a depth where plants can access it.

Groundwater generally refers to the region below the ground surface where soil pore spaces are saturated with water. However, a more in-depth examination of groundwater is relevant here. The groundwater table is defined as the level in the soil where the water pressure is zero. The soil is saturated with water below this level. The region above the groundwater table extending up to the surface is called the vadose zone. Within this zone, the capillary fringe extends upwards from the groundwater table. In this region, capillary forces created by soil grains effectively pull water up from the groundwater table and suction forces hold the water in place. These capillary forces increase in strength as the height increases upwards from the groundwater table.

There are different ways to define the extent of the capillary fringe above the groundwater table. Brutsaert [20] defines the capillary fringe to be “the zone above the water table, where the water content is near saturation” (pg 255). Gillham [21] agrees with this definition. Nielsen [22] defines the capillary fringe as “the zone of variable moisture above the watertable” (pg 503), which implies the inclusion of the region where water content is below saturated but water content due to capillary rise is still greater than zero. These definitions are very general, the term “near saturation” is logistically imprecise, and therefore it is difficult to determine the precise height of the zone. They are not quantitative nor do they account for extreme variability in actual amount of water that can be present. However, the actual depth or thickness of the capillary fringe is highly variable and controlled primarily by the soil pore sizes which in turn are dependent on the grain size distribution of the soil. Soils have been grouped into their typical categories based on the average grain size: e.g., sand, loamy sand, sandy loam, loam, silt, silt loam, sandy clay loam, clay loam, silty clay loam, silty clay, clay loam, and clay.  These soil definitions are based on the classifications in the soil texture triangle [23].  The capillary fringe thickness is thin, less than 1-2 cm for sand, which has large soil particles and large pore spaces; it can extend for several meters in clayey soils, which have small soil particles and small pore spaces [24].

The capillary fringe can be of major importance to plants.  Roots uptake water from pore spaces between soil particles.  Suction forces in the soil dictate how much force a plant needs to apply to uptake the water.  Plants must overcome the suction forces in the soil that are holding the water in place in order to uptake water necessary for their survival.  If the capillary fringe extends into the zone of interaction with plant roots, its presence can provide critical water resources necessary for the survival of plants during periods of no rainfall.  Therefore, more thorough analysis of the capillary fringe is needed, specifically as it relates to plant water availability and plant capacity to access this tightly held water.

The maximum suction that a plant can apply to obtain the soil water has been called the “wilting point pressure”.  Any water stored at a more severe suction value than this is not accessible to the plant.  If this is the only water available in the soil, then the plant will begin to wilt, hence the label “wilting point”.  Plant wilting points can thus be directly linked to the extent and characteristics of the capillary fringe in any given soil.  This research strove to identify the wilting point suction value for groups of species and how these related to the maximum height of the capillary fringe for a given soil type.

The study of the permanent wilting point from a soil water perspective originated with four key researchers: Briggs, Shantz, Veihmeyer, and Hendrickson.  Together they either wrote or were cited in most of the early papers on plant permanent wilting point. The paper most frequently referenced is Briggs and Shantz's paper entitled "The Wilting Coefficient and its Indirect Determination" [25]. Their term "wilting coefficient" was used to describe the initial wilting stage experienced by a plant which, when put in a moist chamber, could not recover. Veihmeyer and Hendrickson called this same stage the permanent wilting percentage [26]. In another study conducted by Briggs and Shantz entitled "The Relative Wilting Coefficients for Different Plants" [27], they noted that "different groups of plants differ widely in their ability to reduce the moisture content of a given soil" (pg 229). They deduced that this could be explained by different plants' needs to withstand drought conditions, and they took over 1300 observations to test their hypothesis. However, their conclusion was that "the variation exhibited by different plants is much less than has heretofore been supposed, and that it is insignificant compared with the range in moisture retentiveness exhibited by different soils" (pg 230). Veihmeyer and Hendrickson [26] explained these results concisely by saying "the permanent wilting percentage was found to be a characteristic of the soil and not of the plant" (pg 78). Veihmeyer endorsed the work of Briggs and Shantz and applied it to a variety of plant species, mostly crops. Many others also believed that the permanent wilting percentage was a function of the soil type and not a function of plant species [28-32].

Furr and Reeve [33] provided another set of commonly cited definitions of plant wilting. According to them, the Briggs and Shantz term "wilting coefficient" and the Veihmeyer and Hendrickson term "wilting point" correspond to a low soil moisture content at the stage of wilting where plants cease to grow. Furr and Reeve defined this same soil water content as the first permanent wilting point. At water contents below this first permanent wilting point, they believed that plants could continue to uptake water from the soil, just at a slower rate. The key for their definitions was in the rate of water uptake to the plant. In fact, the range extending from the first permanent wilting point to a zero rate of water uptake was termed the wilting range. This rate of zero water uptake by the plant was called the ultimate wilting point. At the first permanent wilting point the plant leaves begin to wilt. By the ultimate wilting point, all of the leaves on the plant are wilted. All of the wilting in the wilting range is permanent. “In this paper wilting is called permanent wilting if turgor is not regained by the uninjured leaves when the plant is kept in an approximately saturated atmosphere in a dark humid chamber for 14 to 16 hours” (pg 149-150, Furr and Reeve, 1945). This is very similar to how Briggs, Shantz, Veihmeyer, and Hendrickson tested for permanent wilting percentage. Thus, it can be safely said that the term “first permanent wilting point” is equivalent to the term “permanent wilting percentage”.

For decades it has been generally accepted that the permanent wilting point is at a soil moisture pressure value of –1500 kPa for all plants. This is illustrated by much of the published literature which assumes this value to be true regardless of which plant species is being studied [34-36]. The value has seldom been questioned. However, it is logical that plants can differ greatly in their tolerance to drought and have numerous different adaptations to allow them to overcome periods of low water availability. These strategies include deep rooting depths to access deep groundwater, high tissue salt contents which maximize an osmotic balance that favors water uptake at low water potentials, and different actual wilting points, among others.

In this research I want to go back and reanalyze these results. It is true that soil type does have a significant role in determining the plant permanent wilting point. However, I believe that the plant variation within each soil type is not as insignificant as the original scientists thought. I want to restore the belief that significant variation exists between plant species and encourage scientists to return to examining this plant characteristic.

Several studies agree with the assessment that the permanent wilting point is not -1500 kPa for all plants and does not depend on soil type alone. Slatyer [37] said “the permanent wilting percentage is a value determined not by any particular soil characteristic but by the osmotic characteristics of the plants under study, and as a result could vary considerably from plant to plant” (pg 321). Sykes [38] said “It is obvious that the conclusion of Briggs and Shantz (3), that a permanent wilting point for all soils and all plants occurs at a soil moisture tension of approximately 15 atm., is unjustified. Biologists generally believe, however, that the 15-atm. tension gives a valid estimate of unavailable soil moisture, and this belief is supported by results with many of the better agricultural soils. The fact that the permanent wilting point deviates from the norm with some plants and some soils merely increases the need for a better understanding of this important plant-soil relationship” (pg 164). This research strove to describe the significance of this relationship and identify patterns amongst groups of species. The error made by Briggs, Shantz, Veihmeyer, and Hendrickson was explained by Moore [39]: “In contrast to agronomic species which thrive where the soil water potential is normally above -15 to -20 bars, most desert species must be able to endure and grow in soils where the water potential ($\psi_s$) is seldom that high . . . several halophytic species of Israel were able to grow at soil water potentials of -35 to -50 bars” (pg 2412). All of the work done on the investigation of permanent wilting point by Briggs, Shantz, Veihmeyer, and Hendrickson involved crop (agronomic) plant species. Moore’s analysis helps to explains why Briggs, Shantz, Veihmeyer, and Hendrickson found that the permanent wilting point did not vary between species: they only tested crop species which could not provide an accurate depiction of the value for all plant species. In fact, since they believed that the permanent wilting point was a characteristic of the soil, Veihmeyer and Hendrickson conducted most of their experiments on sunflowers, which they used as the indicator plant for the determination of the permanent wilting percentage of various soils.  However, now it is clear that this strategy led to false conclusions about the permanent wilting point, and I worked towards correcting this misunderstanding.

For plants, the groundwater table and the height of the capillary fringe become even more significant considering climate change.  Both plant rooting depth and soil type are factors in determining a plant's continuing ability to uptake water from the soil.  In order to prevent plant death and ecosystem degradation the maximum depth of the groundwater table in an ecosystem should be identified so that water managers can ensure the sustainability of the ecosystem.

As noted previously, the study of the impacts of climate change on groundwater is increasing, as is the study of management strategies for managing water resources in climate change.  However, the literature fails to discuss how plants can cope with the drought extremes anticipated with climate change.  Since the effects are unknown, there is also no literature describing the best management strategies for maintaining plant life considering climate change.

# CHAPTER 2: OBJECTIVES

The overall goal of this project is to develop an appropriate, logical tool for improving the groundwater management that takes into account the relationship between plant wilting points and rooting depths as they relate to the capillary fringe and water table depth in order to help water professionals more sustainably manage their groundwater aquifers. Plant wilting point information can be used to determine the maximum height of the capillary fringe from which a plant can access water. Combining this data with the plant rooting depth results in the maximum sustainable depth of the groundwater table for that plant species' survival. More specific objectives are to:

a) use a review of the literature to identify actual, experimentally-determined-wilting points and rooting depths for individual plant species;
b) translate the literature wilting values into matric potential pressures for plant species;
c) use equations to calculate the capillary fringe thickness in specific soils as a basis for maximum depth to the groundwater table;
d) synthesize the results into a set of recommendations for groundwater managers to guide safe water yield that sustainably supports natural and crop vegetation;
e) develop guidance tools for managing the maximum groundwater table depth.

# CHAPTER 3: METHODS

The maximum sustainable depth of the groundwater table is calculated by adding the rooting depth of a plant to the wilting point height of the capillary fringe for a given soil type. The rooting depth is a function of plant type, and plants have been grouped into three categories: grasses, herbs and forbs, and trees and shrubs. The wilting point height is a combined function of both soil type and plant species, and could be identified from literature-based studies. While the determination of rooting depth is straight-forward, the determination of wilting point height of the capillary fringe is a bit more complicated.

An extensive literature review was conducted to determine how much this issue had been studied in the past. Since there was no literature directly available on the issue of how plants access capillary fringe water, related literatures searches were conducted on plant wilting, plant growth in soils, and plant water relationships.

## *Vegetation Types*

For the purposes of analysis, the plant species were each assigned to a vegetation category. These categories were: grasses, forbs and herbaceous plants, trees and shrubs. Trees and shrubs were grouped together because they have similar rooting depths and the literature is too sparse to subset woody plants. Each species was categorized based on the growth habitat definitions of the USDA [40]. The growth habitat of each species was identified by entering the scientific name into the Plants Database search engine [41]. The resulting webpage described the plant species including its growth habitat. The USDA classifies ten categories of growth habitats, though only six were relevant to this work. Plants classified as forb/herb by the USDA were given the same classification in this work. Those classified as graminoids were called grasses in this study. Plants classified as shrubs, subshrubs, and trees fell into the tree/shrub category. Those classified as vines were called herbaceous plants in this study. In this way, the USDA provided a reliable technique for identifying plant species vegetation types, which were then classified according to the needs of this study.

### ***Ecoregions***

In addition to separating plant species by vegetation type, the species were also split according to ecoregions. The ecoregions included in this study were all temperate biomes that can be found in the contiguous United States. They were: crops, deserts, grasslands, and forests. Obviously, deserts, grasslands, and forests have very different climates and precipitation patterns. As a result, it is logical that plants living in these various ecoregions have developed their own adaptive strategies for surviving in that ecoregion considering the climate and precipitation there. Therefore, separating species based on these ecoregions helped identify patterns within each ecoregion. Crops tend to be irrigated, and therefore can rely on top-soil moisture on a more regular basis than other plants in natural areas. Thus, their roots may not need to extend as far into the soil since, typically, sufficient water can reliably be attained at the surface. Desert plants tend to have much deeper rooting systems. Top-soil moisture is very limited due to the general lack of precipitation in desert climates. Instead, desert species must rely on deeper soil moistures. Grasslands and forests are each known for certain vegetation types of species which are results of their climates. It is only in periods of drought relative to each ecoregion where the maximum rooting depth of the plant and its limitations on suction are relevant. Considering the anticipated increases in precipitation variability with climate change, it was these drought periods I wished to study.

### *Capillary Suction*

Capillary action occurs in soils resulting in water being pulled upwards from the groundwater table. This is the force that creates the capillary fringe. The resulting pressure is related to a height by dividing by the density of water and by the force of gravity. This height is referred to as suction and units are in meters.

$$\rho_w \phi_m = matric\ potential\ pressure\ (Pa)$$

$$\phi_m = matric\ potential\ (\frac{J}{kg})$$

$$\psi_m = \frac{\phi_m}{g} = matric\ head\ (-m)$$

$$-\psi_m = suction\ (m)$$

These relationships are key to the understanding of soil and water interactions. They explain the relationships between different representations of soil water pressure. It should be noted that this suction height does not correlate exactly with the capillary fringe height. As pointed out by Al-Samahiji [42], the assumption that suction height is the same as the height of the capillary fringe is only accurate for saturations of 85% or more.

This is an interesting point because many of the suggested modeling techniques for understanding capillary action describe treating the soil capillary like a cylindrical tube. In the case of a cylindrical tube the suction pressure height does exactly correlate with the capillary fringe height. However, in soils, the pore spaces cannot accurately be represented by a cylindrical tube. There are other forces employed in holding the water in place, and factors such the angle of pore spaces also play a significant role in determining the pressure experienced by the soil water [24, 43]. Thus, understanding the capillary suction pressure does not imply understanding the capillary fringe height.

Since this research focuses on plant wilting points, this concept is particularly relevant. At severe water stress, plants experience relatively lower water contents and higher matric potentials in the soil surrounding their roots. Typically, these water contents correlate to saturations of less than 85%. Thus, the cylindrical tube suction height technique cannot be applied to my data points and another technique had to be identified.

### ***Soil Water Characteristic Curves***

One of the key components to determining the capillary fringe and the associated wilting point was the use of soil water characteristic (SWC) curves. These curves relate soil water content to pressure experienced by the soil and are important because almost all research on wilting points report it as a function of the soil water content. However, the curves are soil dependent, and each soil type has its own curve. There are numerous techniques for establishing this relationship [24], but the three most common techniques are van Genutchen (VG) [44], Brooks-Corey (BC) [45], and Rawls [46].

The van Genutchen [44] technique uses an empirical model relating the volumetric water content in a soil to a suction height. Soil properties including residual volumetric water content and saturated volumetric water content are the key parameters in the van Genuchten equation. The reason each soil has its own curve stems from soil particle sizes. Larger soil particles have larger pores. Capillary forces are most effective in thin columns. Therefore, small soil particles allow for greater suctions than do large soil particles. Considerable research has been developed using the van Genuchten curve formulas and their underlying mathematical assumptions. For example, Elmaloglou and Diamantopoulos [47] used the van Genuchten model to represent the SWC curves in their mathematical model of subsurface drip irrigation in an agricultural setting. Wang and Cai [48] used the van Genuchten curves to calibrate their SWAP model. Yadav et al [49] used the van Genuchten SWC curve formulas to represent soil water dynamics in their study of root water uptake by plants. The formula is as follows:

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} = dimensionless\ water\ content$$

$$\frac{1}{\alpha}\left(\Theta^{-1/m} - 1\right)^{1/n} = suction$$

where

$$\theta = volumetric\ water\ content$$

$$\theta_r = residual\ volumetric\ water\ content$$

$$\theta_s = saturated\ volumetric\ water\ content$$

$$m = 1 - \frac{1}{n}$$

$$n, \alpha = soil\ parameters$$

Table 1. Carsel Parameters for the van Genuchten Soil Water Characteristic Curves

| Soil type | N | $\theta_r$ | $\theta_s$ | $\alpha$ | n |
|---|---|---|---|---|---|
| Clay | 400 | 0.068 | 0.38 | 0.008 | 1.09 |
| Clay loam | 364 | 0.095 | 0.41 | 0.019 | 1.31 |
| Loam | 735 | 0.078 | 0.43 | 0.036 | 1.56 |
| Loamy sand | 315 | 0.057 | 0.41 | 0.124 | 2.28 |
| Silt | 82 | 0.034 | 0.46 | 0.016 | 1.37 |
| Silt loam | 1093 | 0.067 | 0.45 | 0.020 | 1.41 |
| Silty clay | 374 | 0.070 | 0.36 | 0.005 | 1.09 |
| Silty clay loam | 641 | 0.089 | 0.43 | 0.010 | 1.23 |
| Sand | 246 | 0.045 | 0.43 | 0.145 | 2.68 |
| Sandy clay | 46 | 0.1 | 0.38 | 0.027 | 1.23 |
| Sandy clay loam | 214 | 0.100 | 0.39 | 0.059 | 1.48 |
| Sandy loam | 1183 | 0.065 | 0.41 | 0.075 | 1.89 |

In order to use the VG method, the soil must first be classified into one of the 12 soil types as defined by the soil texture triangle. Once the soil type is known, the relationship between volumetric water content and suction can be established. Parameters for the 12 soil types were provided by Carsel [50]. Other sources, such as Tuller [24], provided alternative parameters for the VG SWC curves. However, Carsel's parameters were based on a much more extensive set of data and were thus chosen to be the parameters employed in this research. These parameter values are presented in Table 1. (The parameter N stands for the number of soils tested.)

The Brooks-Corey [45] model relates effective saturation $S_e$ to the capillary pressure $P_c$. The effective saturation is equivalent to the dimensionless water content Θ in the VG method, and the capillary pressure is equivalent to the matric potential $\phi_m$ of the VG method. The parameters of the BC method are the bubbling pressure $P_b$ and the pore size distribution index λ. Both parameters are characteristics of the soil. The pore size distribution index prevents the need to classify a soil type into one of the 12 categories as the VG method requires. However, in turn it requires more knowledge of the soil makeup, which is rarely included in most plant studies. The equation is as follows:

$$S_e = \left(\frac{P_b}{P_c}\right) \lambda$$

One additional disadvantage with the BC method is that it generates a curve with a discontinuity at the air entry potential, which is essentially at soil saturation. Also, the pore size distribution index is an infrequently defined parameter in literature discussing plant water. Most literature sources concerned with plant water stress study plant reactions to water stress, such as decreasing transpiration. Frequently they did also mention the soil employed, and sometimes they even described the soil distribution. However, this is not sufficient information from which to calculate the pore size distribution required by the BC method.

A third common method was established by Rawls and Brakensiek [46]. Their formula determines the volumetric water content in the soil for a particular matric potential given soil information. Like the BC method, this technique requires extensive information about the soil beyond just the soil classification. This is exemplified by the equation itself:

$$O_x = a + b * sand(\%) + c * silt(\%) + d * clay(\%) + e * organic\ matter(\%) + f * bulk\ density(Mg/m^3) + g * water\ content\ (at - 33kPa) + h * (water\ content\ at - 1500\ kPa)$$

Coefficient values depend on the matric potential desired; these values can be found for several matric potentials in Rawls and Brakensiek [46]. Since coefficient values are only available for certain matric potentials, the shape of the entire SWC curve can at best be estimated between the points for the matric potentials given. Of significant concern when using this technique is that there are no coefficients given for matric potentials lower that -15 bars. As a result, there is no way to determine the shape of the curve at lower matric potentials. Since it is these matric potentials that I wanted to study, the use of this technique was infeasible. Therefore, despite this technique being frequently referenced, it could not even be considered as an option for the calculations required in this study.

For this study, the literature typically provided the soil type, but did not always provide detailed information regarding the soil beyond the type. Knowing the soil type was sufficient for determining which van Genuchten curve would be appropriate and for completing the required calculations. However, only knowing the soil type was not sufficient for determining the pore size distribution index, as required by the BC method, nor was it sufficient to account for all of the terms in the Rawls equation. As a result, the van Genuchten curves were more readily applicable to those data sources than the BC and Rawls methods were, and, thus, it was the method employed in this study.

### *Volumetric Water Content*

In general, the data related to the permanent wilting point found in the literature was presented in volumetric water content, gravimetric water content, or matric potentials; these were the three preferred unit forms. However, not all of the data was presented in this way. For such sources, further investigation into the analysis technique used in the study was required to translate the data into one of the preferred unit forms. Regardless of the initial form of the water content data, volumetric water content values were required for the methodology.

After volumetric water content, the second most common representation of soil water content was gravimetric water content. The conversion of gravimetric water content to volumetric water content was a function of the bulk density $\rho_b$ of the soil:

$$\theta = \frac{\rho_b}{\rho_w} * \ \omega$$

where

$$\rho_w = \ 1 \ g/cm^3 = density\ of\ water$$
$$\omega = gravimetric\ water\ content\ of\ the\ soil$$

Bulk density of a soil depended on the soil particles and the void ratio within the soil. The source used in this research was pedosphere.com [51]. The site provided a bulk density calculation table where percent sand, percent clay, and percent silt were the inputs. There was also an option to choose a point on the soil texture triangle; once chosen, the bulk density was printed as output next to the triangle. Since these calculations were based on the soil texture triangle and that was how the soils were classified in this research, it made sense to use pedosphere [51] to calculate the bulk densities. The bulk density for each soil type and the percentages of sand, silt, and clay used are listed in Table 2.

Table 2: Bulk Density of 12 Basic Soil Types Based on Textural Composition

| Soil type | % sand | % silt | % clay | Bulk density (g/cm$^3$) |
|---|---|---|---|---|
| Clay | 22.0 | 20.0 | 58.0 | 1.22 |
| Clay loam | 31.4 | 34.3 | 34.3 | 1.31 |
| Loam | 40.0 | 40.0 | 20.0 | 1.41 |
| Loamy sand | 86.0 | 4.0 | 10.0 | 1.60 |
| Silt | 7.0 | 85.0 | 8.0 | 1.48 |
| Silt loam | 20.0 | 65.0 | 15.0 | 1.41 |
| Silty clay | 7.0 | 46.0 | 47.0 | 1.22 |
| Silty clay loam | 10.0 | 55.0 | 35.0 | 1.27 |
| Sand | 90.0 | 5.0 | 5.0 | 1.71 |
| Sandy clay | 51.0 | 6.0 | 43.0 | 1.32 |
| Sandy clay loam | 60.0 | 13.0 | 27.0 | 1.40 |
| Sandy loam | 65.0 | 25.0 | 10.0 | 1.56 |

Extensive studies have been performed on soils. The results of these studies indicate some variance in bulk density values for each soil type. One source, Hausenbuiller [52], listed the bulk density values for several soil types, but did not provide a value for all 12 soil classification types. Hausenbuiller had six of the same soil types that the soil texture triangle and pedosphere [51] have classified. For all six of those soil types, the Hausenbuiller bulk density values differed by at least 9% from the pedosphere bulk density values. All of the Hausenbuiller bulk density values were less than the pedosphere values (see Appendix A for a comparison of values). A 9% difference in bulk density will lead to a corresponding difference in volumetric water content. However, when relating this difference to the soil water characteristic curve, the difference becomes much more pronounced since the portion of the curve employed in this research is where small changes in volumetric water content lead to large changes in suction and matric potential, as illustrated and explained in the following section. Clearly, quantifying the bulk density correctly is a significant component to this research and any future studies on the matter.

***Matric Potentials***

Once the volumetric water content and soil type had been identified, the van Genuchten soil water characteristic curves could be employed. An example of one such curve is presented in Figure 1 the VG SWC for silt. All of the VG SWC curves for the 12 soils are included in Appendix B. The straight vertical line on the left depicts the residual volumetric water content; the straight horizontal line represents the value of -1500 kPa, which is the generally accepted value of the permanent wilting point for all plant species. However, the line of interest is the curved, un-dashed line. This curve is the VG SWC for silt. It is through this relationship that the volumetric water content could be translated into a suction pressure height value. This suction height (m) was then converted to a matric potential pressure (Pa) value by multiplying

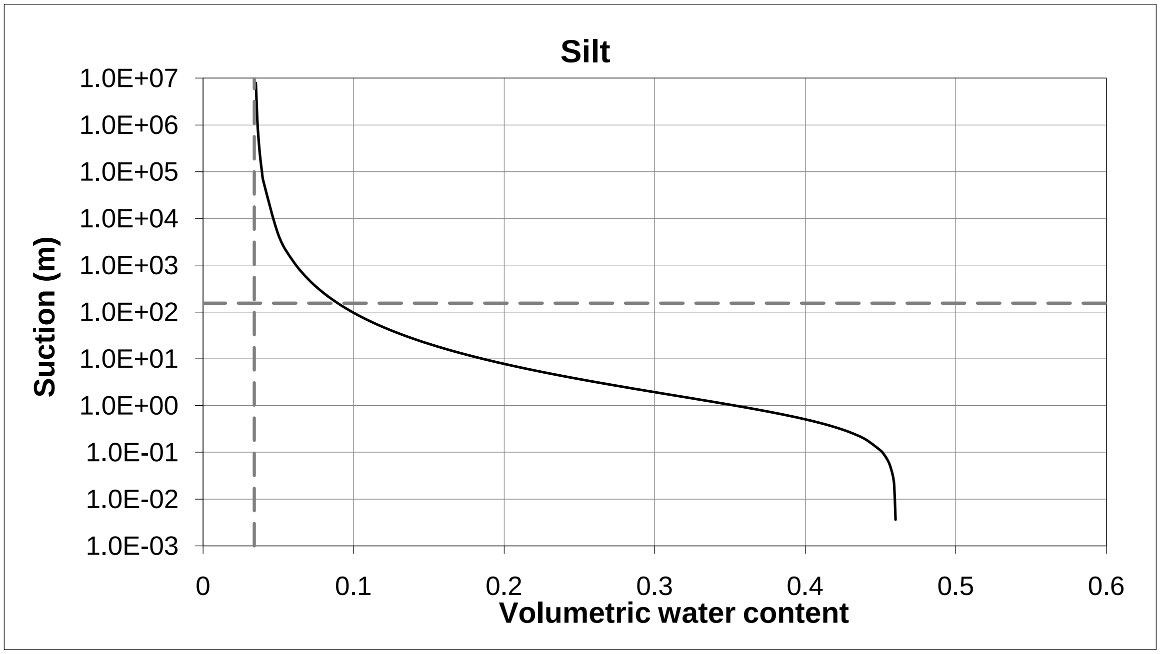


Figure 1. Example of a van Genuchten Soil Water Characteristic Curve

by $-1*g*\rho_w$. From this method I was able to determine the matric potential for literature sources that did not provide it, and this provided the results for the first calculation.

### *Capillary Fringe Heights*

Once the matric potentials were identified, the values could be used to assist in determining the capillary fringe height in the soil at the time of plant wilting. This is one of the two pieces of data needed to calculate the maximum groundwater table depth. Despite an extensive literature search, no acceptable relationship between matric potential and capillary fringe height was found. This lack of information was surprising and identifies a real need for future research. Instead, I was left to develop my own technique for calculating capillary fringe height.

The method deemed most appropriate was to find a relationship between volumetric water content and capillary fringe height for each soil. It has already been established that the volumetric water content can be related to matric potential through the SWC curves. Thus there was no need to force a relationship between the matric potential and the capillary fringe height when using the volumetric water content would be more straightforward.

Next, the type of relationship between volumetric water content and capillary fringe height needed to be determined. The relationship between volumetric water content and matric potential is exponential, as illustrated by the soil water characteristic curves. Also, it was clear from the literature search that the relationship between matric potential and capillary fringe height was not linear. Thus, it was decided that an exponential relationship would be most fitting.

In order to determine an exponential relationship, two data points on which to base the equations needed to be identified for each soil. Al-Samahiji et al. [42]

discussed how the equation for capillary height in a cylindrical tube was only accurate for saturation values of 85% of more. In other words, the suction height due to capillarity in a tube is equivalent to the suction height due to capillarity in a soil for saturations of 85% of more. The 85% saturation was converted into a volumetric water content for each soil. Then the SWC curve was used to determine the suction height, and this suction height was taken to be the capillary fringe height. This was used as the first data point.

The second data point was provided by the maximum capillary fringe height and the residual volumetric water content. It has been previously established that the residual volumetric water content is the point at which water in the soil is held in place by adhesion to soil particles, thereby being inaccessible to plants for water uptake. Also, it is clear that the maximum height of the capillary fringe is the greatest height to which the capillary fringe can extend in the soil; this maximum height is also the lowest water content experienced within the capillary fringe. Thus, these two pieces of information correlate to the same extreme, which is used here as the second of the two data points.

To determine the maximum capillary fringe heights I perused the literature to find sources that discussed capillary fringe heights in soil. I found several articles that grazed the issue of the capillary fringe and provided a height value, including Gillham [21], White et al. [53], and Aubertin et al [54] among others. A list of these reference capillary fringe heights can be found in Appendix C. One such source stood out in particular: El-Kadi and Ling [55] provided a formula for calculating the height of the capillary fringe in different soil types.

$$H = \frac{\left[2^{1/m} - 1\right]^{1/n}}{\alpha}$$

Their formulation involved the same parameters used to create the van Genuchten soil water characteristic curves. Thus, this technique was the best option because it provided consistency in this calculation, and once again the Carsel parameter values were used. The resulting capillary fringe heights are shown in Table 3. I used these values to represent the maximum possible capillary fringe heights in soils.

Table 3. Capillary Fringe Heights Based on El-Kadi and Ling

| Soil type | Capillary fringe height (m) |
|---|---|
| Clay | 2764.38 |
| Clay loam | 4.72 |
| Loam | 0.87 |
| Loamy sand | 0.12 |
| Silt | 3.84 |
| Silt loam | 2.53 |
| Silty clay | 4423.01 |
| Silty clay loam | 19.95 |
| Sand | 0.09 |
| Sandy clay | 7.39 |
| Sandy clay loam | 0.66 |
| Sandy loam | 0.25 |

Thus, two data points were identified to establish the exponential relationship between volumetric water content and capillary fringe height for each soil. These data points are shown in Table 4. From these data points, graphs were generated in Excel and exponential trendlines were fit to the points. All 12 exponential relationships are shown in Table 5.

Once the calculations for capillary fringe heights were established, they were implemented for each of the plant wilting data points. Most of the plant wilting data points already had a volumetric water content associated with them since that is how the matric potentials were calculated using the SWC curves for many of the points. However, a few of the plant literature sources had simply given the matric potential.

In these cases, the SWC curves were used in the opposite direction to determine a volumetric water content based on the matric potential experienced in the soil.

Table 4. Two data points used to establish relationships between volumetric water content and capillary fringe height

| | x1 Theta 85% | y1 Suction 85% | x2 Theta r | y2 Max cf height |
|---|---|---|---|---|
| Clay | 0.3332 | 6.6251 | 0.068 | 2764.38 |
| Clay loam | 0.36275 | 0.5212 | 0.095 | 4.72 |
| Loam | 0.3772 | 0.1943 | 0.078 | 0.87 |
| Loamy sand | 0.35705 | 0.0500 | 0.057 | 0.12 |
| Silt | 0.3961 | 0.5433 | 0.034 | 3.84 |
| Silt loam | 0.39255 | 0.4072 | 0.067 | 2.53 |
| Silty clay | 0.3165 | 10.6001 | 0.070 | 4423.01 |
| Silty clay loam | 0.37885 | 1.3030 | 0.089 | 19.95 |
| Sand | 0.37225 | 0.0438 | 0.045 | 0.09 |
| Sandy clay | 0.338 | 0.4826 | 0.100 | 7.39 |
| Sandy clay loam | 0.3465 | 0.1268 | 0.100 | 0.66 |
| Sandy loam | 0.35825 | 0.0834 | 0.065 | 0.25 |

Table 5. Exponential relationships between volumetric water content and capillary fringe height

| Soil type | Exponential relationship |
|---|---|
| Clay | $y = 12987e^{-22.75x}$ |
| Clay loam | $y = 10.315e^{-8.229x}$ |
| Loam | $y = 1.286e^{-5.01x}$ |
| Loamy sand | $y = 0.1417e^{-2.92x}$ |
| Silt | $y = 4.614e^{-5.401x}$ |
| Silt loam | $y = 3.6845e^{-5.611x}$ |
| Silty clay | $y = 24539e^{-24.48x}$ |
| Silty clay loam | $y = 46.111e^{-9.414x}$ |
| Sand | $y = 0.0994e^{-2.202x}$ |
| Sandy clay | $y = 23.258e^{-11.47x}$ |
| Sandy clay loam | $y = 1.289e^{-6.694x}$ |
| Sandy loam | $y = 0.3189e^{-3.743x}$ |

***Rooting Depth***

Roots are commonly grouped into two categories: vertical roots and lateral roots. These two groups serve different functions for the plant. Vertical roots include tap roots which reach straight down below the plant deep into the soil to access deeper water sources. Lateral roots, on the other hand, spread out horizontally around the plant to access water in the top layers of the soil. In periods of drought, lateral roots are only minimally effective as the water in the top layers of the soil has typically dried out. As a result, for the purposes of this research, my interest was in the deepest rooting depth of the plant, and thus in the depth of the tap roots. The rooting depth of a plant species is the second component needed for determining the depth of the groundwater table.

Two extensive, recent reviews on plant roots provided a solid basis for the root depth information and were supplemented with individual research reports. Canadell, et al. [56] provided rooting depths for a broad diversity of plant species in a variety of biomes. For this study, only temperate biomes were considered. For simplification to the needs of this study, these plants were classified into one of the three vegetation types. Classifications were based on the USDA Plant Database Growth Habit definitions. Rooting depths of plants with the same classification type and from the same biome were averaged based solely on Canadell's work. The results of these averages are shown in Table 6.

Table 6. Rooting depth by species type in each of the major ecoregions found in the co-terminus U.S. (average depth is reported in meters).

| | Vegetation class | | |
|---|---|---|---|
| Ecoregion | Grass | Herb/Forb | Tree/Shrub |
| Crops | 1.8 | 2.3 | |
| Grasslands | 2.0 | 2.7 | 2.9 |
| Desert | 2.0 | | 9.9 |
| Forest | | | 3.3 |

Weaver [57-60] also provided a lot of information regarding rooting depths of different plant species. He tested several plants within the same species, and then found the rooting depth for the species. Whenever a range of depth values was provided for a given species, the lowest value in that range was taken to be the rooting depth of the species. This was done to make a conservative estimate of the rooting depth and a corresponding conservative estimate of the maximum groundwater table depth.

For determining the rooting depth for each data point, four different strategies were employed and prioritized based on the information available. First, if the literature source provided the rooting depth of the species, then that value was used in the calculation of the maximum groundwater table depth. Second, if the first option was not feasible, then both the Canadell and Weaver sources were checked to see if they provided rooting depth information for that species in the same ecoregion. Third, if the first two options weren't feasible, then the rooting depth for a species within the same genus and found in the same ecoregion was used as the representative rooting depth for the species; such information was found in the Canadell work. Lastly, if none of the other options worked, then the default value for the vegetation class and ecoregion presented in Table 6, based on the Canadell averages, was used as the rooting depth for the species.

In multiple studies, Weaver [58-59] pointed out that plant species rooting depth can vary by soil type. However, for the purposes of this study, this was assumed to not be the case. There is simply not enough information in the literature regarding rooting depth in various soil types for all of the species included in this study to make rooting depth variation by soil type a feasible addition in my calculations.

### ***Summary of Methodology***

Since the issue of plants accessing the capillary fringe has not been studied extensively in the past, there is no standard protocol for reporting information. Instead, the information relating soil water to plant wilting is represented in a variety of ways. The van Genuchten curves provide a crucial element in wilting point calculations. They translate volumetric water contents into suction heights for each specific soil. Therefore, when working with the literature data, values had to be converted into volumetric water content before the van Genuchten curves could be used. The resulting suction height was a representation of the pressure experienced by the water molecules held in place by soil particles. This was the pressure (aka the matric potential) that plant roots had to overcome in order to uptake that water from the soil.

After the matric potential values, the plant rooting depth was the next value of interest to be determined from literature sources. This value was required for the calculation of the maximum depth of the groundwater table. In addition to rooting depth, the height of the capillary fringe at the plant wilting point was also needed to calculate the maximum depth of the groundwater table. However, no literature source could provide a technique for determining this value. Instead, this paper presents a technique for calculating the capillary fringe height based on the wilting point pressure, which is described later.

Data was classified into different categories based on soil type, vegetation type, and ecoregion. Once sufficient data had been collected, the results were categorized to identify similarities with each group and to determine guidance values.

# CHAPTER 4: RESULTS

The calculations required for my analysis were to identify both the matric potential in the soil at plant wilting ($\phi_m$), and the maximum depth of the groundwater table. Matric potentials can be calculated from the suction pressure heights as described above. These suctions are determined based on the soil water characteristic curves using the volumetric water content. To calculate the maximum depth of the groundwater table, the capillary fringe height corresponding to the matric potential at wilting must be identified. This height is then added to the rooting depth of the plant species to identify the maximum depth of the groundwater table.

## ***Wilting Points***

A total of 127 data points were evaluated relative to plant species, rooting depth, and wilting point for different soil types. Research papers on wilting points were found to be one of three types. Many of the studies used the term “wilting point” or “permanent wilting point” as defined by Veihmeyer and Hendrickson. In fact, 57 of the 127 data points [15, 18, 26, 61-71] came from studies that tested for wilting and defined it as specified by Veihmeyer and Hendrickson. A second group of studies, 15 of the 127 data points used, employed Furr and Reeve’s definitions of wilting. Some of the literature sources in this group [37-38] used the term “first permanent wilting point”, which is the term that corresponds more directly with the Veihmeyer and Hendrickson term “permanent wilting point” that I chose to focus on in this study. The other paper in this group [72] used the Furr and Reeve’s term “ultimate wilting point”. Though this term does not correspond exactly with my chosen definition of plant wilting, I needed to use the data to augment my collection. The remaining 55 of the 127 data points did not use either the Veihmeyer and Hendrickson definitions or the Furr and Reeve definitions of plant wilting. Instead, wilting was inferred from the soil water content and plant condition data that were presented. Coleman [73] called it “pronounced leaf wilting”; Martin and Stephens [74] also looked at plants which had most of their leaves droop. Mueller-Dombois and Sims [75] and Barton and Teeri [76] worked with plants that died. From the Sperry and Hacke [77] and Kappen et al. [78] papers, I assumed the wilting point matric potential was that experienced by the plant at the end of the summer drought period. Ugolini [79] and Small [29] simply presented the wilting point of the soil, believing that the wilting point was defined by the soil alone and irrelevant of the plant species. The soil wilting point presented was assumed to be the wilting point of all of the trees in that soil. Gavande and Taylor [80] and Bahrani and Taylor [81] were more interested in plant transpiration. In these two cases, it was assumed that wilting took place at zero transpiration. Pallas et al. [82] discussed the wilting of the plant when it did not recover when put in a moist chamber. Of all of the papers in this group, this Pallas article came closest to the Veihmeyer and Hendrickson definition of plant permanent wilting point. However, it did not specify using the technique established by Veihmeyer and Hendrickson, and, therefore, it cannot be confirmed that the test was conducted in the same manner. In all of the cases in this third group, I assumed the data presented were at the wilting point for the plant in the specified soil. For the purposes of this study, I assumed that all of these wilting data points were all logistically equivalent.

The results from my analysis of wilting point matric potential are illustrated in Figures 2 and 3. Of the 127 wilting point matric potentials determined, 123 of them are presented in the figures. Four of the data points were excluded because they did not belong to temperate ecoregions, and therefore could not be used to assist in determining patterns within temperate ecoregions. Figure 2 separates the wilting matric potentials by ecoregion, while Figure 3 separates them by vegetation type.

Both figures distinguish between the matric potential values that were calculated using my method and the values that were provided by the literature. As shown, the provided matric potentials fall scattered throughout the values calculated using my method. This validates the spread of values observed through my method.

As shown in Figures 2 and 3, many species had wilting points much greater and much lower than the -1500 kPa value. Additionally, there are some general observations from Figures 2 and 3 that should be noted. Clearly, grassland and forest ecoregions tend to provide sufficient soil water for plant survival. The species from those two ecoregions are able to overcome less pressure when uptaking soil water than some of the species from the crop or desert ecoregions. Thus, the grassland and forest ecoregions must typically provide enough water for their sustenance on a regular basis. Conversely, the crop and desert species see a much wider range of wilting point matric potentials. This implies that many species within these categories are capable of withstanding more severe water stress than other species. They can continue to survive at lower soil water contents and can combat stronger capillary forces holding

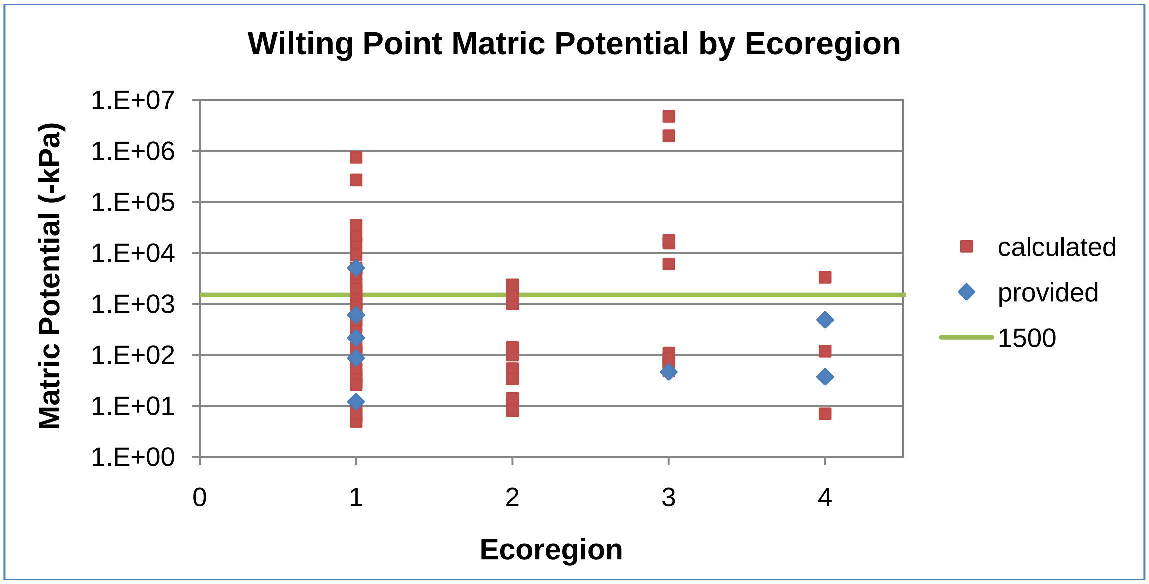


Figure 2. Wilting Point Matric Potential by Ecoregion
Ecoregions: 1=crop, 2=grassland, 3=desert, 4=forest

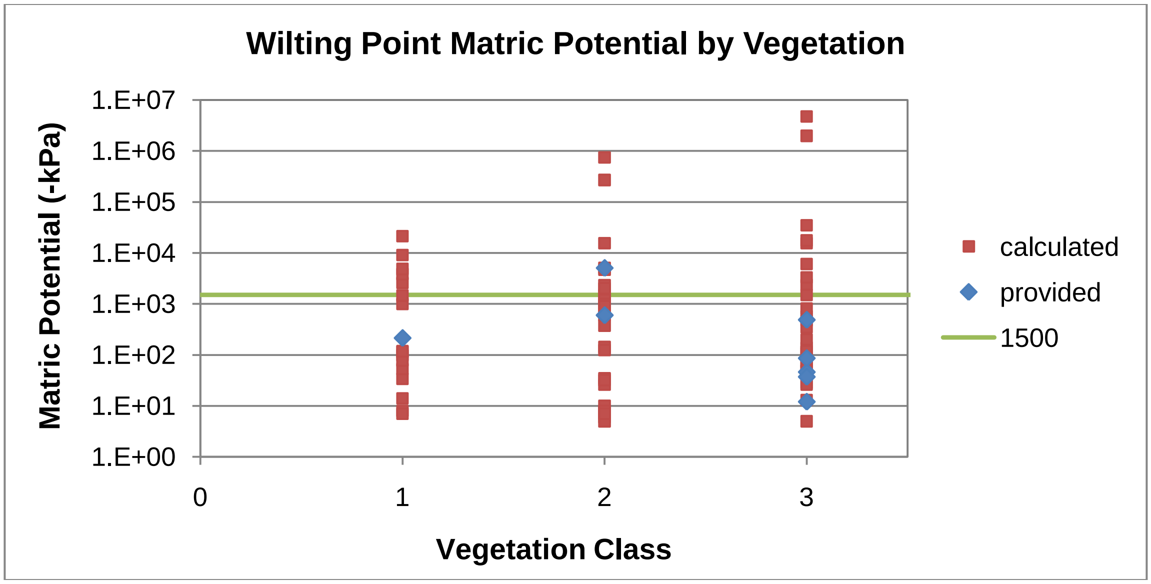


Figure 3. Wilting Point Matric Potential by Vegetation
Vegetation classes: 1=grass, 2=forb, 3=tree/shrub

the soil water in place. Similar observations can be made about the wilting point matric potentials based on vegetation class. Here it is shown that trees and shrubs have a wider range of wilting point matric potentials than grasses and forbs tend to have. Some trees and shrubs are capable of handling much more water stress than forbs are, and forbs, in turn, are capable of handling much more water stress than grasses are.

Overall, wilting points ranged widely from the -1500 kPa standardly reported. In fact, of the 127 data pieces used in this study, the matric potentials ranged from -5 kPa to -4,749,778 kPa; the wilting point matric potential pressures varied by 6 orders of magnitude. Clearly, plants exhibit a wide variation in their ability to pull up water from the soil, and it would be inaccurate to describe all of this variation in a single value for plant wilting point. All 127 plant wilting data points are shown in Table 7.

Table 7. Plant wilting point matric potentials.

| Species name | Ecoregion | Veg class | Soil type | Matric potential (kPa) |
|---|---|---|---|---|
| Acer rubrum | forest | tree | silt loam | -3304 |
| Acer saccharum | forest | tree | silt loam | -3304 |
| Agropyron intermedium | crop | grass | loam - Clarion | -124 |
| Agropyron intermedium | crop | grass | silty clay loam - Mumford | -747309 |
| Andropogon gerardi | grassland | grass | loamy sand | -13 |
| Andropogon gerardi | grassland | grass | sand | -8 |
| Andropogon scoparius | forest | grass | sandy loam - Ruston | -118 |
| Arctostaphylos . . . | crop | shrub | loam - Gleason | -26 |
| Artemisia herba-alba | desert | shrub | silty loam | -35000 |
| Atriplex canescens | desert | shrub | sand | < -15600 |
| Atriplex canescens | desert | shrub | sandy loam | < -6100 |
| Atriplex confertifolia | desert | shrub | sand | < -15600 |
| Atriplex confertifolia | desert | shrub | sandy loam | < -6100 |
| Beta vulgaris | crop | herb | loam - Yolo | -119 |
| Bromus inermis | grassland | grass | sandy loam | -86 |
| Bromus inermis | grassland | grass | loam | -5078 |
| Calamagrostis canadensis* | boreal | grass | loamy sand | -12 |
| Calamagrostis canadensis* | boreal | grass | sand | -6 |
| Carpinus caroliniana | forest | tree | silt loam | -3304 |
| Carya ovalis | forest | tree | silt loam | -3304 |
| Carya ovata | forest | tree | silt loam | -3304 |
| Cassia fasciculata | crop | herb | silty clay loam - Mumford | -269301 |
| Castanea sativa | forest | tree | sandy loam | less than residual |
| Chrysothamnus nauseosus | desert | shrub | sand | < -15600 |
| Chrysothamnus nauseosus | desert | shrub | sandy loam | < -6100 |
| Chrysothamnus parryi | desert | shrub | sand | < -15600 |
| Chrysothamnus parryi | desert | shrub | sandy loam | < -6100 |
| Chrysothamnus viscidiflorus | desert | shrub | sand | < -15600 |
| Chrysothamnus viscidiflorus | desert | shrub | sandy loam | < -6100 |
| Coleus blumei* | tropical | herb | sandy loam | -31 |
| Cornus florida | forest | tree | silt loam | -3304 |
| Fagopyrum esculentum | crop | herb | sandy loam | -109 |
| Fagus americana | forest | tree | silt loam | -3304 |
| Fraxinus americana | forest | tree | silt loam | -3304 |
| Fraxinus pennsylvanica lanceolata | grassland | tree | sandy loam | -37 |
| Fraxinus pennsylvanica lanceolata | grassland | tree | loam | -214 |
| Gossypium barbadense | crop | shrub | sandy clay loam | -3849 |

Table 7 (Continued)

| | | | | |
|---|---|---|---|---|
| Gossypium hirsutum | crop | shrub | sandy clay loam - Cecil | -600 |
| Grayia spinosa | desert | shrub | sand | < -15600 |
| Grayia spinosa | desert | shrub | sandy loam | < -6100 |
| Helianthus annuus | crop | herb | sandy loam - Ruston | -2380 |
| Helianthus annuus | crop | herb | sand | -5 |
| Helianthus annuus | crop | herb | clay | -4693 |
| Helianthus annuus | crop | herb | sandy loam - Fresno | less than residual |
| Helianthus annuus | crop | herb | sandy loam - Yolo | -8 |
| Helianthus annuus | crop | herb | loam - San Joaquin | less than residual |
| Helianthus annuus | crop | herb | clay loam - Madera | -2596 |
| Helianthus annuus | crop | herb | loam - Yolo | -51 |
| Helianthus annuus | crop | herb | loamy sand (fine) - Arvin | -6 |
| Helianthus annuus | crop | herb | silt loam - Yolo | -376 |
| Helianthus annuus | crop | herb | loam - Gleason | -26 |
| Helianthus annuus | crop | herb | loam - Aiken | -35 |
| Helianthus annuus | crop | herb | loam - Clarion | -42 |
| Helianthus annuus | crop | herb | silty clay loam - Mumford | -5106 |
| Helianthus annuus | crop | herb | clay loam - Yolo | -1193 |
| Juglans . . . | crop | tree | loam - Yolo | -73 |
| Koeleria cristata | grassland | grass | loamy sand | -14 |
| Koeleria cristata | grassland | grass | sand | -10 |
| Larix decidua | forest | tree | sandy loam | less than residual |
| Ligustrum lucidum | crop | shrub | sandy clay loam | -4862 |
| Lolium sp. | forest | grass | sandy loam | -7 |
| Lycopersicon esculentum | crop | herb | sandy clay loam | -2026 |
| Lycopersicon esculentum | crop | herb | sandy loam | -1000 |
| Malva sylvestris | grassland | herb | sandy loam | less than residual |
| Medicago sativa | crop | herb | silt loam - Millville | -900 |
| Mimosa pudica* | tropical | herb | sandy loam | less than residual |
| Nicotina attenuata | crop | herb | loam - Clarion | -53 |
| Nicotina attenuata | crop | herb | silty clay loam - Mumford | -9119 |
| Nyssa sylvatica | forest | tree | silt loam | -3304 |
| Phaseolus lunatus | crop | herb | loam - Yolo | -28 |
| Phaseolus vulgaris | crop | herb | sandy loam | -49 |

Table 7 (Continued)

| | | | | |
|---|---|---|---|---|
| Pinus discolor | desert | tree | derived from volcanics | < -1500 |
| Pinus engelmannii | desert | tree | derived from volcanics | < -1000 |
| Pinus leiophylla | desert | tree | derived from volcanics | -115 |
| Pinus ponderosa | desert | tree | derived from volcanics | < -1000 |
| Pinus strobiformis | desert | tree | derived from volcanics | -99 |
| Pinus taeda | forest | tree | sandy loam - Ruston | -118 |
| Prunus armeniaca | crop | tree | silty clay loam - Yolo | -17605 |
| Prunus avium | forest | tree | silt loam | -3304 |
| Prunus domesticus | crop | tree | loam | -34 |
| Prunus domesticus | crop | tree | loamy sand (fine) - Arvin | -5 |
| Prunus domesticus | crop | tree | sandy loam - Yolo | -7 |
| Prunus domesticus | crop | tree | loam - Yolo | -70 |
| Prunus persica | crop | tree | sandy loam - Fresno | less than residual |
| Prunus persica | crop | tree | clay loam - Madera | -2324 |
| Prunus persica | crop | tree | loam - Yolo | -143 |
| Prunus persica | crop | tree | loam - Yolo | -86 |
| Prunus serotina | forest | tree | silt loam | -3304 |
| Prunus sp. | forest | tree | silt loam | -3304 |
| Pyrus sp. | crop | tree | silty clay loam - Meyer | -1461 |
| Pyrus sp. | crop | tree | clay adobe - Meyer | -4749778 |
| Pyrus sp. | crop | tree | clay adobe - Meyer | -1986134 |
| Pyrus sp. | crop | tree | clay - Meyer adobe | -575 |
| Pyrus sp. | crop | tree | loam - Yolo | -32 |
| Quercus alba | forest | tree | silt loam | -3304 |
| Quercus bicolor | forest | tree | silt loam | -3304 |
| Quercus coccinea | forest | tree | silt loam | -3304 |
| Quercus palustria | forest | tree | silt loam | -3304 |
| Quercus robur | forest | tree | sandy loam | less than residual |
| Quercus rubra | forest | tree | silt loam | -3304 |
| Quercus sq. | forest | tree | silt loam | -3304 |
| Quercus velutina | forest | tree | silt loam | -3304 |
| Robinia pseudoacacia | grassland | tree | sandy loam | -46 |

Table 7 (Continued)

| | | | | |
|---|---|---|---|---|
| Robinia pseudoacacia | grassland | tree | loam | -487 |
| Saccharum officinarum | crop | grass | loam | less than residual |
| Salix viminalis | forest | tree | clay - compacted Oxford | -1500 |
| Salix viminalis | forest | tree | sandy loam | -200 |
| Sarcobatus vermiculatus | desert | shrub | sand | < -15600 |
| Sarcobatus vermiculatus | desert | shrub | sandy loam | < -6100 |
| Solanum gandarillasii | crop | herb | loam | -600 |
| Solanum lycopersicum | crop | herb | sandy loam | -12 |
| Solanum lycopersicum | crop | herb | loam | -54 |
| Solanum lycopersicum | crop | herb | silt loam - Yolo | -348 |
| Solanum tuberosum | crop | herb | loam | -600 |
| Tetradymia glabrata | desert | shrub | sand | < -15600 |
| Tetradymia glabrata | desert | shrub | sandy loam | < -6100 |
| Trifolium sp. | forest | herb | sandy loam | -7 |
| Ulmus americana | forest | tree | silt loam | -3304 |
| Vitis L. | crop | herb | sandy loam - Fresno | less than residual |
| Vitis L. | crop | herb | loam - San Joaquin | less than residual |
| Vitis L. | crop | herb | sandy loam - Yolo | -8 |
| Zea mays | crop | grass | silt loam - Clarion | -140 |
| Zea mays | crop | grass | sand - Plainfield | less than residual |
| Zea mays | crop | grass | silt loam - Clyde | -477 |
| Zea mays | crop | grass | loam - Washington | -810 |
| Zea mays | crop | grass | loam - Clarion | -77 |
| Zea mays | crop | grass | silty clay loam - Mumford | -21393 |

*Species was not included with the temperate data points because it is from a different ecoregion.

### *Matric Potential Comparisons*

A few of the literature sources reported the soil water content and the associated wilting point. For these sources, the reported wilting points were used in this study. However, it is worth comparing my technique for calculating the wilting point to the wilting point reported in the literature. There were five papers which provided both the water content and the wilting point. These sources are displayed in Table 8.

Table 8. Comparison of Matric Potential Results

| | | Given data | | | | My calculations | |
|---|---|---|---|---|---|---|---|
| Species | Source | Soil | Water content | SWC curve | Wilting point (kPa) | SWC curve | Wilting point (kPa) |
| Solanum gandarillasii | [73] | Loam | 10% vol. | | -600 | VG | -385 |
| Solanum tuberosum | [73] | Loam | 10% vol. | | -600 | VG | -385 |
| Zea mays | [68] | Washington loam | 8% grav. | given | -810 | VG | -170 |
| Gossypium barbadense | [37] | sandy clay loam | 10.2% grav. | | -3849 | VG | -89 |
| Lycopersicon esculentum | [37] | sandy clay loam | 11.8% grav. | | -2026 | VG | -37 |
| Ligustrum lucidum | [37] | sandy clay loam | 9.7% grav. | | -4862 | VG | -130 |
| Artemisia herba-alba | [78] | silty loam | 3.5% grav. | | -35000 | VG | less than residual |
| Salix viminalis | [74] | Clay | 31% vol. | | -1500 | VG | -198 |
| Salix viminalis | [74] | sandy loam | 22% vol. | | -200 | VG | -3 |

The first column lists the plant species, while the second column lists the literature source by first author. The next four columns detail the information provided by the literature.

As shown in the fifth column of Table 8, only the Haynes [68] paper provided their own soil water characteristic curve. For this source only, the wilting point matric potential was not provided, but instead was determined based on the water content and the specific soil water characteristic curve defined by the paper. All of the other sources did not provide a soil water characteristic curve. Instead, they just stated both the water content and the associated wilting point. The last two columns represent the elements involved in my calculation of the wilting point matric potential. For all species, I used the soil type and water content provided by the source literature. Then the van Genuchten SWC curves and the source water content were used to determine the wilting point.

By comparing the 6th and 8th columns of Table 8, it is clear that the matric potential pressure values are quite different depending on how they were determined. Coleman [73] used Theta probes to develop a soil water characteristic curve, and then simply reported the soil water matric potential at plant leaf wilting. As explained previously, Haynes [68] provided the SWC curve and allowed the reader to determine the soil water matric potential based on the water content given. Slatyer [37] used a different technique altogether. He employed a method which called for working "directly with soil cores by equilibrating them in vapour of known vapour pressure" (pg 324). Unfortunately, Kappen [78] does not explain how the soil water matric potential was determined; after mentioning the water content of the soil, the literature simply says "and corresponds to a water potential of about -350 bars" (pg 178). Martin [74] used a soil water release curve, which is another name for a soil water characteristic curve. The curve itself is provided in the paper, though it did not need to be referenced since both the soil water matric potential and the volumetric water content at wilting were given.

For eight of the nine data points provided by the literature the matric potentials based on my calculation method were less severe than the ones given. And therefore would imply that my method is a conservative estimate. This could be a function of my method, or it could be a function of the techniques employed in determining the matric potential at wilting. One other possible explanation is based on the soil. The VG SWC curves that were employed are for general soil classification categories. It is likely that the SWC curves for the general soil categories are not 100% accurate for the more specific soils within the category. Thus, minor differences may be present, and such discrepancies could be significant enough to explain the differences observed in the table above. For the *Artemisia herba-alba*, the gravimetric water content given by the literature corresponded to a volumetric water content less than the residual water content parameter for the silt loam SWC curve. Thus, a matric potential could not be determined using my technique. Back-calculating from the matric potential using the silt loam SWC curve, it was determined that -35000 kPa corresponded to a gravimetric water content of 5.47%, which is higher than the 3.5% given in the paper. Once again, this discrepancy could be attributed to the generalized soil application of the VG SWC curves.

### *Maximum Depth of the Groundwater Table*

Once the capillary fringe height at wilting and the rooting depth had been determined, the maximum depth of the groundwater table could be calculated. The results are presented in Table 9. It shows the water contents associated with the wilting of each plant species, the rooting depth of the plant species, the soil in which the plant was grown, and the height of the capillary fringe associated with the soil type. This table presents a general picture of how deep the groundwater table can get and still maintain plant life. We know that for a given soil, lower water contents

Table 9. Maximum Groundwater Table Depth by Category

| Soil Type | Vegetation Type | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Grasses | | | Herbs/Forbs | | | Trees/Shrubs | | |
| | Species | MGWD | Ecoregion | Species | MGWD | Ecoregion | Species | MGWD | Ecoregion |
| Sand | Zea mays | 1.3939 | crop | Helianthus annuus | 2.7871 | crop | Atriplex canescens | 8.0900 | desert |
| | Andropogon gerardi | 2.1889 | grassland | | | | Atriplex confertifolia | 8.0900 | desert |
| | Koeleria cristata | 0.5492 | grassland | | | | Chrysothamnus nauseosus | 2.0900 | desert |
| | | | | | | | Chrysothamnus parryi | 2.0900 | desert |
| | | | | | | | Chrysothamnus viscidiflorus | 2.0900 | desert |
| | | | | | | | Grayia spinosa | 9.9900 | desert |
| | | | | | | | Sarcobatus vermiculatus | 9.9900 | desert |
| | | | | | | | Tetradymia glabrata | 9.9900 | desert |
| Sandy loam | Andropogon scoparius | 2.3442 | forest | Fagopyrum esculentum | 2.5438 | crop | Prunus domesticus | 1.9858 | crop |
| | Lolium sp | 1.1874 | forest | Helianthus annuus | 2.9702 | crop | Prunus persica | 2.0703 | crop |
| | Bromus inermis | 2.2424 | grassland | Helianthus annuus | 2.9420 | crop | Atriplex canescens | 8.2499 | desert |
| | | | | Helianthus annuus | 2.8948 | crop | Atriplex confertifolia | 8.2499 | desert |
| | | | | Lycopersicon esculentum | 2.5377 | crop | Chrysothamnus nauseosus | 2.2499 | desert |
| | | | | Phaseolus | 2.5375 | crop | Chrysothamnus parryi | 2.2499 | desert |
| | | | | vulgaris | 2.5082 | crop | Chrysothamnus viscidiflorus | 2.2499 | desert |
| | | | | Solanum lycopersicum | 2.5647 | crop | Grayia spinosa | 10.1499 | desert |
| | | | | Vitis L | 2.4955 | crop | Sarcobatus vermiculatus | 10.1499 | desert |
| | | | | Vitis L | 1.1874 | forest | Tetradymia glabrata | 10.1499 | desert |
| | | | | Trifolium sp | 2.9501 | grassland | Castanea sativa | 3.7850 | forest |
| | | | | Malva sylvestris | | | Larix decidua | 3.7850 | forest |
| | | | | | | | Pinus taeda | 2.2442 | forest |
| | | | | | | | Quercus robur | 3.7850 | forest |
| | | | | | | | Salix viminalis | 0.9464 | forest |

Table 9 (Continued)

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Fraxinus pennsylvanica | 3.1340 | grassland |
| | | | | | | | Robinia pseudoacacia | 3.1368 | grassland |
| Sandy clay loam | | | | Lycopersicon esculentum | 2.9190 | crop | Gossypium barbadense | 2.7296 | crop |
| | | | | | | | Gossypium hirsutum | 2.6883 | crop |
| | | | | | | | Ligustrum lucidum | 2.1328 | crop |
| Sandy clay | | | | | | | | | |
| Silty clay loam | Agropyron intermedium | 17.8652 | crop | Cassia fasciculata | 16.9858 | crop | Prunus armeniaca | 13.0489 | crop |
| | | | | Helianthus annuus | 12.0182 | crop | Pyrus sp | 8.4276 | crop |
| | Zea mays | 12.8349 | crop | Nicotina attenuata | 12.5473 | crop | | | |
| Silty clay | | | | | | | | | |
| Silt loam | Zea mays | 2.7717 | crop | Helianthus annuus | 4.4612 | crop | Artemisia herba-alba | 6.0409 | desert |
| | Zea mays | 3.1207 | crop | Medicago sativa | 4.4797 | crop | Acer rubrum | 6.0302 | forest |
| | | | | Solanum lycopersicum | 4.0404 | crop | Acer saccharum | 5.8802 | forest |
| | | | | | | | Carpinus caroliniana | 5.4802 | forest |
| | | | | | | | Carya ovalis | 3.9802 | forest |
| | | | | | | | Carya ovata | 3.9802 | forest |
| | | | | | | | Cornus florida | 5.4802 | forest |
| | | | | | | | Fagus americana | 5.4802 | forest |
| | | | | | | | Fraxinus americana | 4.1802 | forest |
| | | | | | | | Nyssa sylvatica | 5.4802 | forest |
| | | | | | | | Prunus avium | 4.2802 | forest |
| | | | | | | | Prunus serotina | 4.2802 | forest |
| | | | | | | | Prunus sp | 4.2802 | forest |
| | | | | | | | Quercus alba | 6.1052 | forest |
| | | | | | | | Quercus bicolor | 6.1052 | forest |
| | | | | | | | Quercus coccinea | 6.1052 | forest |
| | | | | | | | Quercus palustria | 6.1052 | forest |
| | | | | | | | Quercus rubra | 6.1052 | forest |
| | | | | | | | Quercus sq | 6.1052 | forest |
| | | | | | | | Quercus velutina | 5.1802 | forest |

Table 9 (Continued)

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Ulmus americana | 5.4802 | forest |
| Silt | | | | | | | | | |
| Loamy sand | Andropogon gerardi | 2.2165 | grassland | Helianthus annuus | 2.8113 | crop | Prunus domesticus | 1.9091 | crop |
| | Koeleria cristata | 0.5768 | grassland | | | | | | |
| Loam | Agropyron intermedium | 2.9070 | crop | Beta vulgaris | 2.5035 | crop | Arctostaphylos sp | 4.1068 | crop |
| | | | | Helianthus annuus | 3.2736 | crop | Juglans sp | 6.1575 | crop |
| | Saccharum officinarum | 2.9965 | crop | Helianthus annuus | 3.2963 | crop | Prunus domesticus | 2.3667 | crop |
| | | | | Helianthus annuus | 3.2307 | crop | Prunus domesticus | 2.4532 | crop |
| | Zea mays | 1.9639 | crop | Helianthus annuus | 3.6846 | crop | Prunus persica | 2.5180 | crop |
| | Zea mays | 2.0308 | crop | Helianthus annuus | 3.3182 | crop | Prunus persica | 2.4749 | crop |
| | Bromus inermis | 2.8477 | grassland | Nicotina attenuata | 2.9225 | crop | Pyrus sp | 1.7607 | crop |
| | | | | Phaseolus lunatus | 2.8432 | crop | Fraxinus pennsylvanica | 3.6465 | grassland |
| | | | | Solanum gandarillasii | 2.1792 | crop | Robinia pseudoacacia | 3.6899 | grassland |
| | | | | Solanum lycopersicum | 2.9256 | crop | | | |
| | | | | Solanum tuberosum | 2.1792 | crop | | | |
| | | | | Vitis L | 3.2309 | crop | | | |
| Clay loam | | | | Helianthus annuus | 5.9373 | crop | Prunus persica | 4.9968 | crop |
| | | | | Helianthus annuus | 5.6222 | crop | | | |
| Clay | | | | Helianthus annuus | 46.0449 | crop | Pyrus sp | 19.5637 | crop |
| | | | | | | | Pyrus sp | 93.4488 | crop |
| | | | | | | | Pyrus sp | 73.8802 | crop |
| | | | | | | | Salix viminalis | 28.4010 | forest |

correspond to more severe pressures that the plant will have to overcome in order to uptake that water. These lower water contents also correspond with greater heights above the groundwater table. Conversely, greater water contents correspond to less severe water pressures and lower heights above the groundwater table. The conditions that are better for plants are higher water contents and greater heights above the groundwater table. However, these conditions are reached in a counteractive manner if the groundwater table is falling. Thus, from a management perspective, it is crucial to monitor the depth of the groundwater table. If it falls too far, then the capillary fringe height and the plant roots will not meet and plants will not be able to uptake water from the soil in times of drought.

The data in Table 9 is organized by ecoregion and vegetation type. Within each combination of categories the data is organized by soil type, going from clay to sandy loam. In this way, it is easy to see how the maximum depth of the groundwater table varies across the soil types, with the lowest values being associated with sandy soils.

As clearly shown in Table 9, the literature provides a significant amount of data on crop species in a variety of soil types. In other ecoregions, however, the soil type is less varied. Deserts tend to have mostly sandy soils, and this is confirmed by the data presented. The vegetation types observed in each ecoregion also express plant species expected for each region. Crops include all types of vegetation. Grasslands support mostly grass, trees, and shrubs. Deserts mainly contain trees and shrubs and have few grasses and forbs. Forests primarily have trees, but do support some grasses and forbs.

There are 118 data points presented in the table above. Table 10 is primarily organized by ecoregion, then by vegetation type, then by soil type, and then alphabetically by species. Of the original 127 data points, four were excluded from

Table 10.  Maximum groundwater table depth calculations.

| Species name | Ecoregion | Veg. class | Soil type | Rooting depth (m) | Capillary fringe height (m) | Max GWT depth (m) |
|---|---|---|---|---|---|---|
| Agropyron intermedium | crop | grass | loam | 2.2 | 0.7070 | 2.9070 |
| Saccharum officinarum | crop | grass | loam | 2.0 | 0.9965 | 2.9965 |
| Zea mays | crop | grass | loam | 1.3 | 0.6639 | 1.9639 |
| Zea mays | crop | grass | loam | 1.3 | 0.7308 | 2.0308 |
| Zea mays | crop | grass | silt loam | 1.3 | 1.4717 | 2.7717 |
| Zea mays | crop | grass | silt loam | 1.3 | 1.8207 | 3.1207 |
| Agropyron intermedium | crop | grass | silty clay loam | 2.2 | 15.6652 | 17.8652 |
| Zea mays | crop | grass | silty clay loam | 1.3 | 11.5349 | 12.8349 |
| Zea mays | crop | grass | sand | 1.3 | 0.0939 | 1.3939 |
| Helianthus annuus | crop | herb | clay | 2.7 | 43.3449 | 46.0449 |
| Helianthus annuus | crop | herb | clay loam | 2.7 | 3.2373 | 5.9373 |
| Helianthus annuus | crop | herb | clay loam | 2.7 | 2.9222 | 5.6222 |
| Beta vulgaris | crop | herb | loam | 1.8 | 0.7035 | 2.5035 |
| Helianthus annuus | crop | herb | loam | 2.7 | 0.5736 | 3.2736 |
| Helianthus annuus | crop | herb | loam | 2.7 | 0.5963 | 3.2963 |
| Helianthus annuus | crop | herb | loam | 2.7 | 0.5307 | 3.2307 |
| Helianthus annuus | crop | herb | loam | 2.7 | 0.9846 | 3.6846 |
| Helianthus annuus | crop | herb | loam | 2.7 | 0.6182 | 3.3182 |
| Nicotina attenuata | crop | herb | loam | 2.3 | 0.6225 | 2.9225 |
| Phaseolus lunatus | crop | herb | loam | 2.3 | 0.5432 | 2.8432 |
| Solanum gandarillasii | crop | herb | loam | 1.4 | 0.7792 | 2.1792 |
| Solanum lycopersicum | crop | herb | loam | 2.3 | 0.6256 | 2.9256 |
| Solanum tuberosum | crop | herb | loam | 1.4 | 0.7792 | 2.1792 |
| Vitis L. | crop | herb | loam | 2.3 | 0.9309 | 3.2309 |
| Helianthus annuus | crop | herb | loamy sand | 2.7 | 0.1113 | 2.8113 |
| Helianthus annuus | crop | herb | silt loam | 2.7 | 1.7612 | 4.4612 |
| Medicago sativa | crop | herb | silt loam | 2.6 | 1.8797 | 4.4797 |
| Solanum lycopersicum | crop | herb | silt loam | 2.3 | 1.7404 | 4.0404 |
| Cassia fasciculata | crop | herb | silty clay loam | 2.3 | 14.6858 | 16.9858 |
| Helianthus annuus | crop | herb | silty clay loam | 2.7 | 9.3182 | 12.0182 |

Table 10 (Continued)

| | | | | | | |
|---|---|---|---|---|---|---|
| Nicotina attenuata | crop | herb | silty clay loam | 2.3 | 10.2473 | 12.5473 |
| Helianthus annuus | crop | herb | sand | 2.7 | 0.0871 | 2.7871 |
| Lycopersicon esculentum | crop | herb | sandy clay loam | 2.3 | 0.6190 | 2.9190 |
| Fagopyrum esculentum | crop | herb | sandy loam | 2.3 | 0.2438 | 2.5438 |
| Helianthus annuus | crop | herb | sandy loam | 2.7 | 0.2702 | 2.9702 |
| Helianthus annuus | crop | herb | sandy loam | 2.7 | 0.2420 | 2.9420 |
| Helianthus annuus | crop | herb | sandy loam | 2.7 | 0.1948 | 2.8948 |
| Lycopersicon esculentum | crop | herb | sandy loam | 2.3 | 0.2377 | 2.5377 |
| Phaseolus vulgaris | crop | herb | sandy loam | 2.3 | 0.2375 | 2.5375 |
| Solanum lycopersicum | crop | herb | sandy loam | 2.3 | 0.2082 | 2.5082 |
| Vitis L. | crop | herb | sandy loam | 2.3 | 0.2647 | 2.5647 |
| Vitis L. | crop | herb | sandy loam | 2.3 | 0.1955 | 2.4955 |
| Pyrus sp. | crop | tree | clay | 1.2 | 18.3637 | 19.5637 |
| Pyrus sp. | crop | tree | clay | 1.2 | 92.2488 | 93.4488 |
| Pyrus sp. | crop | tree | clay | 1.2 | 72.6802 | 73.8802 |
| Prunus persica | crop | tree | clay loam | 1.8 | 3.1968 | 4.9968 |
| Arctostaphylos . . . | crop | tree | loam | 3.6 | 0.5318 | 4.1068 |
| Juglans . . . | crop | tree | loam | 5.5 | 0.6575 | 6.1575 |
| Prunus domesticus | crop | tree | loam | 1.8 | 0.5667 | 2.3667 |
| Prunus domesticus | crop | tree | loam | 1.8 | 0.6532 | 2.4532 |
| Prunus persica | crop | tree | loam | 1.8 | 0.7180 | 2.5180 |
| Prunus persica | crop | tree | loam | 1.8 | 0.6749 | 2.4749 |
| Pyrus sp. | crop | tree | loam | 1.2 | 0.5607 | 1.7607 |
| Prunus domesticus | crop | tree | loamy sand | 1.8 | 0.1091 | 1.9091 |
| Prunus armeniaca | crop | tree | silty clay loam | 1.8 | 11.2489 | 13.0489 |
| Pyrus sp. | crop | tree | silty clay loam | 1.2 | 7.2276 | 8.4276 |
| Gossypium barbadense | crop | tree | sandy clay loam | 2.1 | 0.6296 | 2.7296 |
| Gossypium hirsutum | crop | tree | sandy clay loam | 2.1 | 0.5883 | 2.6883 |

Table 10 (Continued)

| | | | | | | |
|---|---|---|---|---|---|---|
| Ligustrum lucidum | crop | tree | sandy clay loam | 1.5 | 0.6328 | 2.1328 |
| Prunus domesticus | crop | tree | sandy loam | 1.8 | 0.1858 | 1.9858 |
| Prunus persica | crop | tree | sandy loam | 1.8 | 0.2703 | 2.0703 |
| Artemisia herba-alba | desert | tree | silt loam | 3.7 | 2.3909 | 6.0409 |
| Atriplex canescens | desert | tree | sand | 8.0 | 0.0900 | 8.0900 |
| Atriplex confertifolia | desert | tree | sand | 8.0 | 0.0900 | 8.0900 |
| Chrysothamnus nauseosus | desert | tree | sand | 2.0 | 0.0900 | 2.0900 |
| Chrysothamnus parryi | desert | tree | sand | 2.0 | 0.0900 | 2.0900 |
| Chrysothamnus viscidiflorus | desert | tree | sand | 2.0 | 0.0900 | 2.0900 |
| Grayia spinosa | desert | tree | sand | 9.9 | 0.0900 | 9.9900 |
| Sarcobatus vermiculatus | desert | tree | sand | 9.9 | 0.0900 | 9.9900 |
| Tetradymia glabrata | desert | tree | sand | 9.9 | 0.0900 | 9.9900 |
| Atriplex canescens | desert | tree | sandy loam | 8.0 | 0.2499 | 8.2499 |
| Atriplex confertifolia | desert | tree | sandy loam | 8.0 | 0.2499 | 8.2499 |
| Chrysothamnus nauseosus | desert | tree | sandy loam | 2.0 | 0.2499 | 2.2499 |
| Chrysothamnus parryi | desert | tree | sandy loam | 2.0 | 0.2499 | 2.2499 |
| Chrysothamnus viscidiflorus | desert | tree | sandy loam | 2.0 | 0.2499 | 2.2499 |
| Grayia spinosa | desert | tree | sandy loam | 9.9 | 0.2499 | 10.1499 |
| Sarcobatus vermiculatus | desert | tree | sandy loam | 9.9 | 0.2499 | 10.1499 |
| Tetradymia glabrata | desert | tree | sandy loam | 9.9 | 0.2499 | 10.1499 |
| Andropogon scoparius | forest | grass | sandy loam | 2.1 | 0.2442 | 2.3442 |
| Lolium sp. | forest | grass | sandy loam | 1.0 | 0.1874 | 1.1874 |
| Trifolium sp. | forest | herb | sandy loam | 1.0 | 0.1874 | 1.1874 |
| Salix viminalis | forest | tree | clay | 0.7 | 27.7010 | 28.4010 |
| Acer rubrum | forest | tree | silt loam | 3.9 | 2.1802 | 6.0302 |
| Acer saccharum | forest | tree | silt loam | 3.7 | 2.1802 | 5.8802 |

Table 10 (Continued)

| | | | | | | |
|---|---|---|---|---|---|---|
| Carpinus caroliniana | forest | tree | silt loam | 3.3 | 2.1802 | 5.4802 |
| Carya ovalis | forest | tree | silt loam | 1.8 | 2.1802 | 3.9802 |
| Carya ovata | forest | tree | silt loam | 1.8 | 2.1802 | 3.9802 |
| Cornus florida | forest | tree | silt loam | 3.3 | 2.1802 | 5.4802 |
| Fagus americana | forest | tree | silt loam | 3.3 | 2.1802 | 5.4802 |
| Fraxinus americana | forest | tree | silt loam | 2.0 | 2.1802 | 4.1802 |
| Nyssa sylvatica | forest | tree | silt loam | 3.3 | 2.1802 | 5.4802 |
| Prunus avium | forest | tree | silt loam | 2.1 | 2.1802 | 4.2802 |
| Prunus serotina | forest | tree | silt loam | 2.1 | 2.1802 | 4.2802 |
| Prunus sp. | forest | tree | silt loam | 2.1 | 2.1802 | 4.2802 |
| Quercus alba | forest | tree | silt loam | 3.9 | 2.1802 | 6.1052 |
| Quercus bicolor | forest | tree | silt loam | 3.9 | 2.1802 | 6.1052 |
| Quercus coccinea | forest | tree | silt loam | 3.9 | 2.1802 | 6.1052 |
| Quercus palustria | forest | tree | silt loam | 3.9 | 2.1802 | 6.1052 |
| Quercus rubra | forest | tree | silt loam | 3.9 | 2.1802 | 6.1052 |
| Quercus sq. | forest | tree | silt loam | 3.9 | 2.1802 | 6.1052 |
| Quercus velutina | forest | tree | silt loam | 3.0 | 2.1802 | 5.1802 |
| Ulmus americana | forest | tree | silt loam | 3.3 | 2.1802 | 5.4802 |
| Castanea sativa | forest | tree | sandy loam | 3.5 | 0.2850 | 3.7850 |
| Larix decidua | forest | tree | sandy loam | 3.5 | 0.2850 | 3.7850 |
| Pinus taeda | forest | tree | sandy loam | 2.0 | 0.2442 | 2.2442 |
| Quercus robur | forest | tree | sandy loam | 3.5 | 0.2850 | 3.7850 |
| Salix viminalis | forest | tree | sandy loam | 0.7 | 0.2464 | 0.9464 |
| Bromus inermis | grassland | grass | loam | 2.0 | 0.8477 | 2.8477 |
| Andropogon gerardi | grassland | grass | loamy sand | 2.1 | 0.1165 | 2.2165 |
| Koeleria cristata | grassland | grass | loamy sand | 0.5 | 0.1168 | 0.5768 |
| Andropogon gerardi | grassland | grass | sand | 2.1 | 0.0889 | 2.1889 |
| Koeleria cristata | grassland | grass | sand | 0.5 | 0.0892 | 0.5492 |
| Bromus inermis | grassland | grass | sandy loam | 2.0 | 0.2424 | 2.2424 |
| Malva sylvestris | grassland | herb | sandy loam | 2.7 | 0.2501 | 2.9501 |

Table 10 (Continued)

| | | | | | | |
|---|---|---|---|---|---|---|
| Fraxinus pennsylvanica lanceolata | grassland | tree | loam | 2.9 | 0.7465 | 3.6465 |
| Robinia pseudoacacia | grassland | tree | loam | 2.9 | 0.7899 | 3.6899 |
| Fraxinus pennsylvanica lanceolata | grassland | tree | sandy loam | 2.9 | 0.2340 | 3.1340 |
| Robinia pseudoacacia | grassland | tree | sandy loam | 2.9 | 0.2368 | 3.1368 |

this data set because they were from ecoregions not considered here; another five were excluded because their soil type was not described in a way that it would fit within my soil classifications.

To exemplify how the groundwater table depth varies depending on the soil type, Table 11 lists all of the data points based on sunflowers (*helianthus annuus*). For data points within the same soil, similar maximum depths of the groundwater table were observed. Then, for soils with smaller pore spaces, greater maximum groundwater table depths are feasible, while for soils with larger pore spaces lower maximum groundwater table depths are feasible. This trend is accepted and consistent with the literature.

Table 11. *Helianthus annuus* data points in different soils.

| Species name | Ecoregion | Veg. class | soil type | rooting depth (m) | capillary fringe height (m) | max GWT depth (m) |
|---|---|---|---|---|---|---|
| Helianthus annuus | crop | herb | clay | 2.7 | 43.3449 | 46.0449 |
| Helianthus annuus | crop | herb | clay loam | 2.7 | 3.2373 | 5.9373 |
| Helianthus annuus | crop | herb | clay loam | 2.7 | 2.9222 | 5.6222 |
| Helianthus annuus | crop | herb | loam | 2.7 | 0.5736 | 3.2736 |
| Helianthus annuus | crop | herb | loam | 2.7 | 0.5963 | 3.2963 |
| Helianthus annuus | crop | herb | loam | 2.7 | 0.5307 | 3.2307 |
| Helianthus annuus | crop | herb | loam | 2.7 | 0.9846 | 3.6846 |
| Helianthus annuus | crop | herb | loam | 2.7 | 0.6182 | 3.3182 |
| Helianthus annuus | crop | herb | loamy sand | 2.7 | 0.1113 | 2.8113 |
| Helianthus annuus | crop | herb | silt loam | 2.7 | 1.7612 | 4.4612 |
| Helianthus annuus | crop | herb | silty clay loam | 2.7 | 9.3182 | 12.0182 |
| Helianthus annuus | crop | herb | sand | 2.7 | 0.0871 | 2.7871 |
| Helianthus annuus | crop | herb | sandy loam | 2.7 | 0.2702 | 2.9702 |
| Helianthus annuus | crop | herb | sandy loam | 2.7 | 0.2420 | 2.9420 |
| Helianthus annuus | crop | herb | sandy loam | 2.7 | 0.1948 | 2.8948 |

# CHAPTER 5: DISCUSSION

The more precise analyses of wilting points relative to groundwater and capillary fringe provided some valuable insights for improving groundwater management in the face of climate change and the associated increasing probability of droughts in many regions. It also highlighted several critical areas where more extensive research is obviously needed. Overall, this work documented that the use of a standardized reference of permanent wilting point of -1500 kPa for the past half century, although highly useful, is heavily biased towards both crop species, irrigated systems, and towards more mesic climates. It is an imprecise, inaccurate and misleading measure for semi-arid and arid regions because native plant species in these regions have adapted a diverse suite of strategies to deal with frequent dry soil conditions, including the ability to uptake water from lower water potentials. The ability to access more tightly bound water gains importance when considered in terms of the capillary fringe above the groundwater table. Surprisingly, little research is available documenting the characteristics of the capillary fringe and, in particular, the properties and physics of the capillary fringe in fine-textured soils. However, the capillary fringe is a critical player because it can provide moisture to maintain surface plant communities above the groundwater table. Plants able to overcome lower soil moisture pressures can survive lower groundwater table depths by accessing the capillary fringe higher above the groundwater table.

## ***Permanent Wilting Point***

Synthesis of the literature highlighted how historical development of this concept has lead to the misconception that -1500 kPa is a good representative value for the permanent wilting point for all plant species. Much of the early work done used a single plant species, *helianthus annuus*, which assumed that interspecific differences were negligible and that soil was the only significant factor determining plant wilting point. Similarly most of the work was done on crops, which, although differing in plant type, are maintained at soil water conditions that maximize growth and yield. Thus, this category of species is also an inaccurate representation of all plant species. My calculations have shown that wilting point matric potentials can vary significantly from -1500 kPa. Additionally, the analysis of permanent wilting points showed overall differences among plant type and ecosystem type. Not surprisingly, semi-arid and arid habitats had overall higher suction values, i.e. they can live and function at very low soil moistures. The lowest wilting point reported was -4,749,778 kPa for a pear tree (*pyrus sp.*) in clay soil. Thus, it is safe to conclude that the assumption of -1500 kPa as a wilting point for all plant species in all soil types is far too general and should be used more cautiously.

Finding data values related to plant wilting points was challenging. So, to augment the data set, I also depended on extrapolation from reported soil water contents of dying plant communities. A few sources dealt with tree die-back. This growing body of studies needs to incorporate more careful measures of soil moisture conditions in the future.

Before studying plants to determine their wilting point, the first step should be to standardize a technique for determining this wilting point in any plant species. A variety of methods have been used historically, including the technique described by Briggs and Shantz [83], the one described by Furr and Reeve [33], and many others that were used in individual experiments. Due to these differences in techniques, the permanent wilting point for any given plant species in any given soil "may vary considerably unless some well-defined criteria are established for judging when the selected stage [of wilting] has been reached" [33] (pg 155). This variability leads to inaccurate science. However, such variability can be avoided by determining a standardized technique now before further studies are conducted.

Part of the ideal technique should include defining a soil water characteristic curve for the targeted soil of interest. I have previously discussed the validity of the van Genuchten curves with respect to this study. While their applicability was for the 12 general soil categories, the concept of a soil water characteristic curve is still highly valid when studying plant wilting pressures. One study that was used included their own soil water characteristic curve for the soil [68]. This was found to be very helpful in determining the suction experienced by the plant at that water content. For all the other studies used in this research, no such soil water characteristic for the soil was given. Instead, the van Genuchten curves were employed as approximations of the various soil types. While the van Genuchten curves may not have accurately represented specific soils within each soil classification, the concept of a soil water characteristic curve is still valid. For greatest accuracy, any future studies on plant wilting should include a soil water characteristic curve as part of the project. In this way, the wilting pressure experienced by the plant in a given soil can be established more accurately. The bulk density of the soil is needed to convert between the gravimetric water content and the volumetric water content. This soil characteristic should also be determined in order to make sure of the SWC curve.

There are a couple of limitations to this methodology. My primary tool for determining the matric potential of different species was the van Genuchten soil water characteristic curve. This curve related volumetric water content to suction pressure, which correlates directly to matric potential pressure. As mentioned previously, discrepancies were observed when comparing my technique to matric potential values provided by the literature. However, even the values reported varied quite a bit, with only one actually having a -1500 kPa value. Additionally, there is a great deal of uncertainty regarding soil suction at low water contents. This issue has been faced by many who study in this field. How this low water content correlates to the capillary fringe and the suction experienced by plants accessing it is still unknown. I have presented a method for describing this relationship. However, this method is completely theoretical and has not been verified by experimental evidence. Clearly, this is an area of science that has yet to be clarified, and thus, an area of science that should continue to be explored.

### *Influence of Capillary Fringe*

As Gillham (1984) says the capillary fringe "has been neglected in hydrogeological investigations, and little attention has been given to the potential significance in the interpretation of hydrologic process" (pg 308). Also, in areas characterized with uncertainty related to climate change and areas where drier climates are already observed, the conservative approach will be to assume a very dry climate and plan accordingly. This includes assuming natural plant communities' reliance on the water in the capillary fringe when the groundwater table becomes out of reach. Groundwater tables will need to be monitored closely, especially in periods of drought. Recognizing the potential water benefits offered by the capillary fringe can help water managers plan for sustaining ecosystems considering climate change.

Translating wilting points and relating them to capillary fringe heights was surprisingly difficult, mainly because the capillary fringe is very poorly investigated. Currently, there are insufficient techniques for determining the capillary fringe height. Most of the available literature on the capillary fringe zone discusses movement of particles and flows through it; they do not address capillary fringe heights during a drought period when water flow through the soil above the groundwater table is minimal. Additionally, coarse sands have been studied more frequently than other soils. When it is studied, the capillary fringe height has been determined and reported based on empirical and model results. However, use of formulas all suggest that fine grained soils can actually move waters to heights of hundreds of meters or more. These values are so unusually high that researchers such as Aubertin et al. [54] were hesitant to even report these values. Interestingly, it is this exact intersection of the lowest suction values, high up in the capillary fringe, that are relevant to the plants wilting points. More research is definitely needed to better understand the properties of the capillary fringe. This research should take on both empirical and model based forms.

For the purpose of this study, I used some broad generalizations and logical jumps to determine a technique for calculating the capillary fringe height. The choice of an exponential relationship was very reasonable since the relationship between water content and capillary fringe height is expected to be closer to an exponential relationship than to a linear one. Also, the choice of the two representative data points was quite logical. The 85% saturation data point was proven by Al-Samahiji et al. [42] to be accurate in its correlation between the suction height and the capillary fringe height. The maximum capillary fringe height point can also be reasonably correlated to the residual volumetric water content experienced by the soil. The formula for calculating the maximum capillary fringe height was described by El-Kadi and Ling [55] and employed the parameters already in use in this study. All of the relationships between volumetric water content and capillary fringe height were based on the two points described above. While these equations have not been proven by experiment, they are theoretically justifiable and are as feasible as any of the other techniques for determining capillary fringe height presented in the literature.

Using the El-Kadi and Ling [55] formula led to some high values for maximum capillary fringe heights, as shown previously in Table 3. The two values that seem quite large are 2764.38 m for clay and 4423.01 m for silty clay. Previous literature [54] has intentionally excluded the high values for capillary fringe heights for fine-grained soils because the values seemed unreasonable. However, it is my belief that such extreme capillary fringe heights are in fact feasible and similar large values have been reported by other sources [84-85]. The nature of fine-grained soils is such that the pore spaces within the soil are small and thereby facilitate capillary suction, which in turn leads to greater capillary fringe height. Considering the smaller diameter of soil particles and pore spaces in clayey soils, it is not unreasonable for there to be enough suction to carry water thousands of meters above the groundwater table.

### ***Rooting Depth***

Rooting depths of different species have been well summarized in several papers. For ecoregion managers, the rooting depth of the plant species in the ecoregion is a crucial factor in understanding the maximum depth of the groundwater table. Identifying typical rooting depths for the vegetation types native to the ecoregion can assist many ecoregion managers in defining this maximum depth. Table 12 presents the suggested rooting depth approximations for use by ecoregion managers.

Table 12. Suggested rooting depth approximations by ecoregion and vegetation type (in meters).

| | Vegetation class | | |
|---|---|---|---|
| Ecoregion | Grass | Herb/Forb | Tree/Shrub |
| Crops | 1.8 | 2.3 | 1.9 |
| Grasslands | 2.0 | 2.7 | 2.9 |
| Desert | 2.0 | | 9.9 |
| Forest | 1.6 | 1.0 | 3.3 |

The difference between this table and Table 6 presented earlier lies in the inclusion of an average rooting depth value for tree and shrub crops. Table 6 describes Canadell's information used as the default values in my calculations. Since there was no value for tree and shrub crops from Canadell, this value was left blank in the previous table. However, my data sources provided rooting depths for all of the tree and shrub crops used in this study. Thus, the average rooting depth of the species in that combined category was taken to be the average rooting depth for tree and shrub crops. The same technique was applied to forest grasses and forest forbs. However, in both of these cases, there were far fewer species from which to base the average. Unfortunately, I did not have any data on desert forbs and are unable to provide an average rooting depth for those species. This may not prove to be much of a hindrance since few herbs and forbs grow in the desert.

### *Maximum Groundwater Table Depth*

Integration of these parts into maximum groundwater depths showed that in sandy and coarse grained systems maximum depth of the groundwater table should be roughly 2 m, for silts and loams it should be less than 4 m, and for clayey soils it can be much deeper. These guidelines assume a pure soil, without larger pores or organic matter, and they do not consider compaction at greater depths. All of these factors would alter the continuity of the capillary tubes needed to transport water upward, some inhibiting, some encouraging. However, the guidelines provide a useful framework for planning groundwater management.

Figures 4-7 provide an additional depiction of the results for each ecoregion. Each ecoregion figure depicts the soil texture triangle and the maximum allowable groundwater depth (GWD) for the soils that I had data points for. The values shown represent the minimum MGWD (maximum groundwater depth) calculated for that

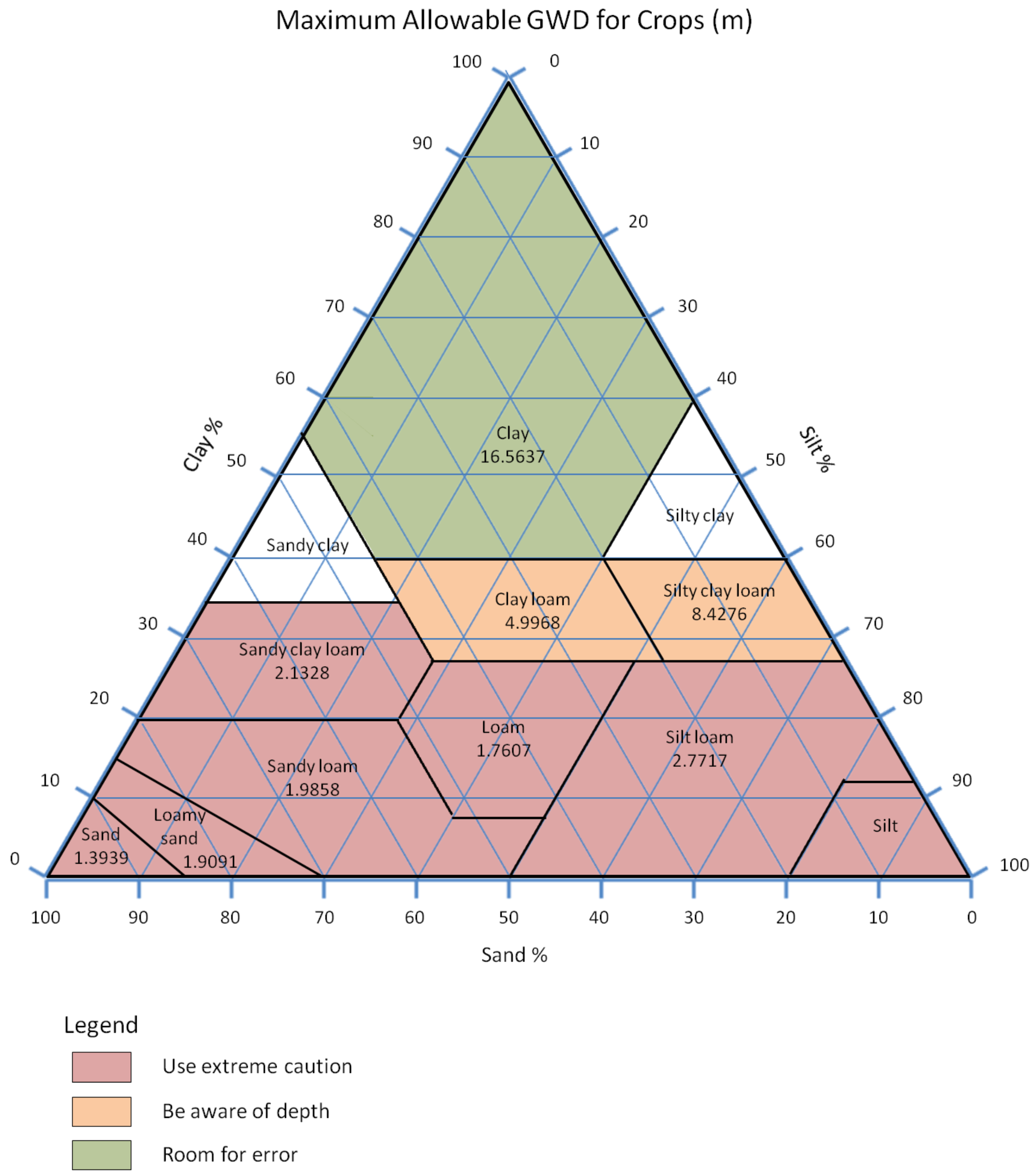


Figure 4. Maximum Allowable Groundwater Depth Guidance for Crops (m)

ecoregion and soil, across all vegetation types, from the data in this study. Taking the minimum MGWD value ensures that all other plants in that ecoregion with the same soil type will also survive at that groundwater table depth. In the figures, the red region represents soils that must be closely watched in order to ensure that the required shallow groundwater table remains at a depth that will sustain plant life. The

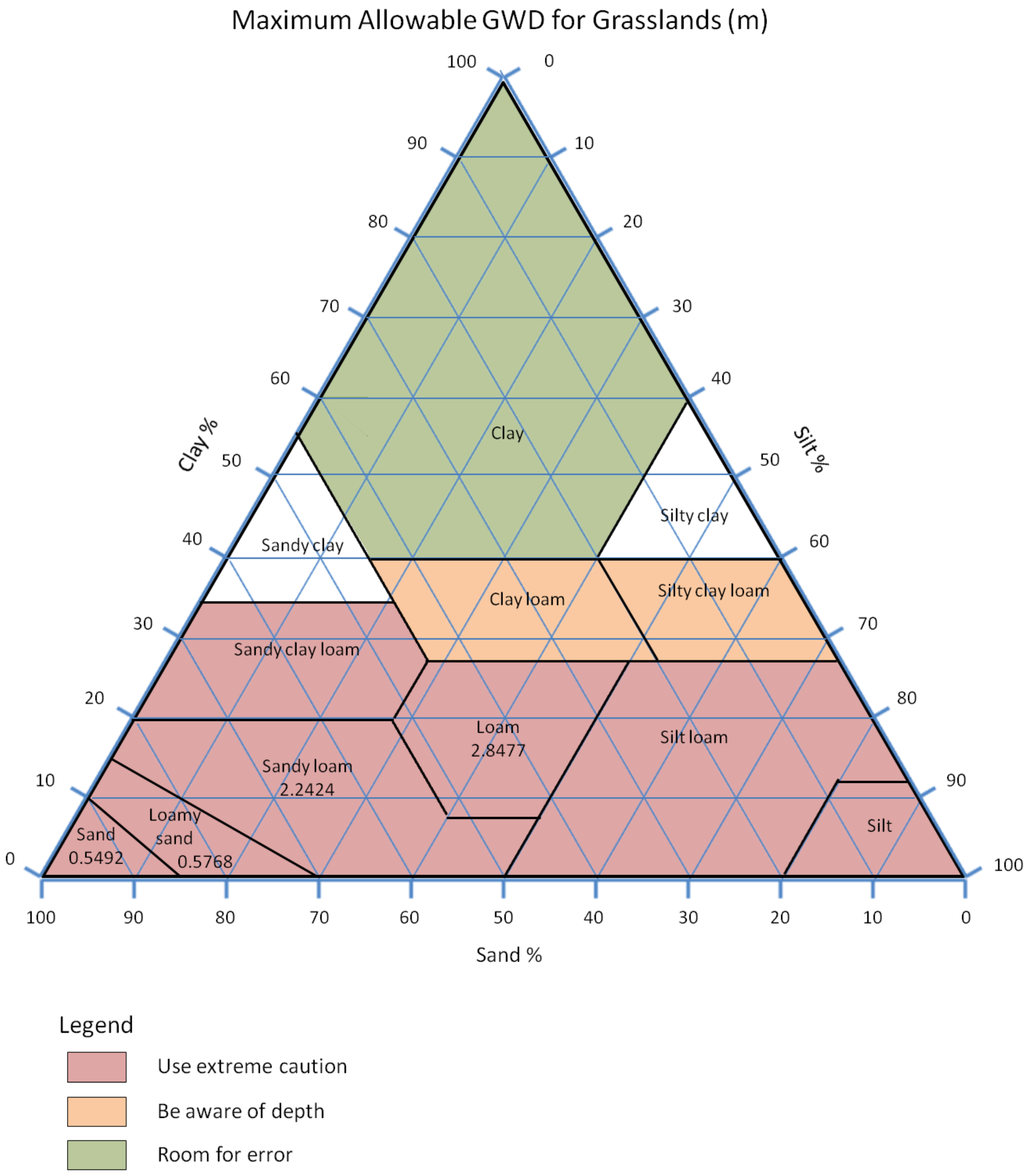


Figure 5. Maximum Allowable Groundwater Depth Guidance for Grasslands (m)

yellow region represents soils that should be monitored, but require a less shallow groundwater table. The green region represents soils where the maximum allowable GWD is quite deep. Sandy clay and silty clay soils are left uncolored in the figures because I have no data points for these two soils. Thus, the maximum allowable GWD could not be determined for these soils in any of the four ecoregions.

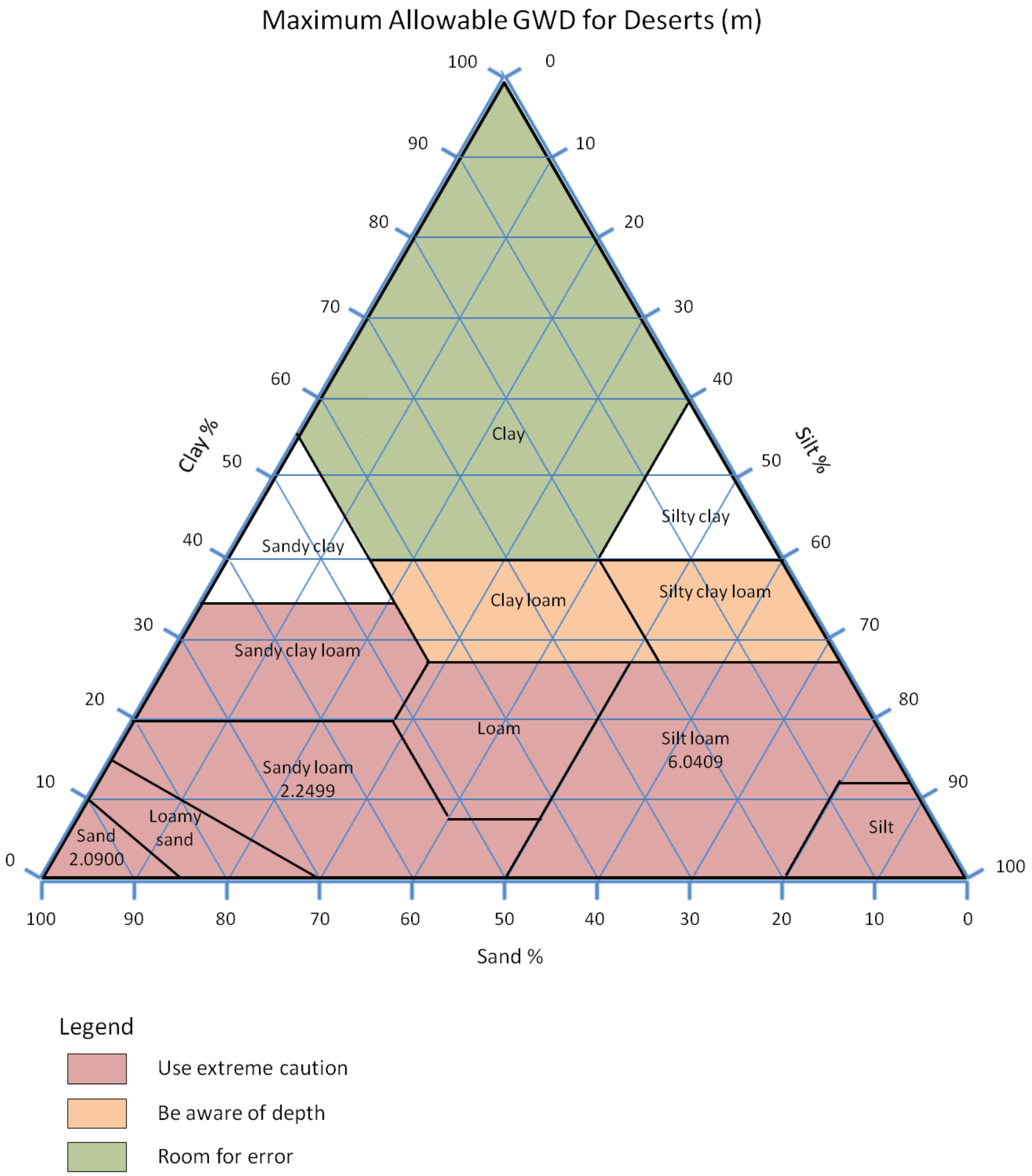


Figure 6. Maximum Allowable Groundwater Depth Guidance for Deserts (m)

Ecosystem managers can use these figures for guidance. The figures provide an idea of the maximum depth the groundwater table should be in order to sustain plant life in a particular soil within a particular ecoregion. By employing these figures, ecosystem managers would not need to conduct their own studies on the soil, water content, and plant wilting for all of the species in the region.

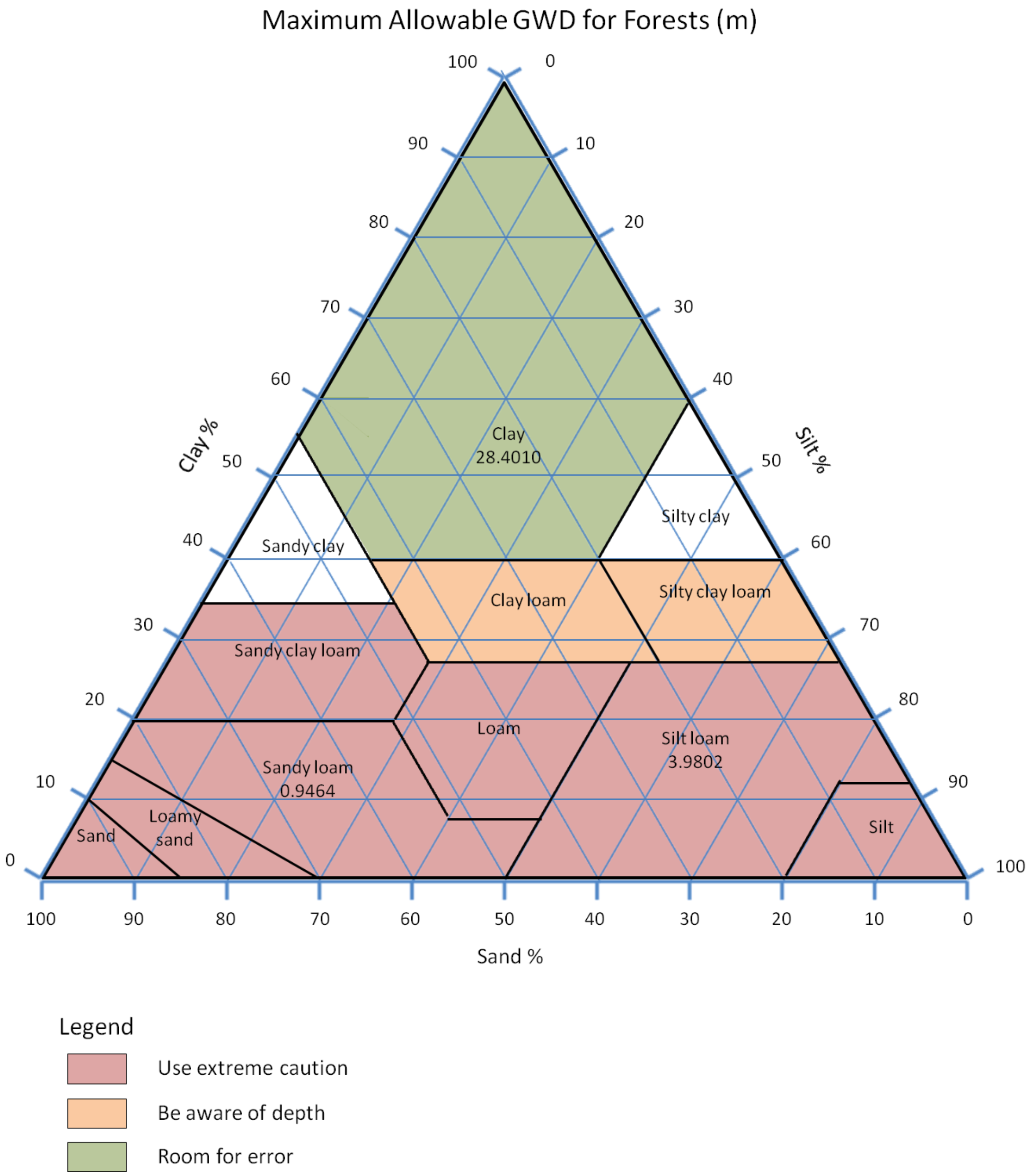


Figure 7. Maximum Allowable Groundwater Depth Guidance for Forests (m)

These figures are intended to provide a starting point for guidance and further scientific research in this field. Once further scientific studies have been conducted and additional data has been collected, the figures can be improved for the benefit of ecosystem managers. Currently, the color coding is the same between regions; however, this may change with the augmentation of the data set.

To determine the maximum depth of the groundwater table for an ecosystem requires knowledge of all of the plant species in the ecosystem. The question then becomes, which plant species should determine the maximum groundwater depth? Surely some plants will benefit from a shallower groundwater table than others. But others will be able to survive with deeper groundwater tables, which allows for greater human use of groundwater. There are a multitude of options for deciding the maximum depth of the groundwater table for an ecosystem. A manager could base it on the plant with the shallowest roots, or the plant with the deepest roots, or the mean rooting depth of the plants in the ecosystem. It is up to the manager to weigh the balance between plant survival and human need for water.

### ***Management Strategies***

When taken in sum, it is clear that many ecosystems are well-adapted to drought conditions under normal circumstances. Many plant species can access deep groundwater directly via roots, or can handle low water potentials and take advantage of the capillary fringe. Interestingly there is a third strategy that also helps maintain these plant communities. Discussed by Caldwell, Dawson, and Richards [86-89], hydraulic lift is a process whereby certain species actually transport water from deeper depths up to surface soil layers where it is released. Other plant species are then able to live off of this water. Moreira, et al. [90] studied hydraulic lift produced by tree species *Byrsonima crassa* and *Blepharocalyx salicifolius* in a tropical savanna in Brazil. They observed that both species were able to lift water from greater soil depths to shallower soil depths. Then, surrounding plant species, such as *Myrsine guianensis* and *Periandra mediterranea*, were able to uptake this water for their own use. This suggests that natural systems, if left alone with intact groundwater systems will be relatively resilient to changing frequency of droughts. Hydraulic lift is not restricted to any one plant type. In fact, plants classified as trees, shrubs, herbs, and grasses have all been documented to possess this valuable quality [89]. One would expect hydraulic lift to be a characteristic of plants in arid climates. While this is true, hydraulic lift is also a characteristic of plants found in other biomes [88-89]. Clearly, knowledge of plants in an ecosystem which have this property can be useful for a water manager.

Other ecosystem management strategies have been discussed in the literature. Tallis et al. [91] present the integrated ecosystem assessment (IEA) framework, which is designed to consider many aspects of ecosystem management, human influences, and decision making. Management of the groundwater table could easily be incorporated into this structure. Brandyk and Romanowicz [92] discussed groundwater table management specifically. They looked at shallow groundwater tables and incorporated soil moisture flow in their analysis. Their study differed from mine in that it did not cover a broad range of soils or ecoregions, nor did it identify plant rooting needs specifically. It did, however, provide a general mathematical calculation for groundwater table depth considering the flow of water through the soil. The calculated groundwater table depth was then compared to the range of allowable groundwater table depths, where the allowable range was determined based on the root zone of the plants in the region. Groundwater depths within the allowable range maintained current water usage, while groundwater depths below the allowable range implied the need for a change in water usage. The flow of water used in their study was beyond the scope of this study.

Yet another perspective for ecosystem management is presented by Breshears et al. [93]. In their study, they looked at two tree species in a semiarid woodland. The purpose of their study was to analyze the appropriate spacing of each plant species for sustaining sufficient soil water content for plant survival.

One additional possible strategy would be to apply the concept of a rule curve to groundwater management. In this study, groundwater table depths were considered to be static in order to represent the peak of the drought season. However, when looking at conditions year round, the groundwater table depth varies. Rule curves describe necessary actions to be taken when certain thresholds are reached. In the case of groundwater management, the distribution of the groundwater table depth should be determined first. Then, the deepest 75th and 90th percentile values of the groundwater table depth should be identified. When the 75th percentile depth is reached obligatory water conservation measures should be instituted. When the 90th percentile depth is reached groundwater wells should cease to be pumped from. This is one example of a possible rule curve applied to groundwater management.

Clearly, there are a variety of ways to focus ecosystem management strategies. This paper strives to emphasize that, despite the chosen strategy, the appropriate groundwater table depth for sustaining plant life should be a consideration when discussing ecosystem management.

Recently, Fan et al. studied water table dynamics in a series of papers [94-96]. They looked at modeling the groundwater table and climate change influences across the continental United States. More specifically, they studied the equilibrium water table depth, accounting for precipitation, evapotranspiration, and water flux in the soil column. My study contributes an additional element to their framework because it encourages the incorporation of the missing element of the capillary fringe height and its relevance for surface plant species. This would augment the significance of the results presented by Fan et al, especially during drought conditions.

Overall, groundwater will play a key role in addressing increasing water scarcity worldwide due simultaneously to population growth and climate change. Overdraft is a real threat due to the invisible nature of groundwater. Different management strategies are being used but my research indicates that, in particular, ensuring that groundwater decline does not go beyond certain thresholds is the key. These thresholds are dependent on the ecosystem and soil type as they interact to determine the capillary fringe height relative to plant wilting points and rooting depths. Careful management will help sustainable management.

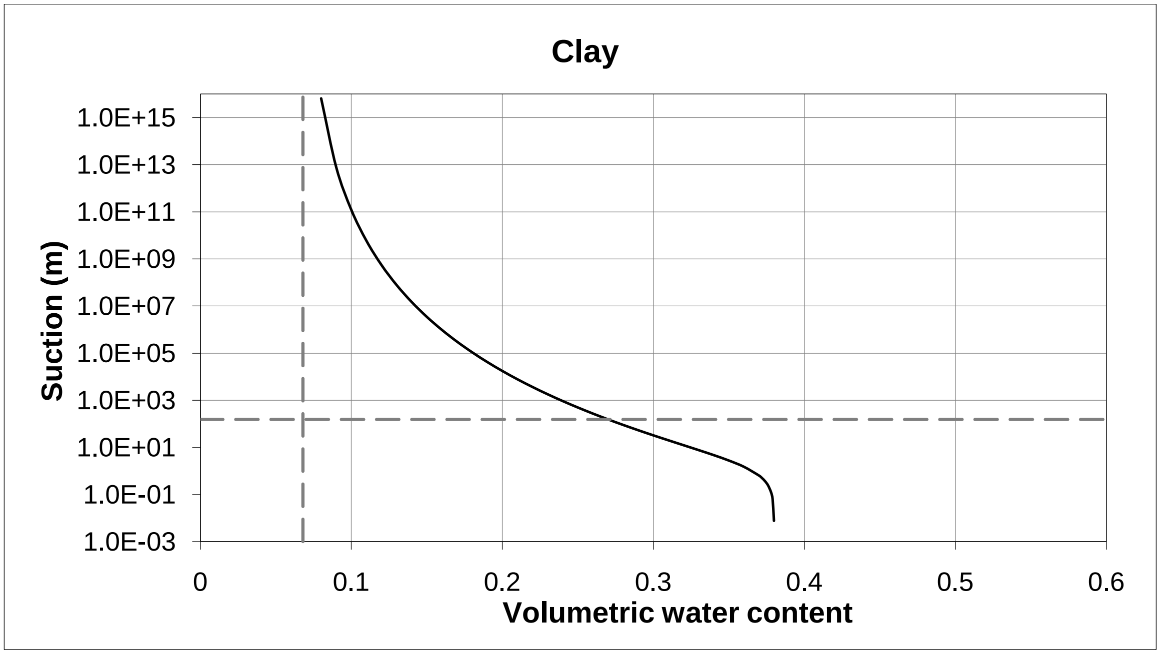
# APPENDIX A

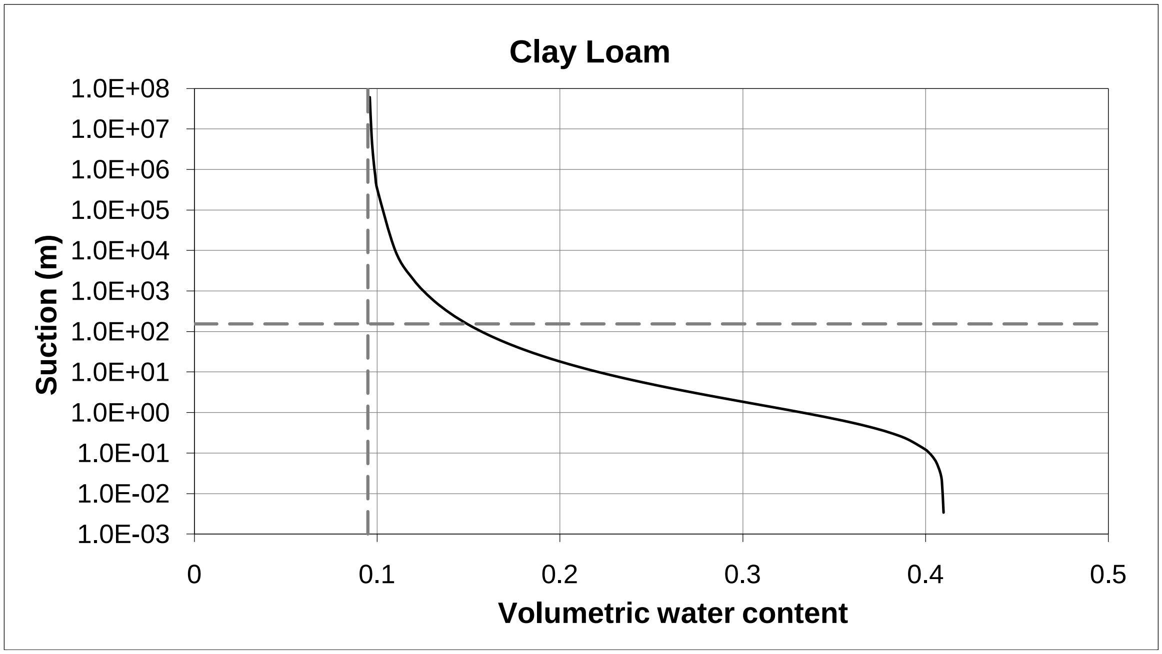
Comparison of pedosphere and Hausenbuiller bulk density values

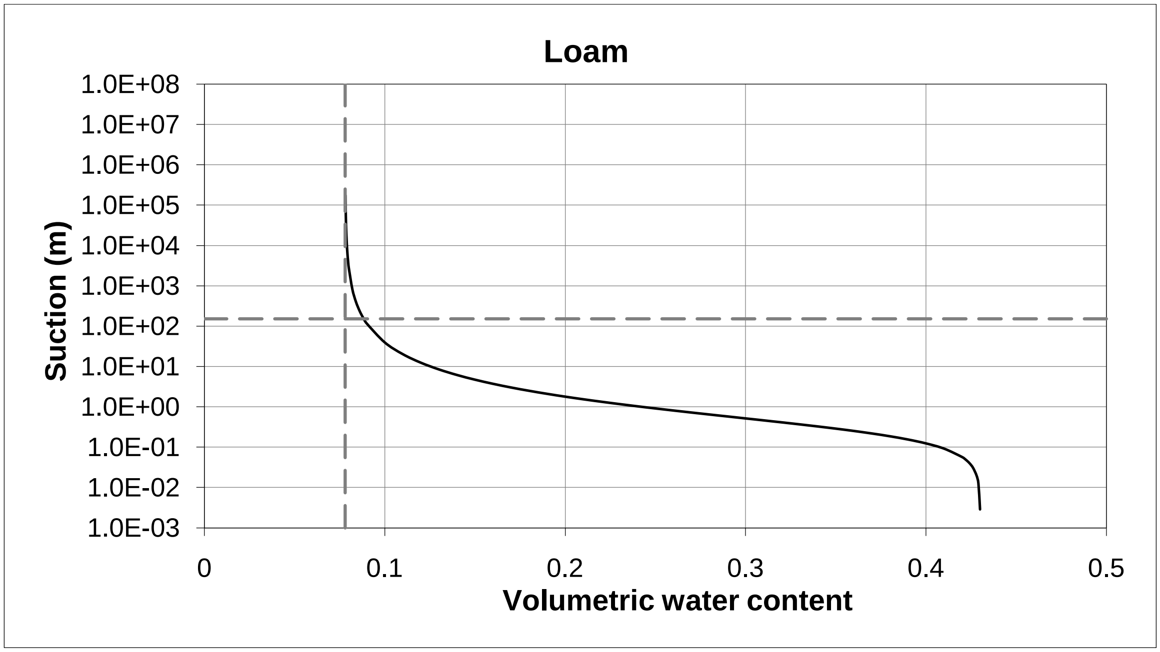
| Soil type | pedosphere bulk density (g/cm$^3$) | Hausenbuiller bulk density (g/cm$^3$) | % difference |
|---|---|---|---|
| Clay | 1.22 | 1.05 | 13.93% |
| Clay loam | 1.31 | 1.10 | 16.03% |
| Loam | 1.41 | 1.20 | 14.89% |
| Loamy sand | 1.60 | -- | -- |
| Silt | 1.48 | -- | -- |
| Silt loam | 1.41 | 1.15 | 18.44% |
| Silty clay | 1.22 | -- | -- |
| Silty clay loam | 1.27 | -- | -- |
| Sand | 1.71 | 1.55 | 9.36% |
| Sandy clay | 1.32 | -- | -- |
| Sandy clay loam | 1.40 | -- | -- |
| Sandy loam | 1.56 | 1.40 | 10.26% |

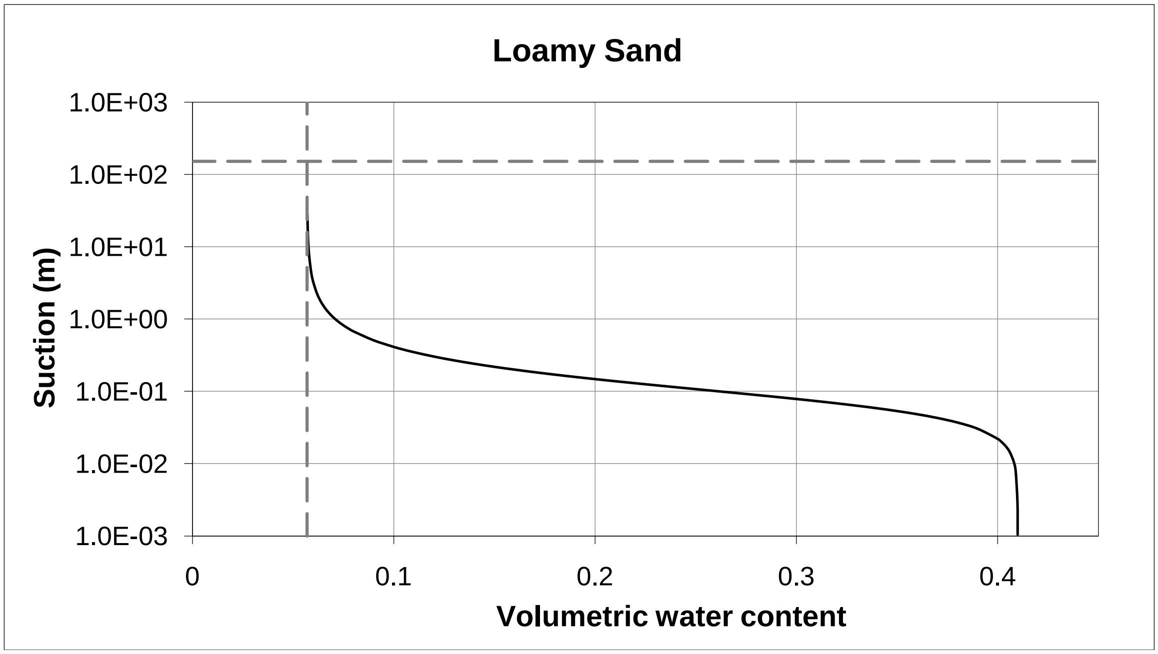
# APPENDIX B

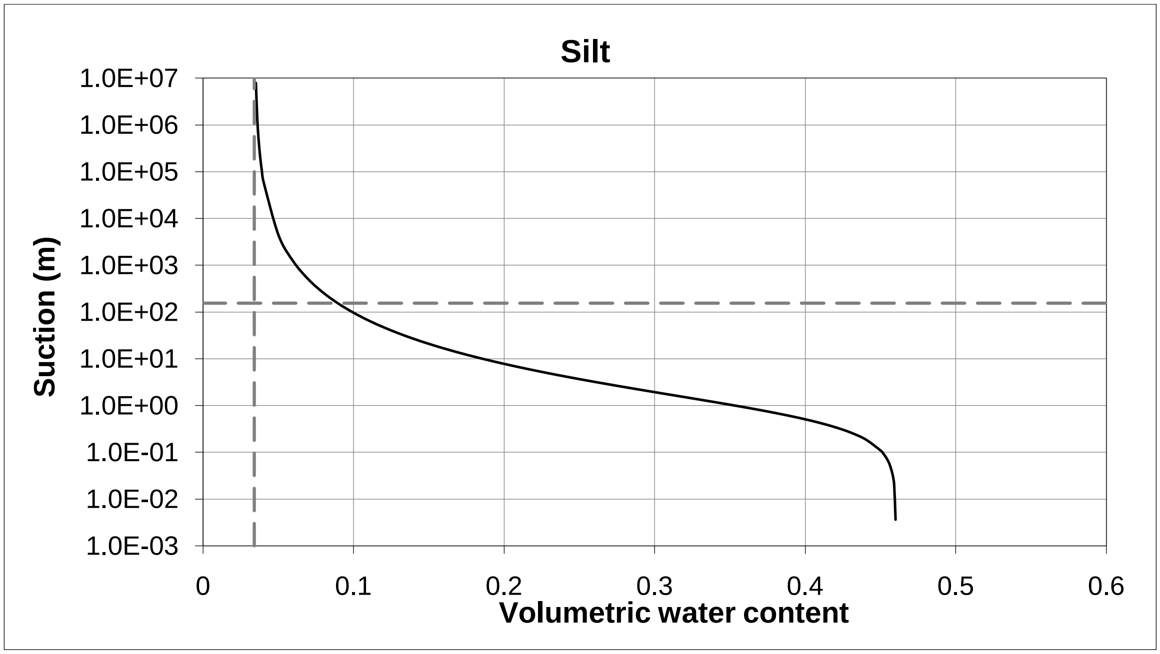
van Genuchten Soil Water Characteristic Curves for All 12 Soil Types Using the Carsel Parameters

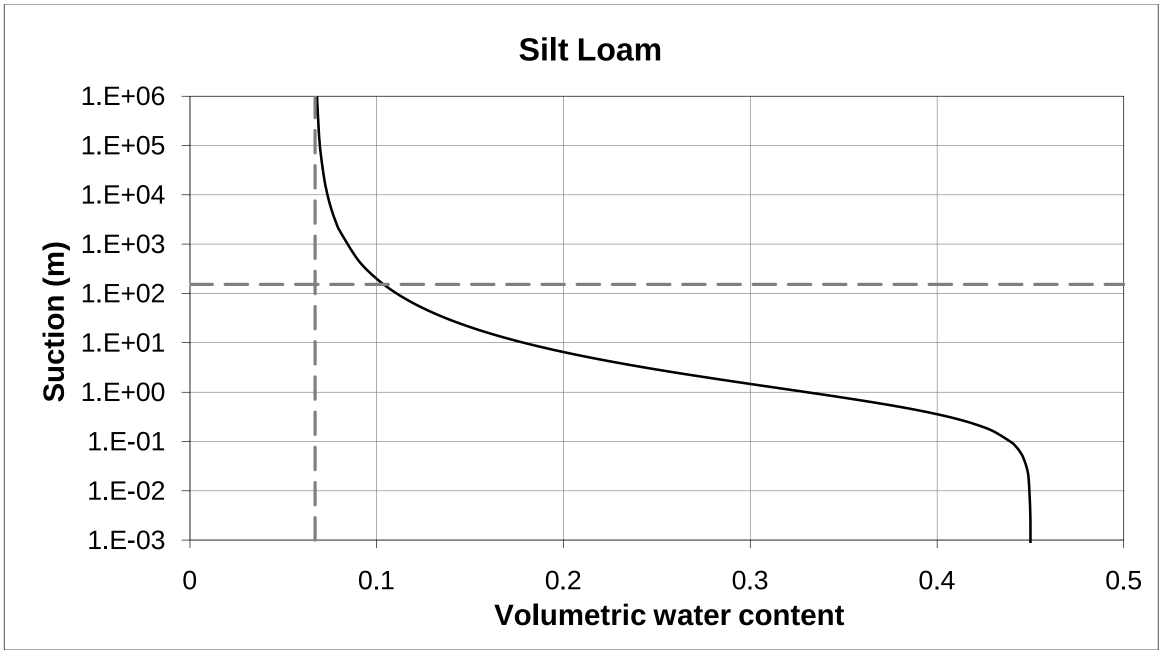


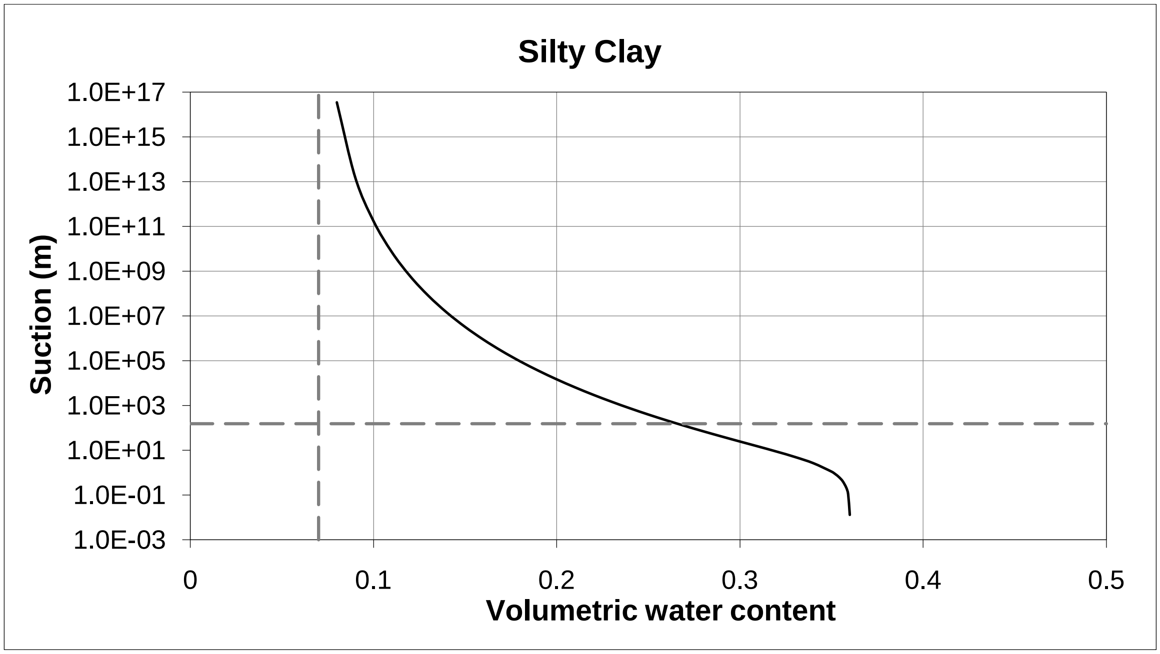


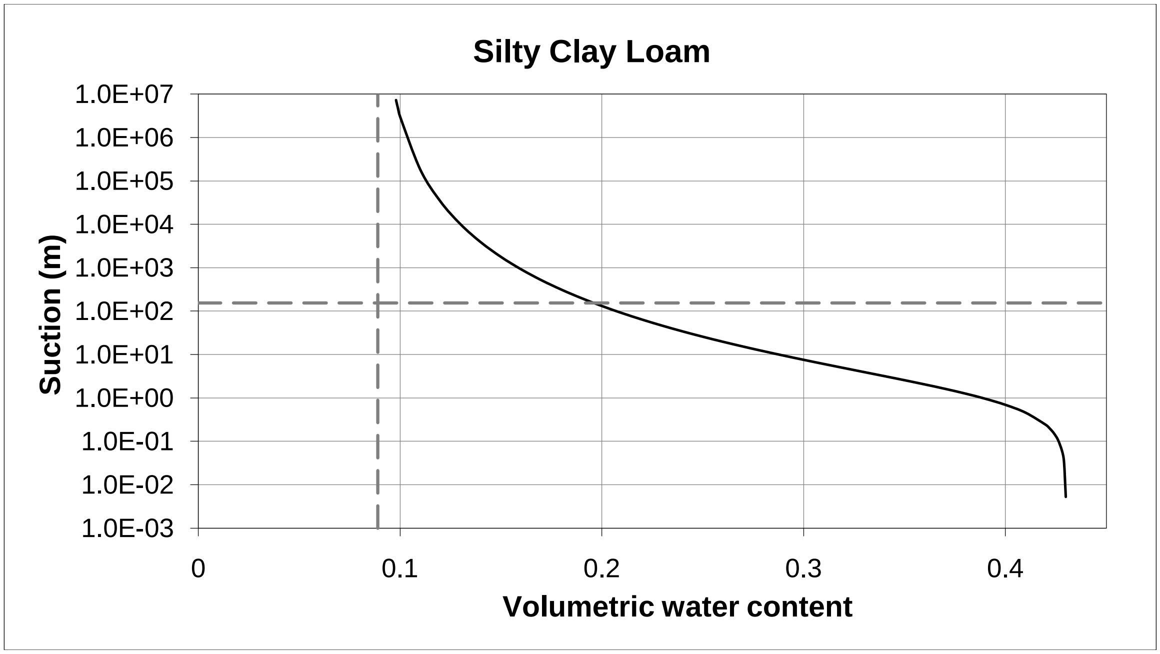

Loam
1.0E+08
1.0E+07
1.0E+06
1.0E+05
1.0E+04
1.0E+03
1.0E+02
1.0E+01
1.0E+00
1.0E-01
1.0E-02
1.0E-03
Suction (m)
0
0.1
0.2
0.3
0.4
0.5
Volumetric water content

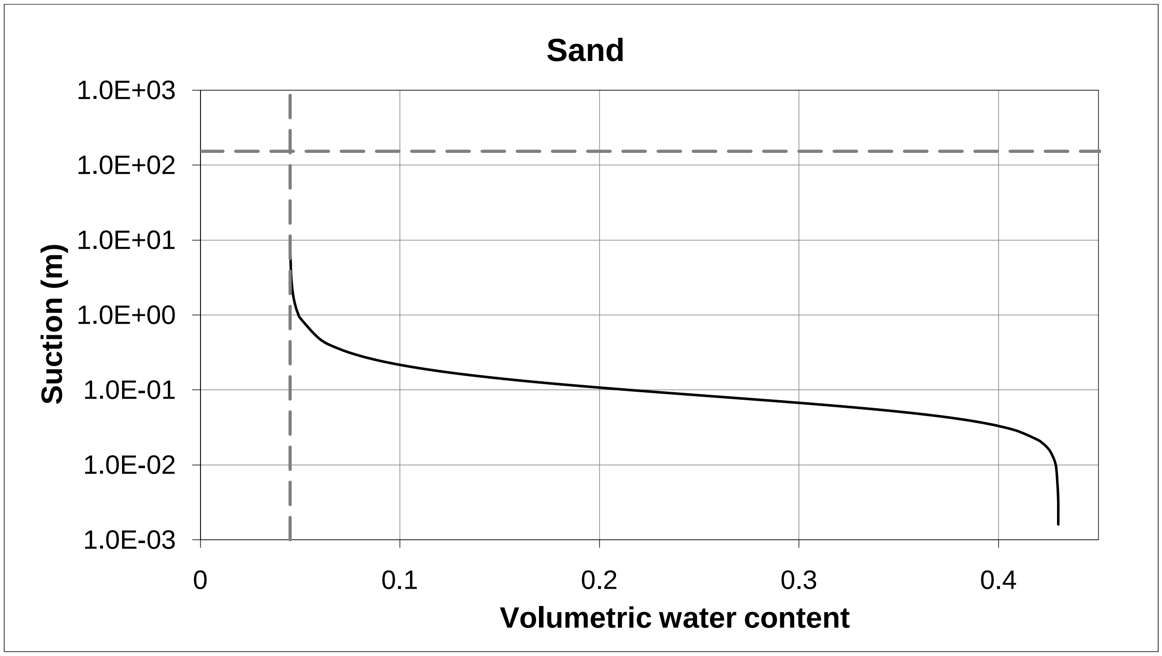

Loamy Sand
1.0E+03
1.0E+02
1.0E+01
1.0E+00
1.0E-01
1.0E-02
1.0E-03
Suction (m)
0
0.1
0.2
0.3
0.4
Volumetric water content

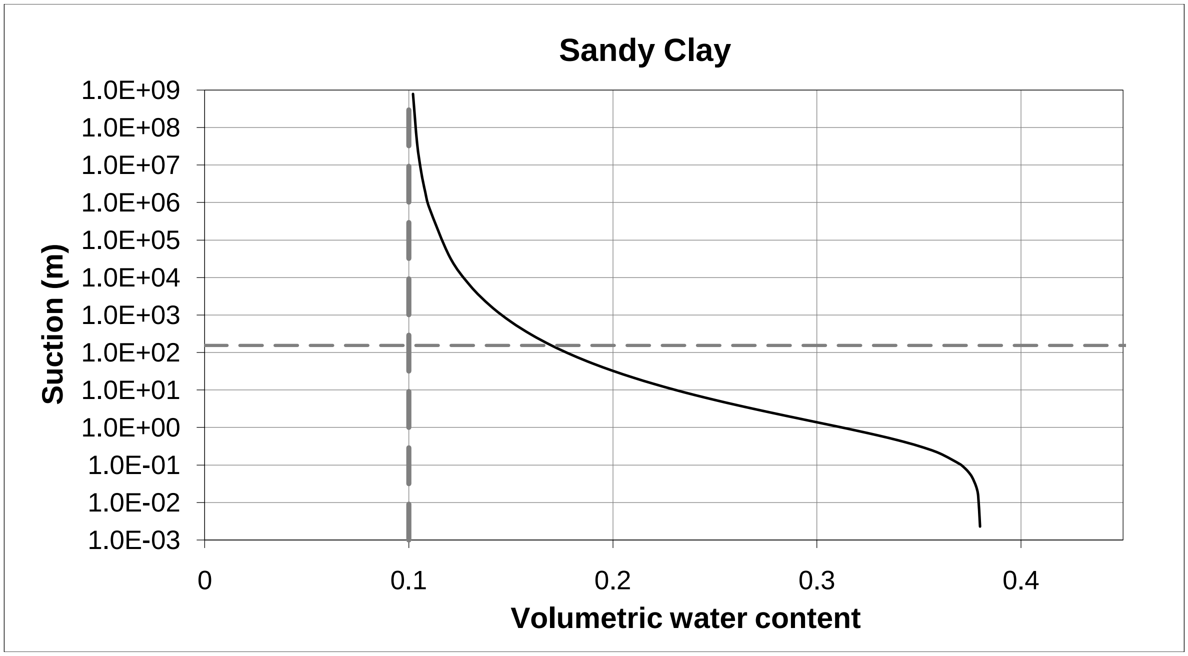

Silt
1.0E+07
1.0E+06
1.0E+05
1.0E+04
1.0E+03
1.0E+02
1.0E+01
1.0E+00
1.0E-01
1.0E-02
1.0E-03
Suction (m)
0
0.1
0.2
0.3
0.4
0.5
0.6
Volumetric water content

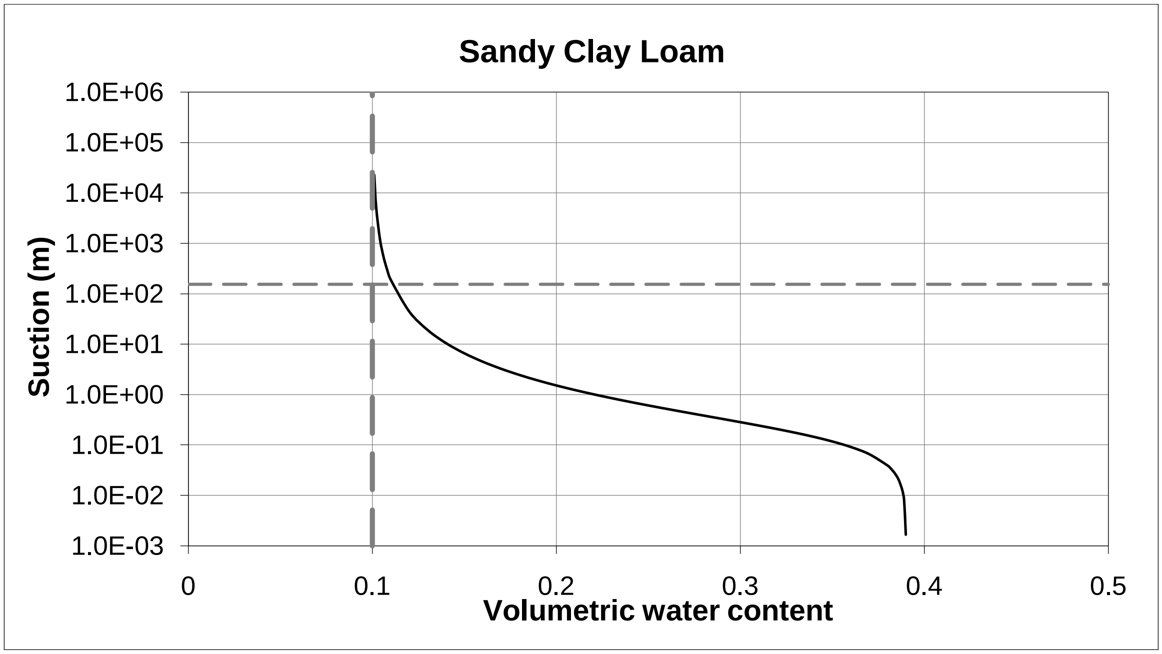

Silt Loam
1.E+06
1.E+05
1.E+04
1.E+03
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
1.E-03
Suction (m)
0
0.1
0.2
0.3
0.4
0.5
Volumetric water content

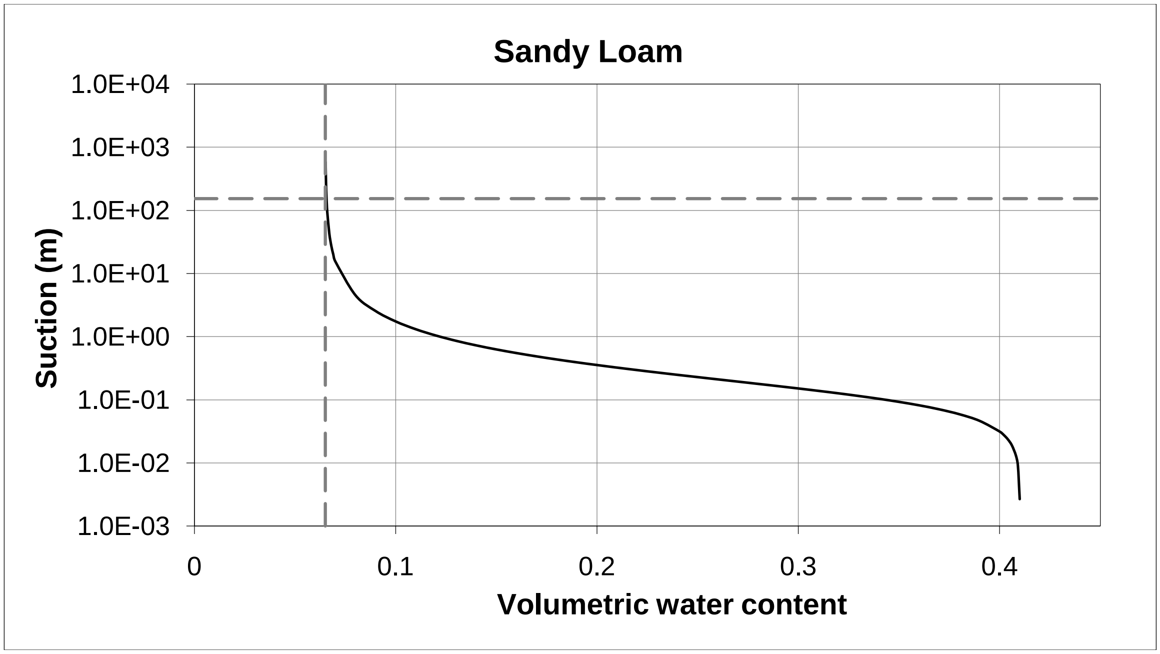

Silty Clay
Suction (m)
1.0E+17
1.0E+15
1.0E+13
1.0E+11
1.0E+09
1.0E+07
1.0E+05
1.0E+03
1.0E+01
1.0E-01
1.0E-03
0
0.1
0.2
0.3
0.4
0.5
Volumetric water content


Silty Clay Loam
Suction (m)
1.0E+07
1.0E+06
1.0E+05
1.0E+04
1.0E+03
1.0E+02
1.0E+01
1.0E+00
1.0E-01
1.0E-02
1.0E-03
0
0.1
0.2
0.3
0.4
Volumetric water content


Sand
1.0E+03
1.0E+02
1.0E+01
1.0E+00
1.0E-01
1.0E-02
1.0E-03
Suction (m)
0
0.1
0.2
0.3
0.4
Volumetric water content


Sandy Clay
1.0E+09
1.0E+08
1.0E+07
1.0E+06
1.0E+05
1.0E+04
1.0E+03
1.0E+02
1.0E+01
1.0E+00
1.0E-01
1.0E-02
1.0E-03
Suction (m)
0
0.1
0.2
0.3
0.4
Volumetric water content


Sandy Clay Loam
Suction (m)
1.0E+06
1.0E+05
1.0E+04
1.0E+03
1.0E+02
1.0E+01
1.0E+00
1.0E-01
1.0E-02
1.0E-03
0
0.1
0.2
0.3
0.4
0.5
Volumetric water content


Sandy Loam
Suction (m)
1.0E+04
1.0E+03
1.0E+02
1.0E+01
1.0E+00
1.0E-01
1.0E-02
1.0E-03
0
0.1
0.2
0.3
0.4
Volumetric water content

# APPENDIX C

Reference Capillary Fringe Heights

| Soil name | Soil type | Capillary fringe height (m) | Source 1 | Source 2 |
|---|---|---|---|---|
| clay | clay | 13.000 | gillham | |
| clay | clay | 7.000 | white | |
| clay | clay | 2764.380 | elkadi | |
| clays | clay | 9.14-27.43 | orr_dp | |
| Gault clay | clay | 904.464 | aubertin | Alimi-Ichola and Bentoumi (1995) |
| clay loam | clay loam | 4.720 | elkadi | |
| loam | loam | 0.870 | elkadi | |
| loamy sand | loamy sand | 0.120 | elkadi | |
| fine silts | silt | 1.000 | horton | |
| London Silt | silt | 10.565 | aubertin | MacKay (1997) |
| silt | silt | 0.700 | gillham | |
| silt | silt | 3.840 | elkadi | |
| silts | silt | 0.914-9.14 | orr_dp | |
| silt loam | silt loam | 2.530 | elkadi | |
| Guadalix Red silty clay | silty clay | 1323.052 | aubertin | Vanapalli et al. (1998) |
| silty clay | silty clay | 4423.010 | elkadi | |
| silty clay loam | silty clay loam | 19.950 | elkadi | |
| Beaver creek sand consolidated at 10kPa | sand | 2.033 | aubertin | Bruch (1993) |
| Beaver creek sand consolidated at 5kPa | sand | 2.018 | aubertin | Bruch (1993) |
| Beaver creek sand consolidated at 5kPa | sand | 0.878 | aubertin | Lim et al. (1998) |
| borden sand | sand | 1.100 | aubertin | Sydor (1992) |
| coarse grey sands | sand | 0.600 | zencich | |
| coarse sand | sand | 0.152 | orr_dp | |
| coarse sand | sand | 0.152 | aubertin | Sydor (1992) |
| fine sand | sand | 0.305-0.914 | orr_dp | |
| modified borden sand | sand | 1.128 | aubertin | Sydor (1992) |
| Ottawa sand | sand | 1.074 | aubertin | MacKay (1997) |
| Sacrete sand | sand | 0.554 | aubertin | Kissiova (1996) |
| Sacrete sand | sand | 0.502 | aubertin | Kissiova (1996) |
| sand | sand | 0.007 | gillham | |
| sand | sand | 5.200 | ronen_2 | |
| sand | sand | 0.330 | ataie | |
| sand | sand | 1.650 | ataie | |
| sand | sand | 0.090 | elkadi | |
| sandy clay | sandy clay | 7.390 | elkadi | |
| Sandy clay till (consolidated at 200 kPa) | sandy clay | 1666.547 | aubertin | Vanapalli et al. (1996) |

| | | | | |
|---|---|---|---|---|
| Sandy clay till (consolidated at 25 kPa) | sandy clay | 1327.066 | aubertin | Vanapalli et al. (1996) |
| Sandy clay till (consolidated at 25 kPa) | sandy clay | 1314.891 | aubertin | Vanapalli et al. (1996) |
| sandy clay loam | sandy clay loam | 0.660 | elkadi | |
| sandy loam | sandy loam | 0.250 | elkadi | |
| Silty sand PPCT11 | silty sand | 671.851 | aubertin | Huang et al. (1998) |
| Silty sand PPCT16 | silty sand | 777.780 | aubertin | Huang et al. (1998) |
| Silty sand PPCT21 | silty sand | 717.355 | aubertin | Huang et al. (1998) |
| Silty sand PPCT26 | silty sand | 847.323 | aubertin | Huang et al. (1998) |
| coarse cobbles | | 0.010 | horton | |
| gravel | | .0305-.1229 | orr_dp | |
| Tailings at 150m | | 2.985 | aubertin | Rassam and Williams (1999) |
| Tailings at 50m | | 1.080 | aubertin | Rassam and Williams (1999) |
| Tailings Bevcon | | 14.215 | aubertin | Ricard (1994) |
| Tailings Bevcon | | 13.494 | aubertin | Ricard (1994) |
| Tailings Bevcon | | 12.052 | aubertin | Ricard (1994) |
| Tailings Bevcon | | 15.576 | aubertin | Kissiova (1996) |
| Tailings Bevcon | | 13.056 | aubertin | Kissiova (1996) |
| Tailings Bevcon | | 9.650 | aubertin | Kissiova (1996) |
| Tailings Senator | | 13.424 | aubertin | Ricard (1994) |
| Tailings Senator | | 11.531 | aubertin | Ricard (1994) |
| Tailings Sigma | | 13.843 | aubertin | Ricard (1994) |
| Tailings Sigma | | 12.897 | aubertin | Ricard (1994) |
| Tailings Sigma | | 11.996 | aubertin | Ricard (1994) |
| Tailings Sigma | | 14.128 | aubertin | Kissiova (1996) |
| Tailings Sigma | | 12.950 | aubertin | Kissiova (1996) |
| Tailings Sigma + 10% Bentonite | | 38.285 | aubertin | Ricard (1994) |
| Tailings Sigma + 10% Bentonite | | 28.308 | aubertin | Ricard (1994) |
| Tailings Simga (coarse) | | 13.995 | aubertin | Authors' results |
| Tailings Simga (coarse) | | 12.615 | aubertin | Authors' results |
| Tailings Simga (coarse) | | 11.483 | aubertin | Authors' results |
| Tailings Simga (fine) | | 12.058 | aubertin | Authors' results |
| Tailings Simga (fine) | | 11.732 | aubertin | Authors' results |
| Till | | 19.590 | aubertin | Authors' results |
| Till | | 17.351 | aubertin | Authors' results |
| Till | | 16.869 | aubertin | Authors' results |
| Till | | 15.375 | aubertin | Authors' results |

| | | | | |
|---|---|---|---|---|
| Till cover | | 1773.010 | aubertin | O'Kane et al. (1998) |
| Record 3713 | | 1314.891 | aubertin | Fredlund (1999) |
| Record 3714 | | 1314.891 | aubertin | Fredlund (1999) |
| Record 3715 | | 1596.025 | aubertin | Fredlund (1999) |
| Record 3716 | | 1511.847 | aubertin | Fredlund (1999) |
| Record 3717 | | 1511.847 | aubertin | Fredlund (1999) |
| Record 3718 | | 1383.427 | aubertin | Fredlund (1999) |
| Record 3720 | | 1312.482 | aubertin | Fredlund (1999) |
| Record 3728 | | 1636.108 | aubertin | Fredlund (1999) |
| Record 55 | | 1508.664 | aubertin | Fredlund (1999) |
| Record 65 | | 1312.482 | aubertin | Fredlund (1999) |
| Record 66 | | 1636.108 | aubertin | Fredlund (1999) |
| Record 70 | | 1613.999 | aubertin | Fredlund (1999) |
| Record 71 | | 1383.427 | aubertin | Fredlund (1999) |
| Record 72 | | 1518.253 | aubertin | Fredlund (1999) |
| Record 73 | | 1314.891 | aubertin | Fredlund (1999) |
| Record 75 | | 1666.547 | aubertin | Fredlund (1999) |
| Record 76 | | 1926.385 | aubertin | Fredlund (1999) |

With all of the sources combined there were a total of 90 capillary fringe height references. However, some of the data points could not be classified into one of the 12 soil types. Several data points from Aubertin (2003) were originally from Fredlund (1999). The soils were called “record” followed by some number. Unfortunately, I was unable to access the Fredlund (1999) work, and therefore could not verify the soil type according to the classification system employed here. Many of the other data points provided by Aubertin (2003) were “tailings”, which I could also not classify into any of the 12 soil types. For that reason, I moved all of the “record” and “tailing” data points to the end of the list. Also, there were a couple of other data points that described larger gravels that I am not considering, and a few that employed silty sand, which I also did not know how to classify. Those too are below the classified data points in the table above. This left 40 data points which fell into the soil classification system. The capillary fringe height reference values from the El-Kadi article were calculated based on the equation provided in the article, and the Carsel parameters values. Thus, these were not actual capillary fringe height observations. These represent 12 of the 40 data points within the soil classifications.

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