Florida Onsite Sewage Nitrogen Reduction Strategies Study

Task D.8

Complex Soil Model Development

Revised Specification Memo

August 2013

44237-001

HAZEN AND SAWYER
Environmental Engineers & Scientists

In association with:

AET
Applied Environmental Technology

Otis Environmental
Consultants, LLC

Florida Onsite Sewage Nitrogen Reduction Strategies Study

TASK D.8
REVISED SPECIFICATION MEMO

Complex Soil Model Development

Prepared for:

Florida Department of Health
Division of Disease Control and Health Protection
Bureau of Environmental Health
Onsite Sewage Programs
4042 Bald Cypress Way Bin #A-08
Tallahassee, FL 32399-1713

FDOH Contract CORCL

August 2013

Prepared by:

HAZEN AND SAWYER
Environmental Engineers & Scientists

In Association With:

SCHOOL OF MINES COLORADO 1874

Section 1.0
Background

1.0 Background

Task D of the Florida Onsite Sewage Nitrogen Reduction Strategies Study includes development of a complex soil model (Task D.8) to aid evaluation of nitrogen reduction in Florida soils. This complex soil model will enable estimation of site-specific soil treatment in the vadose zone with the model output ultimately serving as the input to the aquifer model (Task D.11). This specification memo was prepared by the Colorado School of Mines (CSM) to document the *conceptual framework, code modification, and code evaluation* for the complex soil model (STUMOD-FL) including the coding and code evaluation required to implement the theory described herein. Final documentation will be conducted as part of Tasks D.16 and D.17.

The basis of the complex soil model is STUMOD (Soil Treatment Unit Model), a user friendly spreadsheet model that is also rigorous enough to include hydraulic and nitrogen-transformation processes. STUMOD is a detailed tool that can estimate nitrogen removal in the unsaturated soil below the infiltrative surface of an onsite wastewater treatment system (OWTS; referred to in Florida as "onsite sewage treatment and disposal systems"). STUMOD was developed at Colorado School of Mines through support from the Water Environment Research Foundation (McCray et al., 2010). Spreadsheet tools, such as STUMOD, enable evaluation of user-specified conditions, but are presented in a simple-to-use format that does not require prior modeling knowledge or lengthy model run times. Of course, achieving these advantages requires that the incorporated treatment processes and operating conditions are simplified (e.g., constant loading rate, one-dimensional infiltration and treatment, etc).

STUMOD is based on fundamental principles of water movement and contaminant transport using an analytical solution to calculate pressure and moisture content profiles in the vadose zone and a simplification of the general advection dispersion equation (Geza et al., 2009 and 2010). STUMOD has been adapted to Florida-specific soil and climate data that includes parameters representing dominant soil properties. In addition, STUMOD was adapted to account for evapotranspiration (ET) and the effect of high/seasonally variable water tables on nitrogen removal in soil. Modifications were also made to the method of calculation for travel time and incorporation of three soil layers. This modified and adapted soil model developed in Task D.8 will be referred to as STUMOD-FL.

The following description of STUMOD is summarized from McCray et al. (2010). The same description applies to STUMOD-FL. STUMOD was developed for transport in the unsaturated zone. Vertical flow is assumed to predominate with contaminants transported by advection (the effect of dispersion ignored). Continuous, steady state effluent application and infiltration is assumed. As the infiltration reaches steady state, the pressure profile or soil moisture profile does not change with time and a steady state concentration with depth is computed based on Monod reaction rates for nitrification and denitrification correlated to the soil moisture profile. The effect of temperature on nitrification and denitrification is also considered. For STUMOD-FL, in addition to a biomat, three soil layers have also been added. STUMOD can accept nitrogen input concentrations as ammonium, nitrate, or a combination of ammonium and nitrate. Ammonium-nitrogen can be removed through both adsorption and denitrification. Nitrate-nitrogen is removed through denitrification.

The STUMOD-FL input parameters include operational parameters (effluent concentrations, hydraulic loading rates) and calibration parameters for hydraulics and nutrient transformation. Default values are provided to aid the user during selection of inputs. However, STUMOD-FL allows user-specified input and can be calibrated to site-specific data. The output is the expected steady-state performance (i.e., constituent concentration) at the centerline under the point of effluent application.

The overall goal is to develop a user friendly tool that enables a wide range of users to assess soil treatment unit performance over a relevant range of Florida conditions. Appropriate use of STUMOD-FL depends on the nature of the problem at hand, the desire and ability to incorporate specific site complexities or climate conditions, the sophistication of the user, the resources available to the user, and the relative risk associated with an improper design or model output. Use of STUMOD-FL requires familiarity with spreadsheets and parameter selection, and understanding of soil hydraulic and treatment mechanisms.

STUMOD-FL primarily addresses the most common operating conditions associated with trench and mound systems. Model outputs provide insight into the behavior of soil treatment and quantitative estimations of nitrogen removal as affected by a range of conditions. These insights and outcomes then aid decisions during design and/or planning through better understanding of the influence of operating and site conditions on soil treatment unit performance. However, it must be recognized that numerous investigations into the fate of nitrogen below OWTS have shown that the percent removal is quite variable even for sites that appear similar. The effects of dispersion, dilution, spatial variability in soil properties, wastewater infiltration rates, and temperature impacts are a few of the factors resulting in this variability in removal rates (Siegrist et al., 2001; Otis, 2007; McCray et al., 2009). Thus, more complex models must address the performance of many complex processes and less-common operating conditions.

Development of STUMOD-FL as described above required modification of STUMOD including: 1) parameter estimation for Florida conditions, 2) development of the theory and associated coding to incorporate the effects of ET, and 3) development of the theory and associated coding to incorporate a high/seasonally variable water table.

Section 2.0
Soil Parameter Estimations for Florida Conditions

2.0 Soil Parameter Estimations for Florida Conditions

The model requires a significant level of user sophistication with regard to using the appropriate input parameters. To aid in this process, the STUMOD-FL graphical user interface includes default parameters estimated from Florida soils. Because, over 400 soil series are described in Florida, it is recognized that no simple tool (or model) can encompass each soil condition. Thus, the methodology used to estimate default STUMOD-FL parameters for Florida soils is described below.

An assessment of soil properties included evaluating all available data records from the Florida Soil Characterization Data Retrieval System (University of Florida, 2007). This database contains a total of 8,272 individual data records. All data records were sorted by soil textural classification and then screened for complete data sets (incomplete data sets were removed from further analysis) and data records applicable to depths of less than 5ft below ground surface. Complete data sets included field sample measurements for: sample depth interval; fraction of sand, silt, and clay; particle size distributions for the sand fraction; saturated hydraulic conductivity (K_{sat}); bulk density; and corresponding water contents at suctions of 3.5, 20, 30, 45, 60, 80, 150, 200, 340, and 15,000 cm. All records for a given soil texture (e.g., sandy clay loam, clay, etc.) were then combined and descriptive statistics were evaluated. Descriptive statistics are: minimum value, maximum value, average, median, standard deviation, and the interquartile range (25 and 75th percentiles). Median values were then used to represent Florida specific properties for the soil texture classification and are used as the default parameter in the STUMOD-FL graphical user interface.

The relevant input parameters for STUMOD-FL are K_{sat}, residual water content (θ_r), water content at saturation (θ_s), and the van Genuchten fitting parameters α and n. K_{sat}, θ_r, and θ_s were estimated as the median value from the reported field data described above. Water content at 15,000 cm suction (15 bar) was assumed to represent θ_r and water content at 3.5 cm suction was assumed to represent θ_s. To approximate the van Genuchten parameters (α and n), the median reported soil moisture values at each suction head were paired. Solver was then executed using the van Genuchten equation while minimizing the sum of the squares. A summary of the default input parameters to be used in STUMOD-FL are summarized in Table 2.1.

Due to the wide variation in the number of complete individual data records within the Florida Soil Characterization Data Retrieval System, parameter estimates were then also determined for individual soil series (e.g., Millhopper, Candler, Myakka, etc.) based on several different approaches depending on the level of information available (Sections 2.1 – 2.3). This approach incorporates soils that represent 70% of the issued permits for trench or beds (information provided by FDOH) and approximately 68% of the total land area. Specifically soils were included in the evaluation and estimation of input parameters for 15,619 of the total 22,362 permits issued and ~18 million of the total ~26 million acres of land area.

Table 2.1
Summary of Estimated Default Parameters for STUMOD-FL based on Florida Soils

		Texture Fractions			Hydraulic Conductivity	Bulk Density	Residual Water Content (at 15 bars)	Saturated Water Content (at 3.5 cm)	Estimated Van Genuch-ten Parameters	
Classification	**n**	**Sand**	**Silt**	**Clay**	K_{sat}	ρ	θ_r	θ_s	α	η
	-	%	%	%	cm/d	g/cm^3	cm^3/cm^3	cm^3/cm^3	1/cm	–
Sand, more permeable*	1092	96.2	2.1	1.5	670.8	1.51	1.30	38.74	0.024	2.52
Sand, less permeable*	707	92.5	4.4	2.5	352.6	1.55	1.10	37.94	0.020	2.24
Clay	88	29.2	13.0	51.3	3.4	1.37	21.46	48.62	0.004	3.79
Clay Loam	9	38.0	30.5	31.4	7.4	1.44	15.24	46.21	0.009	1.76
Loam	23	45.0	35.4	20.1	17.0	1.36	10.35	42.14	0.012	1.63
Loamy Sand	460	84.8	8.1	7.2	164.9	1.57	3.64	37.78	0.020	1.76
Sandy Clay	56	51.9	7.6	38.8	14.2	1.55	15.41	41.64	0.004	3.45
Sandy Clay Loam	122	66.2	7.3	25.2	17.5	1.60	10.54	38.85	0.009	1.84
Sandy Loam	468	76.6	7.8	15.2	36.8	1.61	6.60	36.88	0.011	1.73
Silt	6	0.6	88.7	9.2	371.5	1.08	5.14	60.14	0.003	1.73
Silt Loam	9	5.7	82.0	15.8	185.3	1.01	5.78	60.54	0.003	1.69
Silty Clay**	0	-	-	-	-	-	-	-	-	-
Silty Clay Loam	5	5.8	65.6	28.9	7.4	1.13	27.71	59.86	0.009	1.51

* Sand soil series split into two groupings based on HCA, not textural classification – See D.7 80% Progress Report.
** No complete data records in the Florida database for silty clay (<5ft deep).

2.1 Parameter Estimation Method for Sand

Due to the prevalence of sandy soil textures in Florida, and in context of the finding that relatively few soils series comprise the majority of the land area, a sand soil series was included for further evaluation if the series was ranked in the top 30 of any of three following criteria: 1) most frequently permitted soil series (based on number of recent permits issued), 2) largest areal extent based on total land area (acreage) in Florida, or 3) largest areal extent (again based on acreage) within all sand series. All sand textures (sand, fine sand, very fine sand, etc.) were included in the analysis. Excluded from the analysis were the Urban series. This approach resulted in analyses of 1,799 complete data records representing 40 individual sand series (see Tables 2.2 and 2.4 in the Task D.7 80% Progress report also included in Appendix A for completeness).

For the Task D.7 HYDRUS-2D simulations, these 1,799 data records for sand soil series were summarized into two representative subgroups: a more permeable sand and a less permeable sand. This was done using a hierarchical cluster analysis to determine the subgrouping of sand soil series (see Task D.7 80% Complete progress report). Two groupings were identified: “More Permeable Sand” characterized generally by K_{sat} > 500 cm/d, % very fine sand <10%, and total sand fractions of >95%; and “Less Permeable Sand” characterized generally by K_{sat} <500 cm/d, % very fine sand >10%, and total sand fractions of <95%. These two groupings will be incorporated into the STUMOD-FL graphical user interface to enable users to select either more permeable sand characteristics or less permeable sand characteristics.

To determine the default input parameters, all data records from each grouping were combined and descriptive statistics calculated. Following the method described above (i.e., paring of median soil moisture values at each suction head then solving the van Genuchten equation while minimizing the sum of the squares), default parameters were estimated as listed in Table 2.1. In addition, parameter estimates for each of the 40 individual sand series will be incorporated into STUMOD-FL as a look-up table.

2.2 Parameter Estimation Method for Sandy Clay Loam

To determine model parameters for the sandy clay loam, an individual data record was included for evaluation based on three criteria: 1) the Florida Soil Characterization Data Retrieval System listed the textural classification as “sandy clay loam”, 2) the series was included in the top 60 frequently permitted soil series, *and* 3) the series was included within the top 60 largest areal extent based on total land area in Florida. This ensured that the data evaluated was representative of a sandy clay loam even though the series and/or shallow depths might have a higher sand fraction (e.g., Orangeburg, Dothan, etc.). This approach resulted in analyses of 122 complete data records representing 31 individual soil series (see Table 2.3 in the Task D.7 80% Progress report also included in Appendix A for completeness).

To determine the default input parameters for sandy clay loam, all 122 data records were combined and descriptive statistics calculated. Following the method described above (i.e., paring of median soil moisture values at each suction head then solving the van Genuchten equation while minimizing the sum of the squares), default parameters were estimated as listed in Table 2.1. In addition, parameters were estimated for individual series if 5 or more complete data records were available. These parameter estimates for the individual soil series will be incorporated into STUMOD-FL as a look-up table.

2.3 Parameter Estimation Method for Other Soil Textures

Relative to the sand textures, less data was available for other soil textures (loamy sand, sandy loam, loam, silt loam, silt, silty clay loam, sandy clay, clay loam, and clay) in the Florida Soil Characterization Data Retrieval System (see Table 2.1). For these remaining soil textures, a data record was included for evaluation based on the textural classification listed in the Florida Soil Characterization Data Retrieval System and soil depths <5 ft below the ground surface. For silts, only 11 data records were in the Florida Soil Characterization Data Retrieval System and of these 11 data records, only two were complete data records in the top 5ft of soil. Rather than omit silt textures from STUMOD-FL, the Data Retrieval System was sorted by the % silt and complete records with silt fractions >40% were retained for further analysis. This subset, was further sorted by the silt fraction to identify data records for silt (>87% silt and <20% sand), silt loam (73 – 87% silt and < 50% sand), silty clay loam (>60% silt and >25% clay), and silty clay (> 40% silt and >40% clay). There were no records that qualified as a silty clay.

Again, to determine the default input parameters for each soil texture, all applicable data records were combined and descriptive statistics calculated. Following the method described above (i.e., paring of median soil moisture values at each suction head then solving the van Genuchten equation while minimizing the sum of the squares), default parameters were estimated as listed in Table 2.1. In addition, parameters were estimated for individual series if 5 or more complete data records were available. These parameter estimates for the individual soil series will be incorporated into STUMOD-FL as a look-up table.

Section 3.0
Modifications to Travel Time and Soil Layers

3.0 Modifications to Travel Time and Soil Layers

The method of calculation for travel time was modified in STUMOD-FL. In the previous version (i.e., STUMOD) the velocity was calculated based on unsaturated hydraulic conductivity and hydraulic gradient. The hydraulic gradient was estimated based on pressure profile. While this method is valid, it requires accurate prediction of the unsaturated hydraulic conductivity and hydraulic gradient and thus the pressure profile. An alternate approach, which has been incorporated into STUMOD-FL, is to estimate the velocity or travel time based on hydraulic loading rate and soil porosity. This approach is also valid assuming the hydraulic loading rate is less than the saturated hydraulic conductivity which is the case of OWTS. Both approaches yield the same result provided that the unsaturated hydraulic conductivity and hydraulic gradient are estimated accurately. The approach incorporated into STUMOD-FL requires fewer parameters and is less uncertain than the approach previously used in STUMOD.

Three soil layers have been incorporated into STUMOD-FL, in addition to a biomat. The user can choose only one layer if the soil is assumed to have homogenous properties, otherwise 2 or 3 layers can be selected. If more than one layer is selected due to heterogeneity, STUMOD-FL allows a different soil type to be defined for each of the layers with default parameter values for the selected soil type automatically populated for the layer. The thickness of each layer has to be specified. The user can input the depth to the top of layer 2, and the depth to the top of layer 3 depending on the number of layers to be simulated. The total depth is already specified as either the selected treatment depth or the depth to the water table (STUMOD-FL is specific to the vadose zone only).

These soil layers are further divided into several segments for computational purposes to calculate the changing suction head, soil moisture profile, and nitrogen removal with depth. During development of STUMOD varying the segment interval between 0.5 and 1 cm had insignificant impact on the output results. The number of segments in each layer is set to a default value in STUMOD-FL, but the user can change this value to alter the resolution of the model.

A biomat (also referred to as a clogging zone), typically ranging from 0.5 to 5 cm thick, may form at the infiltrative surface of the soil as a result of the accumulation of suspended solids and organic matter reducing the infiltration rate (Siegrist, 1987; Tyler et al., 1994; McKinley and Siegrist, 2010). The biomat has a lower permeability than the native soil, which enhances unsaturated conditions below the biomat. Other studies have also shown that the biomat affects the hydraulics for a variety of soils with a wide range of hydraulic conductivities (Beach and McCray, 2003; Bumgarner and McCray, 2005; Beal et al., 2008). In STUMOD-FL, the user can select the biomat thickness. In the case of no biomat, the user can enter “0” for the thickness.

The biomat properties in STUMOD-FL are then assigned based on literature values (K_{sat}) or assumed to equal the properties of the top soil layer (van Genuchten parameters). Because data specific to the biomat is not readily available, determination of individual van Genuchten parameters is not possible. Radcliffe and West (2009) assumed that the biomat water retention parameters (θ_r, θ_s, α, and n) were the same as those of the loam textural class. This was a somewhat arbitrary assumption. Beal et al. (2004) assumed that the biomat in their simulations had a silty clay texture, but noted the lack of information in the literature on biomat retention properties. Radcliffe and West (2009) further tested the effect of the biomat water retention properties, by running Hydrus 2D model for 12 soil textural classes with biomat water retention parameters with the values of a loam textural class and with the values of the simulated underlying soil. Assuming that the biomat water retention parameters were the same as the underlying resulted in a slightly wider range of steady trench bottom fluxes for 12 soil textural class simulations and concluded that the saturated hydraulic conductivity of the biomat was more important than the biomat water retention parameters.

Section 4.0
Theory for Evapotranspiration (ET) Effects

4.0 Theory for Evapotranspiration (ET) Effects

The effects of ET are expressed in two primary ways: root water uptake and root nutrient uptake. Thus, the root depth relative to the point of infiltration (i.e., trench depth) is considered. If the root depth extends below the trench depth, the nutrient source is assumed to come from the applied effluent. Even when the point of infiltration is below the maximum root depth, it is assumed that there is still a nutrient contribution from the effluent as a result of capillary movement and diffusion. For this case, the contribution from the effluent is assumed to be partial and in proportion to thickness of the soil between the maximum root depth and the point of infiltration. Thus, the removal efficiency, as a result of plant uptake, is reduced when the plant root does not extend below the point of infiltration. The plant uptake is assumed to be distributed uniformly across the ground surface.

Another key assumption is that both nitrate (NO_3) and ammonium (NH_4) species are assumed to be equally available to plants. Uptake from each species is proportional to its relative amount in the total mineral nitrogen pool (Johnsson et al., 1987). In STUMOD-FL, the nitrogen demand is mainly supplied by ammonium at shallow depths and nitrate at deeper depths. The modeling approach followed here has a flexible formulation that considers a maximum allowable uptake, c_{max}, Michaelis–Menten constant (K_m) that accounts for the effect of concentration on uptake, and minimum uptake (c_{min}) values that will allow users to vary uptake mechanisms among nutrienttypes.

4.1 Root Water Uptake

A large number of approaches to modeling water uptake have been proposed over the years including Molz (1981), Hopmans and Bristow (2002), Wang and Smith (2004), and Feddes and Raats (2004). Some approaches use crop coefficients (K_c) with potential evapotranspiration to estimate specific crop evapotranspiration rates and other methods use soil water suction. Because STUMOD-FL calculates the suction profile, we chose a more rigorous approach where the root water uptake is a function of the soil water pressure head, root characteristics, and meteorological conditions such as evaporative demand. Several approximations have been suggested for root water uptake. One approach assumes that the water uptake rate is proportional to the difference between the soil water pressure head, *h*, and an effective root water or plant pressure head (or potential), h_r, leading to the general form:

$$S(z) = \beta(z)(h - h_r) \tag{4-1}$$

where *S* is the root water uptake term, *β* is a root density function that has been hypothesized in various studies to depend on depth *z*, and *h* is the local average soil water pressure head. Another version of equation 1 that has been used in many numerical simulations is (Whisler et al., 1968; Bresler et al., 1982):

$$S(z) = \beta(z) K(h)(h - h_r) \tag{4-2}$$

in which *β(z)* has been assumed to reflect the relative root distribution in the soil profile, and has been equated to the normalized root density function with units of root length per unit volume of soil (Whisler et al., 1968), *K(h)* is the soil hydraulic conductivity. The value of h_r depends on specific soil, plant, and climatic conditions, and cannot become less than some critical value.

Feddes et al. (1978) and Belmans et al. (1983) suggested a much simpler root extraction term that depends only on the pressure head, root distribution and potential transpiration rate:

$$S(z) = \beta(z)\alpha(h)T_p \tag{4-3}$$

where *β(z)* is the normalized root density distribution (L^{-1}), T_p the potential transpiration rate ($L^3\ L^{-2}\ T^{-1}$), and *α(h)* is a dimensionless water stress response function ($0 \le \alpha \le 1$). Under conditions of no stress, $\alpha = 1$ and equation 4-3 reduces to:

$$S(z) = \beta(z)T_p \tag{4-4}$$

The mathematical form of the equation in STUMOD-FL follows equation 4-3 suggested by Feddes et al. (1978) and Belmans et al. (1983). The details about the method of obtaining *α* and *β* are discussed below.

4.1.1 Water Stress Function (α)

van Genuchten (1987) proposed a smooth, S-shaped reduction function to account for water stress:

$$\alpha(h) = \frac{1}{1 + \left(h/h_{50}\right)^{p_1}} \tag{4-5}$$

where *α(h)* is a dimensionless water stress response function, p_1 is the rate at which the function drops from unity to zero, and h_{50} is the suction at which the transpiration rate is half the potential evapotranspiration, P_T. The parameter h_{50} has a potentially large effect on the rate of water removal from soil when the soil is relatively dry. Values of p_1 = 4 and h_{50} = 1330 cm were chosen based on the vegetation types and soils published by Grinevskii (2011).

Equation 4-5 is implemented in STUMOD-FL where the soil layer is divided into several segments and the soil water pressure, *h*, is calculated using an analytical approach for each segment (Geza et al., 2010). The average of the pressure head at the top and bottom of each elemental depth in STUMOD-FL is used to calculate *α(h)* for each layer in equation 4-5.

4.1.2 Root Distribution Function (β)

A large number of functions for root distribution, *β(z)* have been proposed and used, including constant, linearly decreasing, trapezoidal, and exponential functions. Details are available in Hoffman and van Genuchten (1983) and Hao et al. (2005). The root distribution function by Gale and Grigal (1987) is used in STUMOD-FL given by equation 4-6. The potential transpiration in STUMOD-FL is distributed along the soil profile according to a user-defined root density function. The function results in an exponential decrease in root density.

$$\beta(z) = \frac{Y}{Y_T} = 1 - b^{|z|} \qquad (4\text{-}6)$$

Y/Y_T is the cumulative root distribution from the soil surface down to rooting depth and varies from zero to one as *z* varies from zero to user defined maximum root depth (D). Y/Y_T becomes unity at D. Y/Y_T at any depth corresponds to the proportion of roots from the surface to depth D. High values of Y/Y_T correspond to a greater proportion of roots with depth and the vice versa.

In STUMOD-FL the treatment zone is discretized into several layers and the root distribution for a given layer is calculated as the incremental root distribution (i.e., the difference between the cumulative root fractions between two successive layers). Plant water and nutrient uptake occurs only when this value is greater than zero. Equation 4-6 has been widely used to represent cumulative root biomass distribution data (Jackson 1999; Jackson et al. 1996; 1997; 2000; Feddes et al. 2001; Zeng et al. 1998; Zeng 2001).

The general form of the cumulative root biomass, β, is shown in Figure 4-1. STUMOD-FL will automatically calculate a value for *b* based on user input root depth. The higher the root depth, the larger the *b* value required to distribute the roots throughout the root depth (see Figure 4-1). The user can also input values for *b*. However, appropriate values should be selected for the value of *b* since the model distributes the roots throughout the root depth. If appropriate values are not selected, roots may be distributed too shallow or too deep. Although the drainfield depth will not exceed 75 cm, root uptake will still occur if the roots are present. Values for *b* and properties like the ratio fine/total root biomass, root length, maximum rooting depth, root/shoot ratio, and nutrient content of different terrestrial biomes, can be found in the above-cited references. The root biomass is distributed between the ground surface and the maximum depth based on equation 4-6.

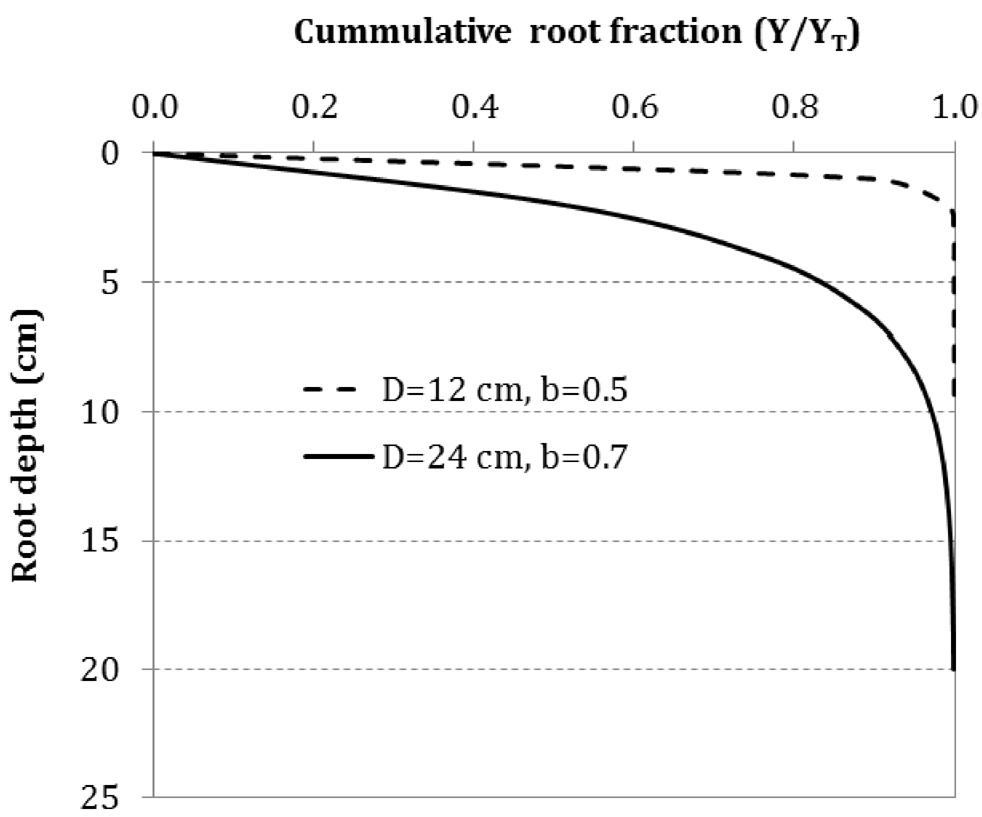

Figure 4-1: Illustration of the Root Distribution Function for Selected Values of Maximum Root Depth (D) and the Root Distribution Parameter (b)

4.1.3 Combined Water Uptake Adjustment Factor, w

In STUMOD-FL, the water stress function *α(h)* is calculated for each soil layer using equation 4-5 and varies with depth and soil type because suction may vary with depth and soil type. The root distribution function, *β(z)* is represented by the incremental fraction $\Delta(Y/Y_T)$, which is the difference between the cumulative fractions of two successive layers. Thus, $\Delta(Y/Y_T)$ is the root fraction within elemental depth in STUMOD-FL. Thus, the combined uptake adjustment in each soil layer w_i is calculated as the product of $\Delta(Y/Y_T)$ and *α(h)* at *z*. The combined stress, *w*, for the entire treatment zone is calculated as the discrete sum. Thus, the total reduction function for the entire root treatment zone is calculated as:

$$w = \sum_{1}^{n} \frac{\Delta Y_i}{Y_T} \alpha_i(h) \tag{4-7}$$

where *n* is the number of segments in a layer. Note that the value of *w* varies between 0 and 1. The actual transpiration (T_a) is then calculated from the combined stress function and potential transpiration (T_p) as $T_a = wT_p$. A similar procedure has been implemented in previous studies Simunek and Hopmans (2008) which used a continuous integral sum approach to calculate the combined water uptake adjustment factor, *w*. A discrete sum approach is implemented in STUMOD-FL. Although this is a simplification over the method described by Simunek and Hopmans (2008), it is still detailed enough to account for spatial variation in water stress and root distribution.

4.1.4 Further Adjustment to Water Uptake Function: Root Water Uptake with Compensation

As previously discussed, the potential transpiration rate is adjusted for the water stress and root distribution (note, $T_a = wT_p$). However, plants have the ability to take water against the moisture gradient. Thus, a factor that accounts for a plants ability to take water under stress is included in STUMOD-FL. As stated earlier, the ratio of actual to potential transpiration for the case of root uptake without compensation is defined as:

$$\frac{T_a}{T_p} = \sum_{1}^{n} \alpha_i(z)\beta_i(z) = w \quad \text{or} \quad T_a = wT_p \tag{4-8}$$

A critical value of the water stress index w_c is introduced which represents a threshold value above which root water uptake reduced in stressed parts of the root zone is totally compensated by increased uptake from other parts as described in Simunek and Hopmans (2008). Some reduction in potential transpiration will occur below this threshold value, although smaller than for water uptake without compensation as shown in Figure

4-2. w_c accounts for the plants ability to take water against gradient. The ratio of actual ET to potential ET for the case of root water uptake with compensation is defined as:

$$\frac{T_a}{T_p} = \frac{\sum_{1}^{n} \alpha_i(z)\beta_i(z)}{w_c} = \frac{w}{w_c} \tag{4-9}$$

A general form of the equation that combines both uncompensated and fully or partially compensated water uptake can be written as:

$$\frac{T_a}{T_p} = \frac{\sum_{1}^{n} \alpha_i \beta_i(z)}{\max[w, w_c]} \tag{4-10}$$

When $w > w_c$, $T_a/T_p = 1$ and $T_a/T_p < 1$ when $w < w_c$. This means that the actual evapotranspiration rates are equal to the potential for $w > w_c$. For the interval where w is smaller than the threshold value w_c, one has $T_a < T_p$. The introduction of the critical value w_c increases the actual water uptake as shown in Figure 4-2 and used to compensate for reduced uptake in stressed parts of the root zone by increased uptake from other parts. When the parameter w_c is equal to 1, non-compensated root water uptake applies, and when w_c is equal to zero we obtain fully compensated uptake (i.e, uptake is equal to the water demand).

O:\44237-001R005\Wpdocs\Report\Final

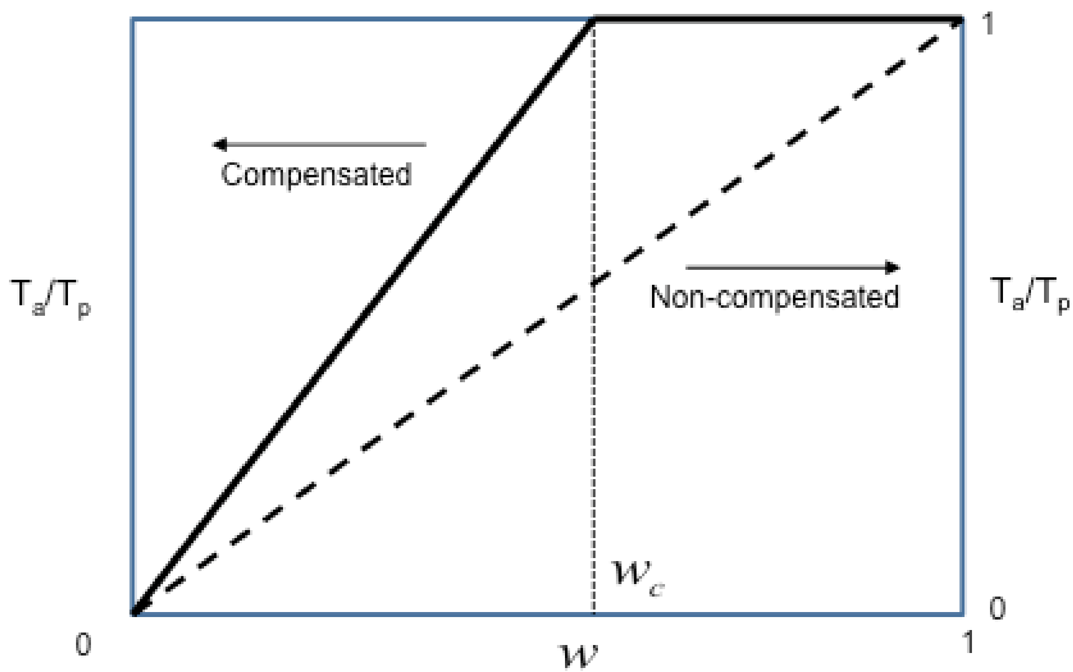

Figure 4-2: Ratio of Actual to Potential Transpiration as a Function of the Stress Index, w

4.1.5 Potential Evapotranspiration

The actual evapotranspiration in STUMOD-FL is calculated from the potential evapotranspiration and reduction factors for soil moisture content and root distribution. Thus, the potential evapotranspiration T_p has to be calculated first. Hargreaves Method is used to calculate T_p. The Hargreaves (1985) equation is one of the simplest and most accurate empirical equations used to estimate ET_0 (Jensen et al., 1997). This equation expressed by Hargreaves and Allen (2003) as:

$$T_p = 0.0023 R_a (TC + 17.8) TR^{0.5} \tag{4-11}$$

where T_p is the reference evapotranspiration (mm/day), R_a is the daily value of extraterrestrial radiation in equivalent mm of water evaporation for a day (mm/day), TC is the average daily air temperature (°C) and TR is the daily temperature range (°C) ($TR = T_{max} - T_{min}$) where T_{max} is the mean daily maximum temperature and T_{min} is the mean daily minimum temperature.

Various equations for prediction of R_a for a given month and latitude were developed by many investigators such as Allen et al. (1989), Yitaew and Brown (1990), Allen (1996), Kotsopoulos and Babajimopoulos (1997) and Chuanyan et al. (2004). R_a was estimated using the equation recommended by Kotsopoulos and Babajimopoulos (1997), developed for latitudes (L_a) $0 \leq L_a \leq 50^oN$, is expressed as:

$$R_a = M + C_1 \cos\left(\frac{2\pi J}{12} + C_2\right) + C_3 \cos\left(\frac{2\pi J}{12} + C_4\right) \tag{4-12}$$

where:

J = order of the month
$M = 14.9423 – 0.0098L_a – 0.00175(L_a)^2$
$C_1 = -0.5801 + 0.1834\ L_a – 0.00066L_a$
$C_2 = 3.1365 – 0.00489\ L_a + 0.00061(L_a)^2$
$C_3 = 0.597 – 5.36 – 10\text{-}6(L_a)^2$
$C_4 = 2.9588 – 0.00909\ L_a + 0.00024(L_a)^2$

4.2 Root Nutrient Uptake

The approach used in STUMOD-FL is similar to one presented in Simunek and Hopmans (2008), but with some simplifications. STUMOD-FL allows for both passive and active root nutrient uptake. The passive uptake describes the mass flow of dissolved nutrients by plant roots associated with water during transpiration. It is also assumed that the passive uptake is the primary mechanism of supplying plants with nutrients, and that active uptake is initiated only if passive uptake is inadequate. The active uptake includes all other possible nutrient uptake mechanisms, including energy-driven processes against concentration gradients.

4.2.1 Uncompensated Nutrient Uptake Model

Simunek and Hopmans (2008) define nutrient uptake as the sum of active and passive uptakes. A time dependent point nutrient uptake function is used to calculate the root uptake throughout the root domain for the entire duration by integrating over time and space. For STUMOD-FL a layer is used instead of a point. The root uptake for each soil layer is used to calculate uptake throughout the root domain using a discrete sum approach and a steady state solution where neither nutrient concentration nor uptake is time dependent.

$$r_a = p_a(z) + a_a(z) \tag{4-13}$$

$$R_a = P_a + A_a \tag{4-14}$$

where r_a, p_a, and a_a define actual total, passive, and active root nutrient uptake rates [$ML^{-2}T^{-1}$], respectively, at any layer (equation 4-13), and R_a, P_a, and A_a denote actual total, passive, and active root nutrient uptake rates [$ML^{-2}T^{-1}$], respectively, for the root zone domain (equation 3-14).

Passive nutrient uptake, P_a, is simulated by multiplying root water uptake with the dissolved nutrient concentration for concentration values below apriori defined maximum concentration (c_{max}). Passive root nutrient uptake for the whole root domain, is calculated as discrete sum of passive root nutrient uptake rate, p_a, over the entire root zone, as:

$$P_a = \frac{T_p}{\max\left[w, w_c\right]} \sum_{1}^{n} \alpha_i(h)\beta_i(z)\min\left[c(z), c_{\max}\right] \tag{4-15}$$

where c is the dissolved nutrient concentration [ML^{-3}] and c_{max} is the maximum allowed solution concentration [ML^{-3}] that can be taken up by plant roots during passive root uptake. All nutrient dissolved in water could be taken up if $c < c_{max}$ demanding on ET and potential nutrient demand. No nutrient is taken up when $c_{max} = 0$ with only active uptake remaining in this case. The maximum solution concentration for passive root uptake, c_{max}, thus controls the proportion of passive root water uptake to total uptake. Using this flexible formulation that considers c_{max}, Michaelis–Menten constant (K_m) and a c_{min} discussed later, uptake mechanisms can vary between specific nutrients.

The potential active uptake is defined as the difference between the potential nutrient demand and the passive nutrient uptake as:

$$A_p = max[R_p - P_a , 0] \tag{4-16}$$

This implies that the active nutrient uptake is initiated only if the passive root nutrient uptake does not fully satisfy the potential nutrient demand of the plant. If passive uptake is reduced or completely turned off ($c_{max} = 0$), the potential active nutrient uptake (A_p) is equal to the potential nutrient demand (R_p). Once A_p is known, the values of potential active nutrient uptake rates for a layer in STUMOD-FL, $a_p(z)$, are obtained by distributing the potential root zone active nutrient uptake rate, A_p, over the root zone domain, using a predefined spatial root distribution, $\beta(z)$, as was done for root water uptake or;

$$a_p(z) = \beta(z) A_p \tag{4-17}$$

Using Michaelis–Menten kinetics (e.g., Jungk, 1991) provides for actual distributed values of active nutrient uptake rates, a_a, allowing for nutrient concentration dependency, or:

$$a_a(z) = \frac{c(z) - c_{min}}{K_m + c(z) - c_{min}} a_p(z) = \frac{c(z) - c_{min}}{K_m + c(z) - c_{min}} \beta(z) A_p \tag{4-18}$$

where K_m is the Michaelis–Menten constant [ML^{-3}] and c_{min} is the minimum nutrient concentration required for active uptake to take effect [ML^{-3}] (Jungk, 2002), thus assuming that active nutrient uptake will occur only if the dissolved nutrient concentration in the soil solution is sufficiently high. The Michaelis–Menten constants for selected nutrients (e.g., N, P, and K) and plant species (e.g., grass, corn, soybean, wheat, tomato, pepper, lettuce, and barley) can be found in the literature (e.g., Bar-Yosef, 1999).

Finally, total active uncompensated root nutrient uptake rate, A_a is calculated as the discrete sum of actual active root nutrient uptake rate, a_a, for each soil layer in STUMOD-FL, over the root domain in analogy with the passive root water uptake term in equation 4-15, or:

$$A_a = \sum_1^n a_a(z) = A_p \sum_1^n \frac{c(z) - c_{\min}}{K_m + c(z) - c_{\min}} \beta(z) \tag{4-19}$$

4.2.2 Compensated Nutrient Uptake Model

The nutrient uptake model includes compensation of the passive nutrient uptake. A similar compensation concept as used for root water uptake in equations 4-9 and 4-10, was implemented for active nutrient uptake rate, by invoking a nutrient stress index.

$$\frac{A_a}{A_p} = \sum_0^D \frac{c(z) - c_{\min}}{K_m + c(z) - c_{\min}} \beta(z) = \pi \tag{4-20}$$

After defining the critical value of the nutrient stress index π_c above which value active nutrient uptake is fully compensated for by active uptake in other less stressed soil regions, the total compensated active root nutrient uptake rate, A_{ac} is calculated as:

$$A_{ac} = \frac{A_p}{\max[\pi, \pi_c]} \sum_0^D \frac{c(z) - c_{\min}}{K_m + c(z) - c_{\min}} \beta(z) \tag{4-21}$$

Equation 4-21 implies that reduction in root water uptake will decrease passive nutrient uptake, thereby increasing active nutrient uptake proportionally. Thus, total nutrient uptake is not affected by soil water stress, as computed by the proportion of actual to potential root water uptake. This is not realistic because plant nutrient requirements will be reduced for water-stressed plants. For that reason, the uptake model includes additional flexibility, by reducing the potential nutrient demand R_p in proportion to the reduction of root water uptake, as defined by the actual to potential transpiration ratio, or:

$$A_p = max\left[R_p \frac{T_{a\,c}}{T_p} - P_a, 0 \right] \tag{4-22}$$

In summary, the presented root nutrient uptake model with compensation requires as input the potential nutrient uptake rate (demand), R_p, the spatial root distribution function $\beta(z)$ as needed for the water uptake term, the Michaelis–Menten constant K_m, the maximum nutrient concentration that can be taken up passively by plant roots c_{max}, the minimum concentration c_{min} needed to initiate active nutrient uptake, and the critical nutrient stress index π_c. The passive nutrient uptake term can be turned off by selecting c_{max} equal to zero. Moreover, active nutrient uptake can be eliminated by specifying a zero value for R_p, or by selecting a very large c_{min} value. It can be expected that π_c for agricultural crops is relatively high implying less capability to compensate for nutrient stress when compared to natural plants that are likely to have more ability to compensate for soil environmental stresses. Other parameters, such as c_{max} will likely need to be calibrated to specific conditions before the model can be used for predictive purposes.

The passive nutrient uptake term can be turned off by selecting c_{max} equal to zero. Active nutrient uptake can be eliminated by specifying a very large c_{min} value. It is likely that values of these parameters are nutrient and plant specific. To ignore plant uptake for example if an onsite system is built on bare land, one can set R_p = 0.

O:\44237-001R005\Wpdocs\Report\Final

Section 5.0
Theory for High/Seasonal Water Table Effects

5.0 Theory for High/Seasonal Water Table Effects

Groundwater level fluctuations can directly impact the migration potential of groundwater plumes (Parker et al., 1994; Parker, 2003). For OWTS, knowledge of groundwater fluctuations is beneficial because the amount of nitrogen that reaches the water table is affected by the separation distance between the water table and the trench bottom.

STUMOD-FL is able to handle a lower boundary condition of saturation that was not present in STUMOD. For applications with a constant head, users can set a pressure head of zero for the lower boundary condition. Two options are provided for the location of the water table. Users can enter either a known water table depth or use the model calculated water table as determined by a water table fluctuation model included in STUMOD-FL described in this section. Free drainage conditions assume that there is no effect on soil moisture distribution from capillary water and is mimicked by setting the water table to a greater depth. Both conditions are included in STUMOD-FL since significant differences were observed in denitrification rates similar to what has been observed in HYDRUS-2D (see Task D-7, 80% complete progress report).

Various approaches have been used to assess the fluctuation of a water table. Several different analytical models have been developed including Hantush (1967), Rao and Sarma (1984), Latnopoulos (1985), Rai and Singh (1995), Rai and Manglik (1999) and Rai et al. (2006). Rasmussen and Andreasen (1959) presented a simple model relating water level fluctuations in response to recharge events for the purpose of estimating groundwater recharge from precipitation events. They assumed that the change of water level over a given time multiplied by the specific yield is equal to the change in storage due to precipitation, extraction/injection, evapotranspiration, etc. An analytical solution has been derived by linearizing the two-dimensional Boussinesq equation to predict time-varying water table height based on groundwater recharge as a function of time (Rai and Singh, 1995; Rai and Manglik, 1999; and Rai et al., 2006).

Park and Parker (2008) presented an extension of the Rasmussen and Andreasen model to describe water table fluctuations in response to precipitation time-series. They developed a simple model to predict water table fluctuations based on discrete record of precipitation such as daily or monthly precipitation data. The model requires precipitation time series and other inputs related to soil that control the reduction in ground water level with time when precipitation is not occurring and water table build up during precipitation. OWTS could then be designed on a more conservative approach based on a maximum precipitation year or a year with high precipitation to PET ratio. The method was implemented in STUMOD-FL. The model was selected because it is a physically based model and was specially developed for aquifer response to precipitation time-series. Model performance was assessed by comparing predicted and observed groundwater fluctuations over a multi-year period in response to precipitation. The model by (Park and Parker, 2008) computes head as:

$$h = ho\exp(kt) + \frac{\alpha P(\exp(kt)-1)}{kn} \tag{5-1}$$

$$h^{i+1} = h^{i}\exp(k\Delta t_i) + \frac{\alpha P_i(\exp(k\Delta t_i)-1)}{kn} \tag{5-2}$$

$$H^{i+1} = h^{i} + H_{\min} \tag{5-3}$$

where h is the head, defined as H-H_{min}, H is the groundwater elevation relative to the reference elevation, H_{min} is the minimum groundwater level in the modeled area, n is the fillable porosity (assumed to be equal to the aquifer specific yield), and k is the rate coefficient (T^{-1}). The rate coefficient, k, controls the water table decline during dry periods and the build-up of the water table during recharge periods and is related to soil properties and hydraulic gradient by:

$$k = \frac{-Ki}{n\bar{h}}\frac{\Delta h}{\Delta x} \tag{5-4}$$

where K is the hydraulic conductivity, i is the main hydraulic gradient of the domain, $\bar{h}$ is the mean hydraulic head in the domain, $\Delta h/\Delta x$ and is the hydraulic gradient at the inlet at the inlet and outlet of the domain. For the case of very low aquifer permeability, the water table build-up is very high and the decline during dry periods is low. With the same amount of recharge, lower permeability aquifer shows slower response.

Park and Parker (2008) further assumed that the recharge rate can be approximated as a fixed fraction of precipitation as:

$$R = \alpha P \tag{5-5}$$

where α is the recharge-precipitation ratio.

Since precipitation data is available at discrete intervals, tabulated time-intervals can be applied treating precipitation as a piecewise-constant function.

We are in the process of evaluating the groundwater fluctuation model for predicting water table elevations in the State of Florida (Task D.9). Groundwater elevation (elevation above NGVD 1029) data was gathered from the USGS National Water Information Services website and precipitation data was obtained from the National Climate Data Center. To make the tool more practical from the user perspective, water table parameter values will be related to readily available inputs such as soil property and topography. We are evaluating extensive data on water table, soils and soil topography to infer plausible relationships.

Section 6.0
Coding and Code Evaluation

6.0 Coding and Code Evaluation

Based on the conceptual framework described in the previous sections, coding and code evaluation has been conducted. Figure 6-1 illustrates the STUMOD-FL graphical user interface (GUI) with code modification to incorporate an ET and plant uptake module, variable water table, and additional input and output tabs. An additional modification to code is the inclusion within STUMOD-FL to handle a lower boundary condition. For applications with a constant head, users can set a pressure head of zero for the lower boundary condition. Users can enter either a known water table depth or use the model calculated water table as determined by a water table fluctuation model. Free drainage conditions assume that there is no effect on soil moisture distribution from capillary water and is mimicked by setting the water table to a greater depth. STUMOD-FL has also been modified such that users can easily see or modify inputs and navigate through outputs from the GUI (Figure 6-1).

Figure 6-2 illustrates the STUMOD-FL GUI when a user inputs multiple soil layers. Florida specific soil parameters are not reflected in Figure 6-2, which is presented to show differences the modified code. From the GUI in Figure 6-2 the user may choose different materials/soil types for layer 2 and 3 and the model will automatically populate layer properties with default inputs. The user can also modify the inputs for any of the layers if site specific values are different from the default values.

o:\44237-001R006\Wpdocs\Report\Draft

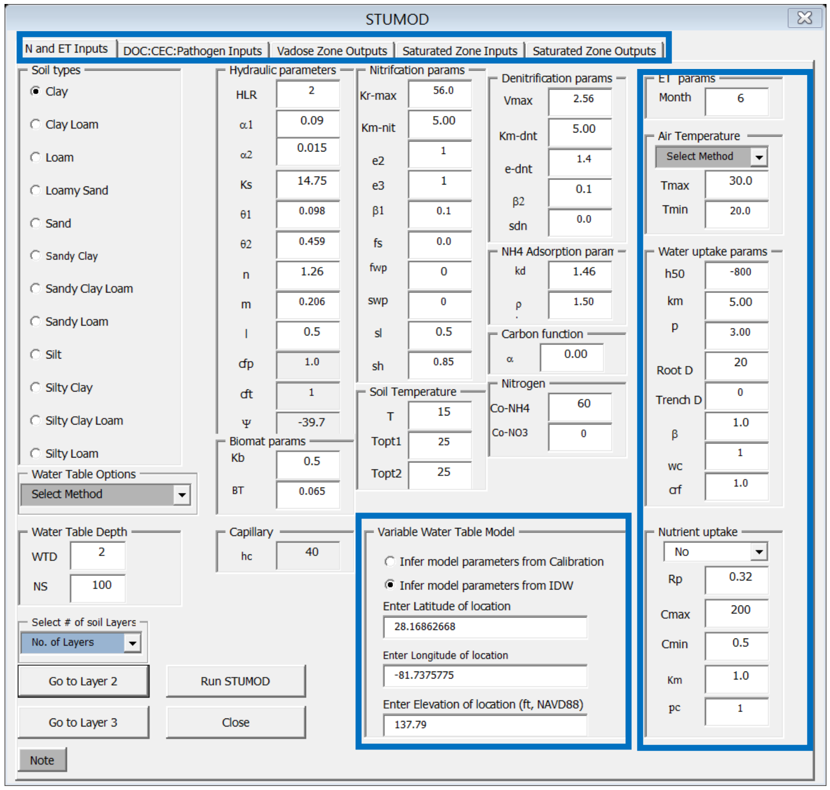

Figure 6-1: STUMOD-FL graphical user interface.

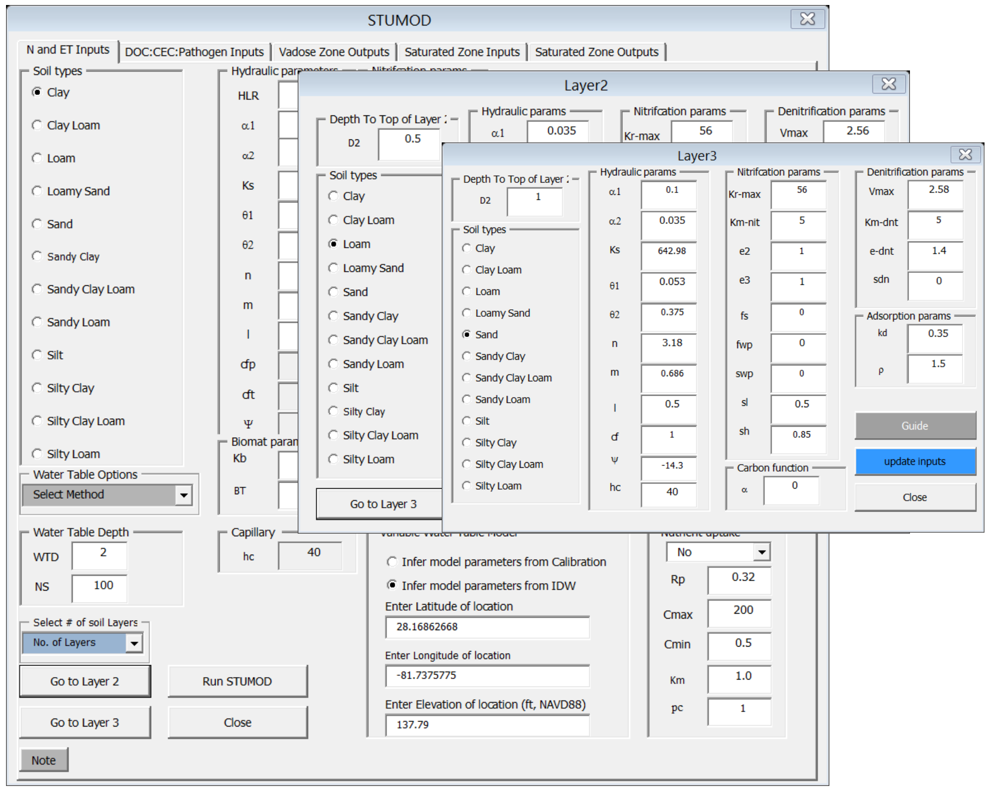

Figure 6-2: STUMOD-FL graphical user interface for multiple layer inputs.

Code evaluation is best illustrated by a series of STUMOD-FL outputs. The following illustrations show the effects of boundary conditions, nutrient uptake, and heterogeneities. Note that Florida specific sand parameters are not reflected in the illustrations below, thus, the illustrations show differences in expected performances based on the modified code. Code evaluation included comparing these performance differences to gain confidence that the modified code was performing as planned. Coorboration and calibration of the code are not part of Task D.8.

Two options are available for a lower boundary condition in STUMOD-FL. For applications with a constant head, users can set a pressure head of zero for the lower boundary condition at the water table. The location of the water table is either user input value or calculated water table as determined by a water table fluctuation model. For free drainage conditions it is assumed that there is no effect on soil moisture distribution from capillary water and is mimicked by setting the water table to a greater depth. Figures 6-3 and 6-4 illustrate outputs for concentrations of nitrogen species for the two conditions. Note that there is more removal in shallow water table condition in the capillary zone. This is attributed to higher moisture content at the capillary zone resulting in improved denitrification. We observed that this is effect more pronounced on sandy soil than on clay soil because clayey soils tend to retain more moisture even under free drainage condition.

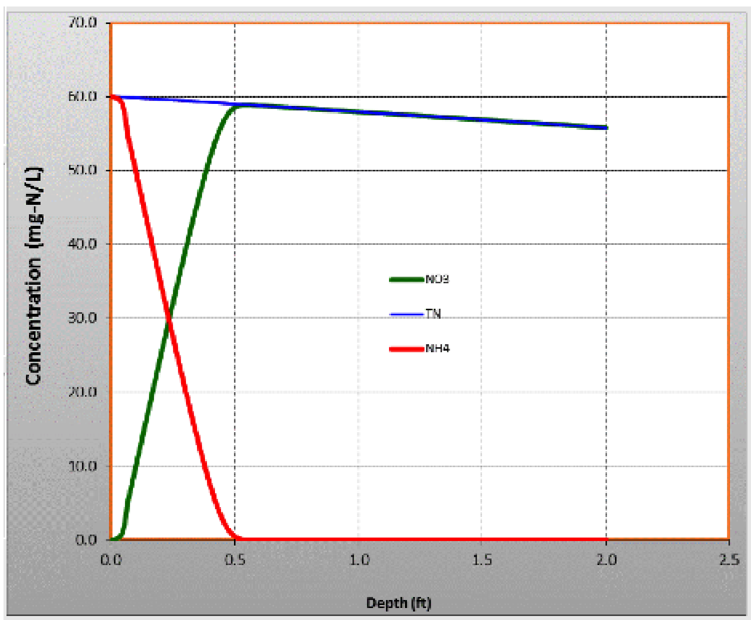

Figure 6-3: STUMOD-FL output: Sandy soil with a deep water table.

O:\44237-001R005\Wpdocs\Report\Final

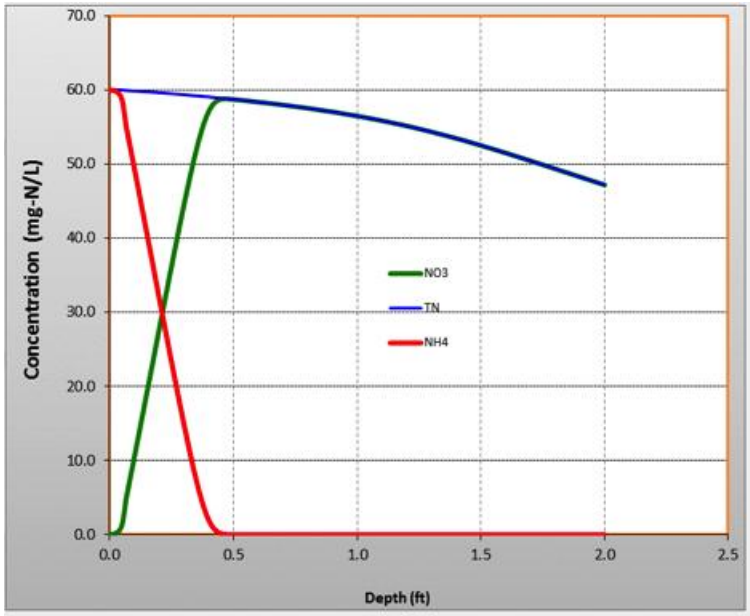

Figure 6-4: STUMOD-FL output: Sandy soil with a water table at 2ft below the infiltrative surface.

Figure 6-5 shows code evaluation for the plant uptake module to account for possible removal of nutrient and reduction in concentration. Figure 6-5 illustrates the STUMOD-FL total nitrogen outputs with and without plant uptake. The effect of layering is illustrated in Figure 6-6 with a sandy layer on top of a clay layer. More removal occurred in clay layer due to better denitrification. The dashed line represents the output when the entire domain (soil layers) was sand and shoes less nitrogen removal as expected in sands compared to clays.

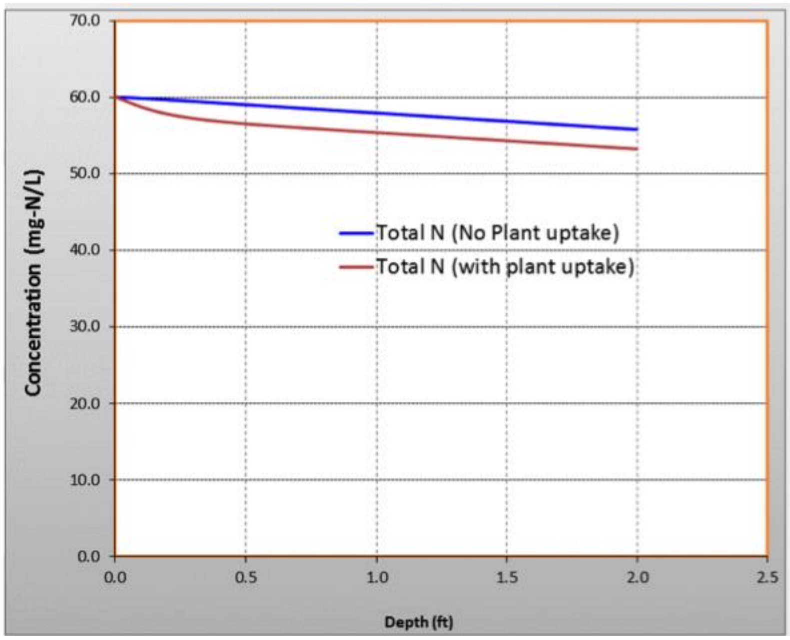

Figure 6-5: STUMOD-FL output: Predicted total nitrogen concentrations with and without plant uptake.

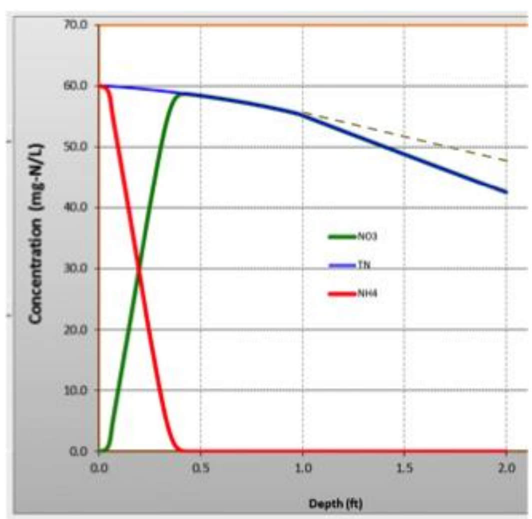

Figure 6-6: STUMOD-FL output: Predicted nitrogen concentrations in heterogeneous layered soils (dashed line illustrates total nitrogen concentration is a homogeneous sandy soil).

Section 7.0
Summary

7.0 Summary

This specification memo documents the *conceptual framework, code modification, and code evaluation* for the complex soil model (STUMOD-FL). STUMOD-FL is based on fundamental principles of water movement and contaminant transport using an analytical solution to calculate pressure and moisture content profiles in the vadose zone and a simplification of the general advection dispersion equation (Geza et al., 2009 and 2010). STUMOD-FL has been adapted to: 1) Florida-specific soil and climate data that includes parameters representing dominant soil properties, 2) account for ET, and 3) account for the effect of high/seasonally variable water tables on nitrogen removal in soil. STUMOD-FL primarily addresses the most common operating conditions associated with trench and mound systems.

Use of STUMOD-FL requires familiarity with spreadsheets and parameter selection, and understanding of soil hydraulic and treatment mechanisms. Default values based on median values obtained from the Florida Soil Characterization Data Retrieval System are used in the STUMOD-FL graphical user interface. However, STUMOD-FL allows user-specified input and can be calibrated to site-specific data. The output is the expected steady-state performance (i.e., constituent concentration) at the center under the point of effluent application. Model outputs provide insight into the behavior of soil treatment and quantitative estimations of nitrogen removal as affected by a range of conditions.

The effects of ET are expressed in two primary ways: root water uptake and root nutrient uptake. The contribution of water and nutrients from the effluent is assumed to be in proportion to thickness of the soil between the maximum root depth and the point of infiltration. Both nitrate (NO_3) and ammonium (NH_4) species are assumed to be equally available to plants. Thus, the removal efficiency, as a result of plant uptake, is reduced when the plant root does not extend below the point of infiltration. This modeling approach for STUMOD-FL has a flexible formulation that considers a maximum allowable uptake, the effect of concentration on uptake, and minimum uptake mechanisms.

STUMOD-FL estimates the water table fluctuations in response to precipitation based on the equation for one-dimensional flow in unconfined aquifers. Assumptions in the model development include that the major cause of water table fluctuation is precipitation and that the time lag from precipitation to water table response is negligible. This is recognized to reduce the model accuracy for deep (> 100 ft) water table conditions. As part of Task D.9 testing the model performance using precipitation data and observed water table fluctuations from diverse locations in State of Florida and determining parameter values is ongoing. Parameter values will be related to readily available inputs such as soil property and topography. To make STUMOD-FL more user friendly, users can add or modify all inputs through a graphical interface and obtain numerical and graphical outputs also through the user interface.

Section 8.0
References

8.0 References

Allen, R.G. (1996). Assessing integrity of weather data for reference evapotranspiration estimation. *J. Irrig. Drain. Eng.* 122(2):97-106.

Allen, R.G., Jensen, M.E., Wright, J.L., and R.D. Burman (1989). Operational estimates of reference evapotranspiration. *Agron. J.* 81:650-662.

Bar-Yosef, B. (1999). Advances in fertigation. *Adv. Agron.* 65:1-77.

Beach, D.N.H. and J.E. McCray (2003). Numerical modeling of unsaturated flow in wastewater soil absorption systems. Ground Water Monitoring & Remediation, 23(2) 64-72.

Beal, C.D., Rassam, D.W., Gardner, E.A., Kirchof, G., and N.W. Menzies (2008). Influence of hydraulic loading and effluent flux on surface surcharging of soil absorption systems. *J. Hydrol. Eng.* 13: 681–692.

Belmans, C., Wesseling, J.G., and R.A. Feddes (1983). Simulation model of the water balance of a cropped soil: SWATRE. *J. Hydrol.* 63: 271-286.

Bresler, E., McNeal, B.L., and D.L. Carter (1982). Saline and Sodic Soils. Springer Verlag, Berlin.

Bumgarner, J. and J.E. McCray (2007). Estimating biozone hydraulic conductivity in wastewater soil-infiltration systems using inverse numerical modeling. *Water Res.* 41: 2349-2360.

Chuanyan, Z., Zhongren, N., and F. Zhaodong (2004). GIS-assisted spatially distributed modeling of the potential evapotranspiration in semi-arid climate of the Chinese loess plateau. *J. Arid Environ*. 58:387-403.

Feddes, R.A., Hoff, H., Bruen, M., Dawson, T., Rosnay, P., Dirmeyer, P., Jackson, R., Kabat, P., Kleidon, A., Lilly, A., and A. Pitmank (2001). Modeling root water uptake in hydrological and climate models. *Bulletin of the American Meteorological Society,* 82(12):2797-2809.

Feddes, R.A., Kowalik, P.J., and H. Zaradny (1978). *Simulation of Field Water Use and Crop Yield*. John Wiley & Sons, New York, NY.

Feddes, R.A. and P.A.C.. Raats (2004). Parameterizing the soil–water–plant root system. In: Feddes, R.A., de Rooij, G.H., van Dam, J.C. (Eds.), Proceedings of the Unsaturated Zone Modelling: Progress, Challenges and Applications.

Gale M.R. and D.K. Grigal (1987). Vertical root distributions of northern tree species in relation to successional status. *Can J For Res* 17:829-834.

Geza, M., J. McCray, K. Lowe, M. Tucholke, A. Wunsch, and S. Roberts (2009). A Simple Tool for Predicting Nutrient Removal in Soil Treatment Units. Proc. National Onsite Wastewater Recycling Association (NOWRA) 18th Annual Technical Education & Exposition Conference.

Geza, M., McCray, J.E., Lowe, K.S., and M.B. Tucholke (2010). A Tool for Predicting Nitrogen Removal in Soil Treatment Units (STUMOD). Presented at the 2010 Ground Water Summit, Denver, Colorado, April 11-14. National Ground Water Assoc., Westerville, OH.

Grinevskii, S.O., (2011). Modeling root water uptake when calculating unsaturated flow in the vadose zone and groundwater recharge, Moscow University Geology Bulletin, v. 66, no. 3, 189-201, DOI: 10.3103/S0145875211030057.

Hantush, M.S. (1967). Growth and decay of ground water mounds in response to uniform percolation. *Water Resour. Res.* 3(1): 227–234.

Hao, X., Zhang R., and A. Kravchenko (2005). Effects of root density distribution models on root water uptake and water flow under irrigation. *Soil Sci.* 170:167–174

Hargreaves, G.H. and R.G. Allen (2003). History and evaluation of Hargreaves evapotranspiration equation. *J. Irrig. Drain. Eng.* 129(1):53-62.

Hoffman, G.H., Van Genuchten, and M.Th (1983). Soil properties and efficient water use: water management for salinity control. In: H.M. Taylor, W. Jordan and T. Sinclair (eds.), "Limitations to Efficient Water Use in Crop Production", pp. 73-85, Am. Soc. Agron., Madison, WI.

Hopmans, J.W. and K.L. Bristow (2002). Current capabilities and future needs of root water and nutrient uptake modeling. *Advances in Agronomy,* 77:103-183.

Jackson, R.B., Canadell, J., Ehleringer, J.R., et al. (1996). A global analysis of root distributions for terrestrial biomes. *Oecologia,* 108(3):389-411.

Jackson, R.B., Mooney, H.A., and E.D. Schulze (1997). A global budget for fine root biomass, surface area, and nutrient contents. *Proceedings of the National Academy of Sciences of the United States of America,* 94(14):7362-7366.

Jackson, R.B., Sperry, J.S., and T.E. Dawson (2000). Root water uptake and transport: using physiological processes in global predictions. *Trends in Plant Science,* 5(11):482-488.

Jensen, D.T., Hargreaves, G.H., Temesgen, B., and R.G. Allen (1997). Computation of ET0 under nonideal conditions. J. Irrig. Drain. Eng. 123(5):394-400.

Johnsson, H., L. Bergstrom, and P-E. Jansson (1987). Simulated nitrogen dynamics and losses in a layered agricultural soil. *Agr. Ecosyst. Environ.* 18:333-356.

Jungk, A.O. (2002). Dynamics of nutrient movement at the soil–root interface. In: Waisel, Y., Eshel, A., Kafkafi, U. (Eds.), Plant Roots, The Hidden Half. Marcel Dekker, Inc., New York, pp. 587-616, Chapter 35.

Kotsopoulos, S. and C. Babajimopoulos (1997). Analytical estimation of modified Penman equation parameters. *J. Irrig. Drain. Eng.* 123(4):253-256.

Latnopoulos, P. (1985). Analytical solutions for periodic well recharge in rectangular aquifers with third-kind boundary conditions. *J. Hydrol.* 77: 293–306.

McCray, J., Geza, M., Lowe, K., Boving, T., Radcliffe, D., Tucholke, M., Wunsch, A., Roberts, S., Amador, J., Atoyan, J., Drewes, J., Kalen, D., and G. Loomis (2009). Quantitative Tools to Determine the Expected Performance of Wastewater Soil Treatment Units: Literature Review. WERF, DEC1R06. 196 pg. PDF available at: www.werf.org

McCray, J., Geza, M., Lowe, K., Boving, T., Radcliffe, D., Tucholke, M., Wunsch, A., Roberts, S., Amador, J., Atoyan, J., Drewes, J., Kalen, D., and G. Loomis (2010). Quantitative Tools to Determine the Expected Performance of Wastewater Soil Treatment Units. Final Reports and Tools: Guidance Manual, User's Guide, Visual Graphics, STUMOD, and NCALC. WERF, DEC1R06. PDF available at: www.werf.org

McKinley J.W. and R.L. Siegrist (2010). Accumulation of organic matter components in soil during conditions imposed by wastewater infiltration. Soil Sci Soc. Amer J. 74(5):1690-1700.

Molz, F.J. (1981). Models of water transport in the soil-plant system: a review. *Water Resources Research,* 17(5):1245-1260.

Otis, R.J. (2007). Estimates of Nitrogen Loadings to groundwater from Onsite Wastewater Systems in the Wekiva Study Area. Task 2 Report, Prepared for the Florida Department of Health Bureau of Onsite Sewage Programs, Tallahassee, Florida.

Parker, J.C. (2003). Physical processes affecting natural depletion of volatile chemicals in soil and groundwater. *Vadose Zone J.* 2: 222-230.

Parker, J.C., Zhu, J.L., Johnson, T.G., Kremesec, V.J., and E.L. Hockman (1994). Modeling free product migration and recovery at hydrocarbon spill sites. *Groundwater*, 32: 119–128.

Park, E. and J.C. Parker (2008). A simple model for water table fluctuations in response to precipitation, *Journal of Hydrology*, *356*(3-4): 344-349.

Radcliffe, D.E. and L.T. West (2009). Design hydraulic loading rates for onsite wastewater systems. *Vadose Zone J.*, 8: 64-74.

Rai, S.N. and R.N. Singh (1995). Two-dimensional modelling of water table fluctuation inresponse to localized transient recharge. *J. Hydrol.* 167, 167-174.

Rai, S.N. and A. Manglik (1999). Modelling of water table variation in response to time-varying recharge from multiple basins using the linearised Boussinesq equation. *J. Hydrol.* 220: 141-148.

Rai, S.N., Manglik, A. and V.S. Singh (2006). Water table fluctuation owing to time-varying recharge pumping and leakage. *J. Hydrol.* 324, 350-358.

Rasmussen, W.C. and G.E. Andreasen (1959). Hydrologic Budget of the Beaverdam Creek Basin, Maryland. US Geological Survey Water- Supply Paper 1472, 106 pp.

Rao, N.H. and P.B.S. Sarma (1984). Recharge to aquifers with mixed boundaries. *J. Hydol.* 74: 43-51.

Siegrist, R.L., E.J. Tyler, and P.D. Jenssen (2001). Design and Performance of Onsite Wastewater Soil Absorption Systems. Invited white paper presented at the National Research Needs Conference: Risk-Based Decision Making for Onsite Wastewater Treatment. EPRI report no. 1001446, Electric Power Research Institute, Palo Alto, CA.

Simunek, J. and J.W. Hopmans (2008). Modeling compensated root water and nutrient uptake. Ecol. Model. DOI:10.1016/j.ecolmodel.2008.11.004.

van Genuchten and M.Th (1987). A numerical model for water and solute movement in and below the root zone. Research Report No 121, U.S. Salinity Laboratory, USDA, ARS, Riverside, CA.

Wageningen. Mededelingen Landbouwhogeschool Wageningen no. 71-12.

Whisler, F.D., Klute, A., and R.J. Millington (1968). Analysis of steady state evapotranspiration from a soil column. Soil Sci. Soc. Am., Proc., 32:167-17.

Yitaew, M. and P. Brown (1990). Predicting daily evapotranspiration (ETd) from short-term values. *J. Irrig. Drain. Eng.* 116(3):387-398.

Wang, E. and C.J. Smith (2004). Modeling the growth and water uptake function of plant root systems: a review. *Aust. J. Agric. Res.* 55:501-523.

Zeng, X.B. (2001). Global vegetation root distribution for land modeling. *Journal of Hydrometeorology,* 2(5): 525-530.

Zeng, X.B., Dai, Y.J., Dickinson, R.E., et al. (1998). The role of root distribution for climate simulation over land. *Geophysical Research Letters,* 25(2): 4533-4536.

O:\44237-001R005\Wpdocs\Report\Final

Appendix A
Supporting Soil Data

Table A.1
Listing of Florida Sand Series Evaluated for Parameter Estimation

Soil Series	# of Permits[1]	Ranking based on Permits	Areal Extent (acres)	Ranking within Total Florida Land Area	Ranking within Sand Series only	# of Records Used in Parameter Estimate
Adamsville	200	30	137,213	57	49	25
Albany	175	36	371,187	19	18	90
Alpin	175	37	249,585	33	29	39
Apopka	265	17	119,259	64	55	13
Arrendondo	235	22	199,867	39	34	26
Astatula	1136	4	493,691	8	8	36
Basinger	221	25	657,908	6	6	46
Blanton	461	10	475,052	10	10	69
Bonifay	226	24	234,420	34	30	27
Candler	2305	1	839,202	3	3	46
Eau Gallie	543	7	465,679	11	11	86
Felda	48	74	253,462	31	27	42
Holopaw	133	43	272,244	28	24	14
Immokalee	462	9	910,565	2	2	64
Lake	273	16	115,712	67	57	29
Lakeland	700	6	739,457	4	4	56
Leon	161	39	572,007	7	7	98
Malabar	121	47	344,605	20	19	62
Matlacha[2]	238	21	78,194	80	66	0
Millhopper	216	27	133,846	58	50	46
Myakka	1028	5	1,400,072	1	1	76
Oldsmar	254	20	297,163	23	21	63
Ortega	234	23	157,567	45	39	15
Otela	202	29	138,103	55	48	32
Paola	531	8	128,181	61	52	43
Pineda	184	33	421,044	16	16	63
Placid	24	102	267,790	29	25	19
Plummer	35	87	438,056	14	14	35
Pomello	265	18	216,530	36	32	55
Pomona	116	48	440,266	13	13	124
Riviera	159	40	491,995	9	9	44
Rutledge	23	103	303,268	21	20	11

o:\44237-001R006\Wpdocs\Report\Draft

Table A.1 (cont.)
Listing of Florida Sand Series Evaluated for Parameter Estimation

Soil Series	# of Permits[1]	Ranking based on Permits	Areal Extent (acres)	Ranking within Total Florida Land Area	Ranking within Sand Series only	# of Records Used in Parameter Estimate
Sapelo	66	66	273,399	27	23	83
Smyrna	350	13	714,008	5	5	61
Sparr	279	15	162,728	44	38	59
St Lucie	257	19	49,231	105	79	22
Tavares	1554	3	375,455	18	17	54
Troup	435	11	459,785	12	12	38
Wabasso	200	31	434,075	15	15	79
Zolfo	337	14	141,258	53	46	27

1 *Information on number of recent permits provided by FDOH (2012).*

2 *Excluded from further analysis – no data records reported in the Florida Soils Characterization Data Retrieval System.*

Table A.2
Listing of Florida Sand Series Evaluated for Parameter Estimation

Soil Series	Series Textural Classification[1]	# of Permits[2]	Ranking based on Permits	Areal Extent (acres)	Ranking within Total Florida Land Area	# of Records Used in Parameter Estimate
Blanton	fine sand	461	10	475,052	10	1
Boca	sand	145	41	210,718	37	1
Bonifay	sand	226	24	234,420	34	2
Bonneau	loamy sand	111	49	147,125	51	9
Chaires	fine sand	11	132	221,332	35	5
Chobee	loamy fine sand	12	130	177,511	41	10
Dothan	sandy loam	193	32	297,410	22	10
Eau Gallie	sand	543	7	465,679	11	1
Esto	fine sandy loam	na	na	24,783	155	1
Felda	fine sand	48	74	253,462	31	1
Floridana	sand	17	118	250,303	32	4
Fuquay	sand	125	46	262,070	30	4
Kendrick	loamy sand	97	56	106,231	70	6
Lucy	loamy sand	70	62	133,837	59	5
Mascotte	fine sand	43	78	281,023	26	2
Maxton	loamy sand	2	215	1,739	307	1
Millhopper	sand	216	27	133,846	58	3
Orangeburg	loamy sand	207	28	282,002	25	15
Otela	fine sand	202	29	138,103	55	1
Pelham	loamy sand	93	57	393,382	17	4
Pineda	sand	184	33	421,044	16	1
Pomona	sand	116	48	440,266	13	8
Riviera	sand	159	40	491,995	9	2
Sapelo	fine sand	66	66	273,399	27	2
Sparr	fine sand	279	15	162,728	44	2
Surrency	loamy sand	1	238	284,796	24	3
Tooles	fine sand	2	221	144,731	52	1
Troup	fine sand	435	11	459,785	12	1
Wabasso	fine sand	200	31	434,075	15	6
Waccasassa	sandy clay loam	na	na	27,154	147	2
Winder	loamy sand	43	79	20,2519	38	8

[1] *Soil series textural classification is listed. However, only individual data records with classification listed as "sandy clay loam" were included in the evaluation.*

[2] *Information on number of recent permits provided by FDOH (2012).*

o:\44237-001R006\Wpdocs\Report\Draft

Table A.3
Summary of Soil Parameters for Individual Sand Series[1].

Soil Series	Sand Particle Distribution (%)					Particle Distribution (%)							Model Fitting Parameters	
	Very Coarse Sand	Coarse Sand	Medium Sand	Fine and	Very Fine Sand	Total Sand	Total Silt	Total Clay	K_{sat} (cm/)	Bulk Density (g/cm^3)	Θ_r (cm^3/ cm^3)	Θ_s (cm^3/ cm^3)	α (1/cm)	n
Adamsville	0	1.9	25.0	51.3	8.4	97.0	1.8	1.1	938.4	1.55	0.62	38.13	0.025	2.92
Albany	0.2	3.2	18.9	50.3	12.4	91.0	6.3	2.3	337.6	1.54	1.36	38.18	0.020	2.25
Alpin	0.1	4.2	25.3	51.4	14.8	95.0	3.5	1.6	615.6	1.52	0.92	38.53	0.023	2.65
Apopka	0.1	1.5	26.9	61.6	6.8	95.8	2.3	2.0	946.8	1.53	1.27	37.74	0.034	2.11
Arredondo	0	2.1	20.2	51.4	11.0	92.6	4.0	2.9	445.2	1.54	1.62	36.11	0.021	2.42
Astatula	0	0.6	12.2	78.9	3.0	98.0	0.9	1.0	1515.4	1.43	0.54	39.54	0.030	2.96
Basinger	0	2.5	24.1	64.5	4.3	97.3	1.2	1.2	567.6	1.58	1.20	36.94	0.020	2.63
Blanton	0.1	3.4	17.0	53.4	11.4	91.4	5.4	2.6	552.0	1.54	1.35	38.92	0.023	2.43
Bonifay	0.5	11.0	32.1	29.7	7.3	87.6	6.0	5.2	195.6	1.61	2.87	35.83	0.032	1.80
Candler	0	0.8	17.6	65.9	6.1	97.3	1.4	1.4	890.4	1.50	0.79	38.56	0.023	3.57
Eau Gallie	0	1.1	16.8	61.6	10.2	95.0	2.8	1.6	342.0	1.53	2.12	38.74	0.017	2.08
Felda	0	1.0	8.2	51.6	13.6	93.6	2.9	3.3	211.8	1.58	2.88	37.97	0.015	2.29
Floridana	0	2.0	35.0	39.3	4.5	90.1	5.5	4.6	184.1	1.59	4.09	40.18	0.015	1.58
Holopaw	0	0.2	3.0	75.2	5.2	92.7	3.4	1.5	295.8	1.54	1.17	38.36	0.017	2.23
Immokalee	0	4.1	36.0	51.4	4.0	97.4	1.6	1.2	717.6	1.54	1.66	38.08	0.026	2.34
Lake	0	1.0	20.0	69.8	5.0	95.0	2.1	2.8	1435.2	1.45	1.63	40.03	0.030	2.52
Lakeland	0.3	9.7	48.0	30.0	2.2	93.6	3.8	2.5	1174.8	1.52	1.20	39.72	0.037	2.38
Leon	0	5.6	30.2	48.8	5.0	94.3	3.8	1.8	481.0	1.53	1.82	38.58	0.026	2.02
Malabar	0	2.4	18.0	63.6	8.0	97.1	1.8	0.9	448.8	1.58	1.31	36.83	0.021	2.43
Millhopper	0	2.8	27.0	50.4	7.2	95.0	2.9	2.2	690.6	1.54	1.30	38.98	0.026	2.41
Myakka	0	1.6	17.3	65.0	7.2	95.3	2.4	2.0	433.2	1.50	2.60	40.96	0.022	2.00
Oldsmar	0	3.8	40.5	40.7	5.0	96.5	2.0	1.5	607.2	1.55	2.07	37.18	0.030	2.06
Ortega	0	0.8	11.5	80.6	3.3	97.6	1.2	1.2	994.8	1.47	0.61	40.10	0.024	3.56
Otela	0.1	2.1	16.6	53.4	22.1	94.4	3.8	2.0	397.8	1.58	0.85	37.20	0.016	2.96

Table A.3 (cont.)
Summary of Soil Parameters for Individual Sand Series[1]

Soil Series	Sand Particle Distribution (%)					Particle Distribution (%)							Model Fitting Parameters	
	Very Coarse Sand	Coarse Sand	Medium Sand	Fine Sand	Very Fine Sand	Total Sand	Total Silt	Total Clay	K_{sat} (cm/d)	Bulk Density (g/cm^3)	Θ_r (cm^3/ cm^3)	Θ_s (cm^3/ cm^3)	α (1/cm)	n
Paola	0	6.2	33.6	54.3	1.7	98.2	0.8	1.0	1684.8	1.45	0.85	38.98	0.041	2.68
Pineda	0	2.4	19.0	59.8	4.6	96.1	2.0	1.8	350.4	1.63	1.12	36.21	0.017	2.49
Placid	0	0.9	12.9	52.4	13.3	93.3	3.6	2.9	330.7	1.56	1.68	38.67	0.021	1.76
Plummer	0.1	3.0	18.3	52.2	17.4	92.3	4.5	2.4	232.8	1.57	1.48	38.28	0.017	2.34
Pomello	0	1.6	18.3	65.3	8.1	97.2	1.9	0.9	673.8	1.44	1.60	39.19	0.022	2.80
Pomona	0	1.8	16.9	51.4	14.0	93.4	3.8	2.5	305.2	1.52	2.74	38.02	0.021	1.92
Riviera	0	0.8	11.0	61.6	9.8	93.2	2.4	3.6	310.0	1.60	2.06	38.66	0.017	2.42
Rutledge	0	0.6	3.0	78.4	9.0	90.8	3.7	3.6	102.7	1.56	2.61	36.90	0.016	1.97
Sapelo	0	1.4	11.2	60.0	13.0	92.3	5.2	2.3	294.0	1.51	1.78	39.07	0.019	2.06
Smyrna	0	0.7	11.6	67.4	10.3	94.8	2.9	2.4	438.0	1.47	2.21	40.83	0.021	2.25
Sparr	0	1.4	16.5	52.2	16.6	94.0	3.8	2.2	426.0	1.53	1.46	38.03	0.023	2.32
St Lucie	0	5.0	61.6	30.9	1.0	98.7	0.6	0.5	2170.2	1.46	1.50	39.00	0.060	2.84
Tavares	0	1.3	16.7	68.5	6.6	96.8	1.7	1.6	825.6	1.50	0.74	38.96	0.024	2.97
Troup	1.5	11.0	30.6	37.4	8.9	88.6	5.7	4.0	528.6	1.58	2.01	35.69	0.037	1.90
Wabasso	0	2.2	22.5	48.6	11.7	92.1	3.9	2.1	219.7	1.55	2.75	37.90	0.019	1.90
Zolfo	0	0.8	10.2	70.6	15.6	96.0	2.5	1.3	598.8	1.0	0.89	39.69	0.019	4.21

[1] *Median values listed for soil properites were determined based on complete records in the Florida Soils Characterization Data Retrieval System. Model fitting parameters (α and n) listed were estimated using solver to and the lowest sum of the squares for the van Genuchten equation.*