SSSA Onsite
Wastewater Conference
April 7-8, 2014

The Florida Onsite Sewage Nitrogen Reduction Strategies (FOSNRS) Project

FOSNRS 6: STUMOD-FL - A Tool for Predicting Fate and Transport of Nitrogen in Soil Treatment Units in Florida

April 7, 2014

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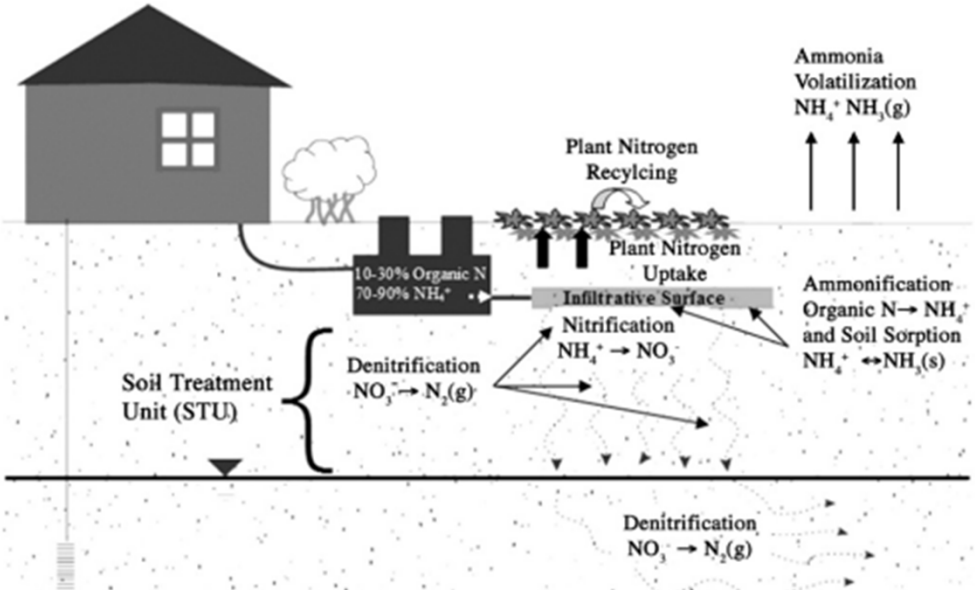
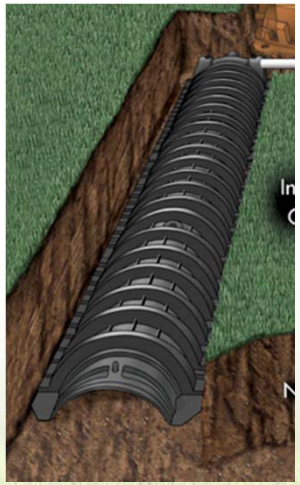
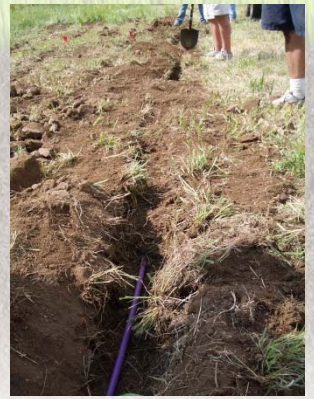
Onsite wastewater treatment systems

- Onsite wastewater treatment systems serve a significant portion of U.S. households
- Vast majority of onsite wastewater systems utilize native soil for disposal and treatment



Vadose zone





Collaboration

HAZEN AND SAWYER
Environmental Engineers & Scientists

FLORIDA DEPARTMENT OF HEALTH

SCHOOL OF MINES 1874 COLORADO

Goal

Develop a set of <u>tools</u> for assessing nitrogen fate and transport in the saturated and unsaturated zone under Florida conditions

Tools

- Look-Up Tables that provide insight for treatment based on generalized site and operational conditions based on outputs from a numerical model

- STUMOD-FL: A vadose zone model; spreadsheet tool for technically trained (hydrologist, soil scientists, engineers)

- Aquifer module for fate and transport in the saturated zone

What can STUMOD-FL do?

- Removal through sorption, reaction, plant uptake
- Steady state suction, soil moisture & concentration profiles
- Effect of degree of saturation on nitrification & denitrification
- The effect of temperature and concentration
- Carbon content depth function for denitrification
- Root water and nutrient uptake
- Heterogeneous layers, a biomat, capillary zone effects
- Accepts NH4, NO3 or both as an input

Advantages

- **Simple for operation**
- **Physically based (Soil moisture profile is based on Darcy's equation- Chemical transport is based on ADE**
- **Scenarios can be evaluated in a relatively short time**

$$R\frac{dc}{dt} = D_L \frac{\partial^2 C}{\partial x^2} - v_x \frac{\partial C}{\partial x} - R\lambda C$$

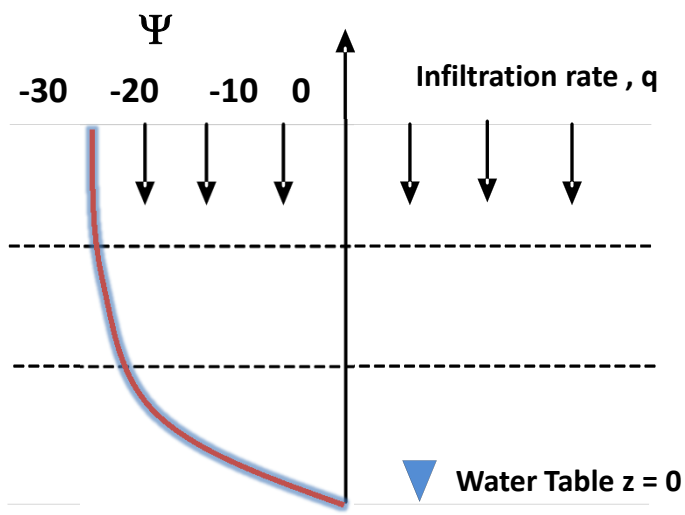
Geza, et al, 2013. STUMOD- a Tool for Predicting Fate and Transport of Nitrogen in Soil Treatment Units. Environ Model Assess DOI 10.1007/s10666-013-9392-0

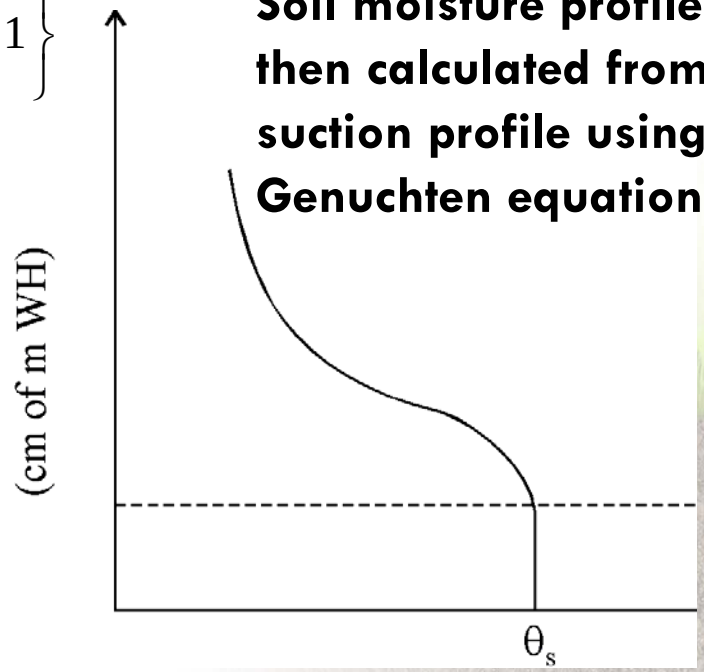
STUMOD has since then been modified !

Soil moisture and suction profile

STUMOD-FL calculates suction profile using a combination of Gardners and the Buckingham Darcy equation.

$$\psi = \psi_o - z + \frac{1}{\alpha}\ln\left\{\frac{v}{K_o}e^{-\alpha\psi_o}\left(e^{\alpha z}-1\right)+1\right\}$$





Soil moisture profile is then calculated from suction profile using Van Genuchten equation.

Soil moisture profile is used to adjust nitrification, denitrification, sorption rates and plant water and nutrient uptake

Chemical Transport

- **A steady state model based on a simplification of ADE**

$$R\frac{dc}{dt} = D_L \frac{\partial^2 C}{\partial x^2} - v_x \frac{\partial C}{\partial x} - R\mu C \longrightarrow c + k_m \ln(c) - c_o + k_m \ln(c_o) - R\mu_{\max} f_z f_t f_{sw} \frac{z}{v_z} = 0$$

- **Monod function to account for the effect of concentration**
- **Sorption - Ammonium**
- **Reactions - Nitrification (NH4) and denitrification (NO3)**

Adjusted nitrification and denitrification rates

- Nitrification and denitrification rates are adjusted for the effect of degree of saturation , temperature & concentration

- Adjusted rate = Optimum/maximum rate (μ_{max})
  x a factor for degree of saturation (f_{sw})
  x a factor soil temperature (f_t) &
  x a factor for concentration (Monod)

- For denitrification a carbon content function (f_c) is included; for STU - assumed sufficient carbon is available

Effect of degree of saturation on nitrification and denitrification

Nitrification and Denitrification

- Nitrification requires oxygen, converts ammonium to nirate. Requires oxygen (aerobic) conditions.

$$NH_4 + 2O_2 \rightarrow NO_3^- + 2H^+ + H_2O$$

- Denitrification takes place in the absence of oxygen, converts nitrate to nitrogen gas. Requires anaerobic conditions.

$$4NO_3^- + 4H^+ \rightarrow 2N_2 + 5O_2 + 2H_2O$$

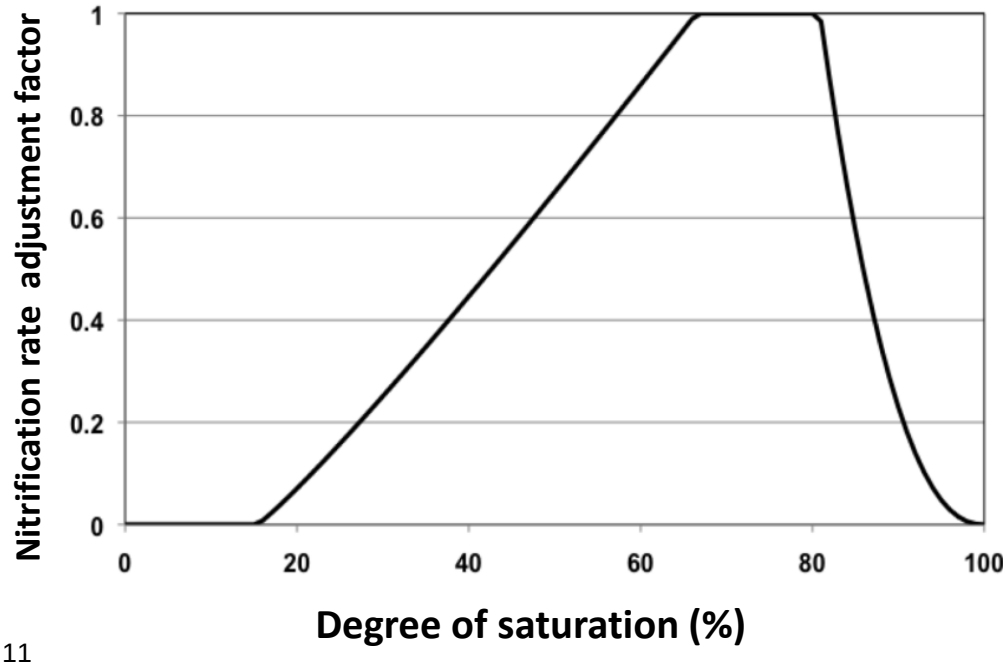
- **The degree of saturation (calculated in STUMOD) is used as a surrogate for the aerobic and anaerobic condition to adjust nitrification and denitrification rates**

- **Degree of saturation is also used in retardation**

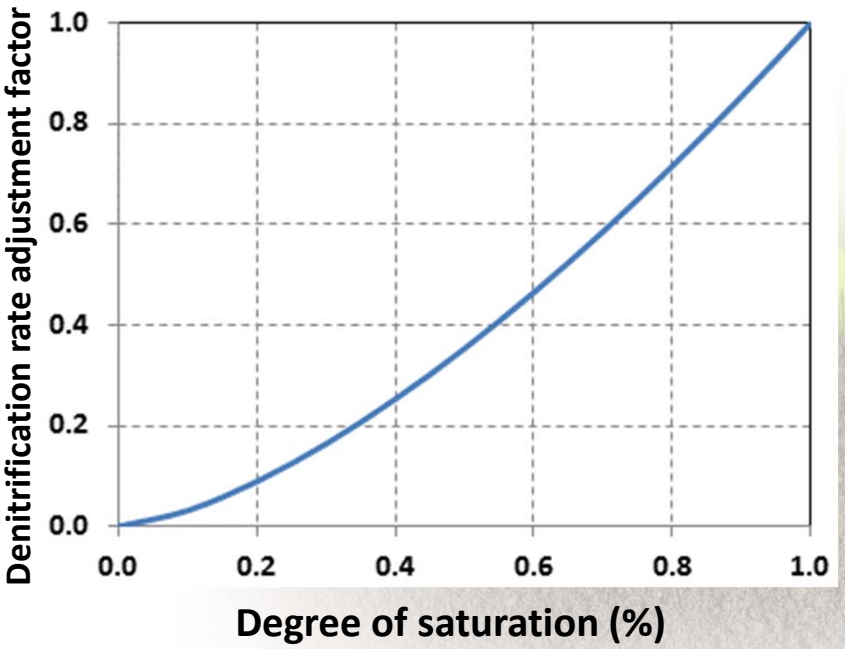
Rate adjustment for degree of saturation

- **Adapted from DRAINMOD**

Nitrification rate adjustment



Denitrification rate adjustment



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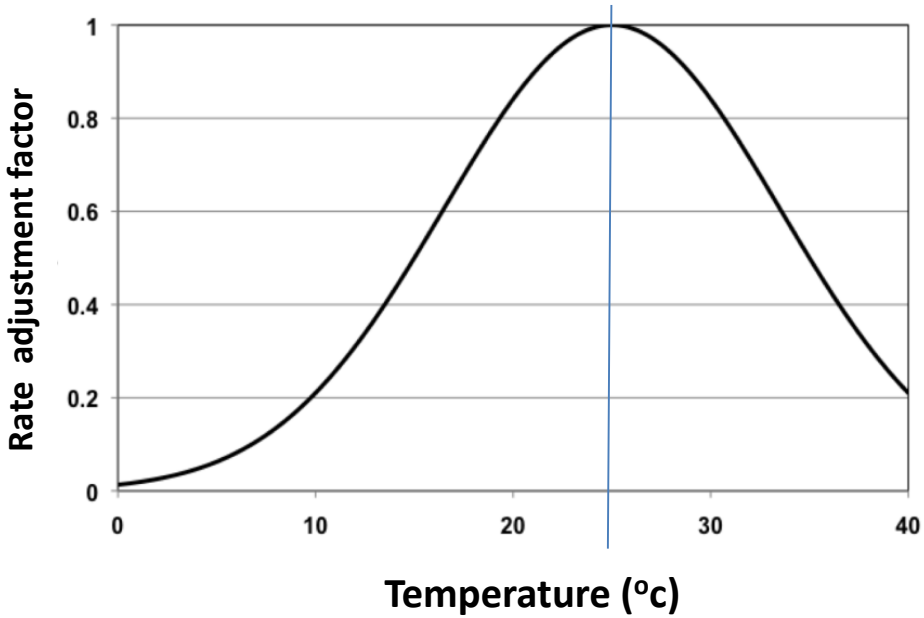
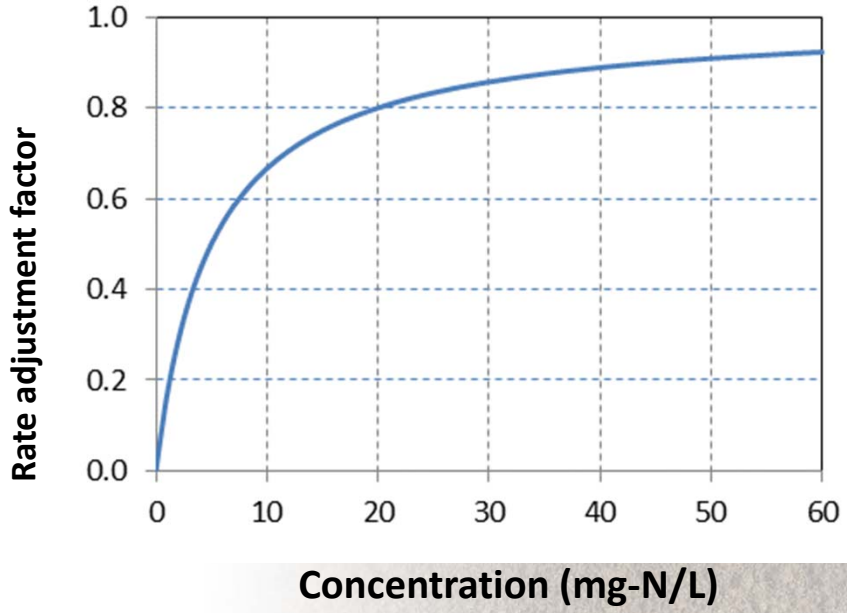
Rate adjustment for temperature and concentration

Rate adjustment for temperature



Temperature response function, similar van't-Hoff)

Rate adjustment for concentration

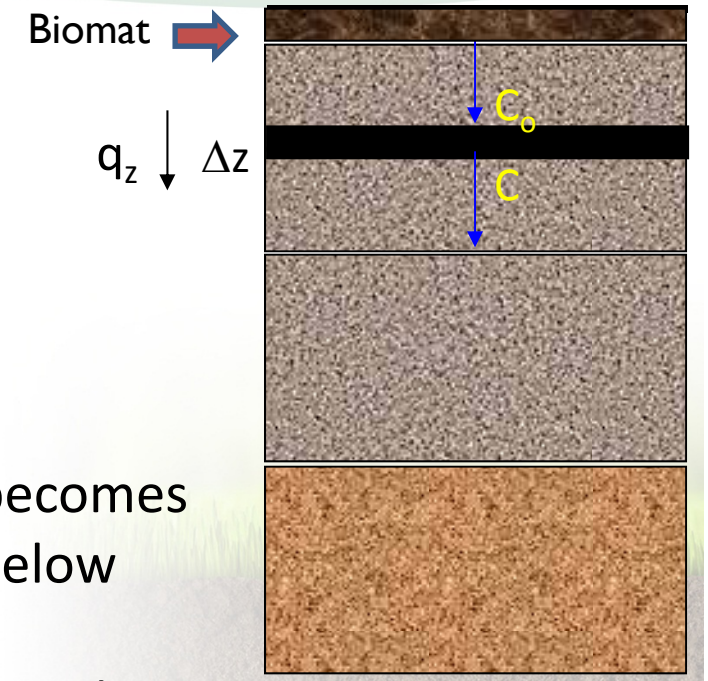


Monod function- removal rate reduced at low concentration

Model switches to zero-order at high concentration and first order at low concentration

Heterogeneous layers

- Allows up to 4 soil layers including a biomat
- Soil hydraulic properties can be varied by layer
- Each layer is further divided into segments
- Outflow concentration from a segment above becomes inflow or boundary concentration to segment below
- Removal may vary from segment to segment based on soil moisture content and concentration



Plant nutrient uptake in STUMOD-FL

- Nutrient uptake in STUMOD-FL is driven by actual Evapotranspiration (ET) and nutrient availability

- Nutrient uptake is incorporated in to nitrogen fate and transport equation; it reduces concentration reaching the water table just like other removal processes

- Nutrient uptake = Concentration X upward water flux (ET) < less than or equal to crop nutrient demand

- Nutrient uptake is less than demand when soil water nutrient concentration or ET is small. If there is sufficient denitrification, the soil water nutrient concentration in STU changes with depth, thus uptake decreases with depth

Nutrient uptake in STUMOD-FL

- Both NO_3 and NH_4 species are assumed to be equally available to plants (no preference by plants).
- In STUs, at shallow depth most of the nitrogen is ammonium. Thus, in STUMOD-FL **at shallow depth most of the nitrogen demand is supplied as NH4 and the nutrient supply becomes nitrate as depth increases dependent on root distribution**

Plant water and nutrient uptake in STUMOD-FL

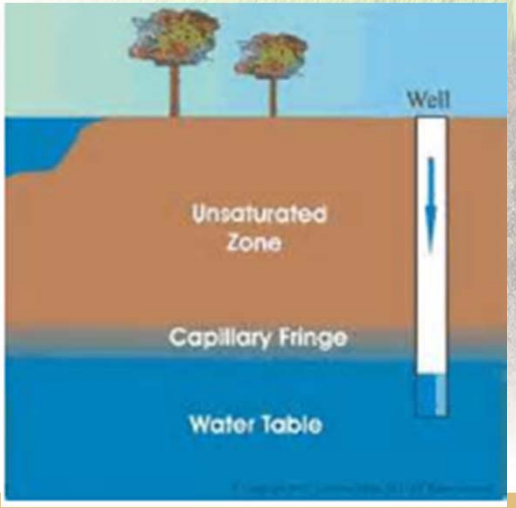
- Important factors
  - Crop nutrient demand (kg/ha/day) is a user input
  - Soil water nutrient concentration is calculated by the model
  - ET is calculated by the model
- Actual evapotranspiration (ET) is calculated from PET adjusted for the effect of soil moisture content & root distribution
- PET calculated using Hargreaves Method
- ET = PET x a factor for soil moisture status (0 to 1)

  x a factor for root distribution with depth

Boundary conditions

- Shallow water table - soil moisture affected by capillary rise; a pressure head of zero at the water table

- Deep water table - no effect on soil moisture due to capillary (free drainage) -mimicked by setting the water table to a greater depth.



Water table depth (WTD) options in STUMOD-FL

- Contaminant loading to water table depends on the thickness of the vadose zone (separation distance b/n Water table & infitrative surface)
- Location of the water table needs to be specified when loading to water table is to be estimated.
- Two options available in STUMOD-FL
  - User input water table depth
  - WTD calculated by the model
- Analytical model for water table fluctuations in response to precipitation was implemented
- Water table rise depends on recharge and soil properties
- Water table decline depends on a rate coefficient for rise and fall of water table that depends on soil hydraulic conductivity, fillable porosity (specific yield) and hydraulic gradient
- This is not a fully coupled model, the WTD calculation is intended to get available treatment depth and implemented to Florid conditions only.

STUMOD-FL INPUT

Some input parameters are summarized from literature

e.g. Septic tank effluent quality: A median value from CFD, ~ 60 mg-N/L

Nitirifcation and denitrification rates were also derived from CFD of literature date

Several of the hydraulic parmeters were obtained from Schaap et al. (2001)

Parameters	Clay	Clay loam	Loam	Loamy sand	Sand	Sandy clay	Sandy clay loam	Sandy loam	Silt	Silty clay	Silty clay loam	Silty loam	Data Source
Biomat parameters													
K sat	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	L[a]
Thickness	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	L[a]
Effluent Input concentrations, Co													
NH4-N	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	L[m]
NO3-N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	L

Soil types and hydraulic parameters specific to Florida were identified

Soil type	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
Group 1 –More Permeable Sand	670.8	1.51	1.3	0.3874	0.024	2.52
Group 2 – Less Permeable Sand	352.6	1.55	1.7	0.3794	0.020	2.24
Sandy clay loam	24.7	1.63	10.0	0.3800	0.009	1.84

STUMOD-FL INPUT

Nitrification Parameters													
kr-max	56.0	56.0	56.0	56.0	56.0	56.0	56.0	56.0	56.0	56.0	56.0	56.0	L^m
km-nit	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	L
e2	2.27	2.27	2.27	2.27	2.27	2.27	2.27	2.27	2.27	2.27	2.27	2.27	P
e3	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	P
fs	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	P
fwp	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	P
swp	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	P
sl	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	P
sh	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	P
β1	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	P
Topt1	25	25	25	25	25	25	25	25	25	25	25	25	L
Denitrification Parameters													
Vmax	2.56	2.56	2.56	2.58	2.58	2.58	2.58	2.58	3.32	3.32	3.32	3.32	P
Km-dnt	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	P
ednt	3.77	3.77	3.77	2.87	2.87	2.87	2.87	2.87	3.87	3.87	3.87	3.87	P
sdn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	P
β2	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	P
Topt2	25	25	25	25	25	25	25	25	25	25	25	25	L
α_c	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	L
Ammonium Sorption Parameters													
Kd	1.46	1.46	0.35	0.35	0.35	1.46	1.46	0.35	0.35	1.46	1.46	0.35	L^m
ρ	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	L^m

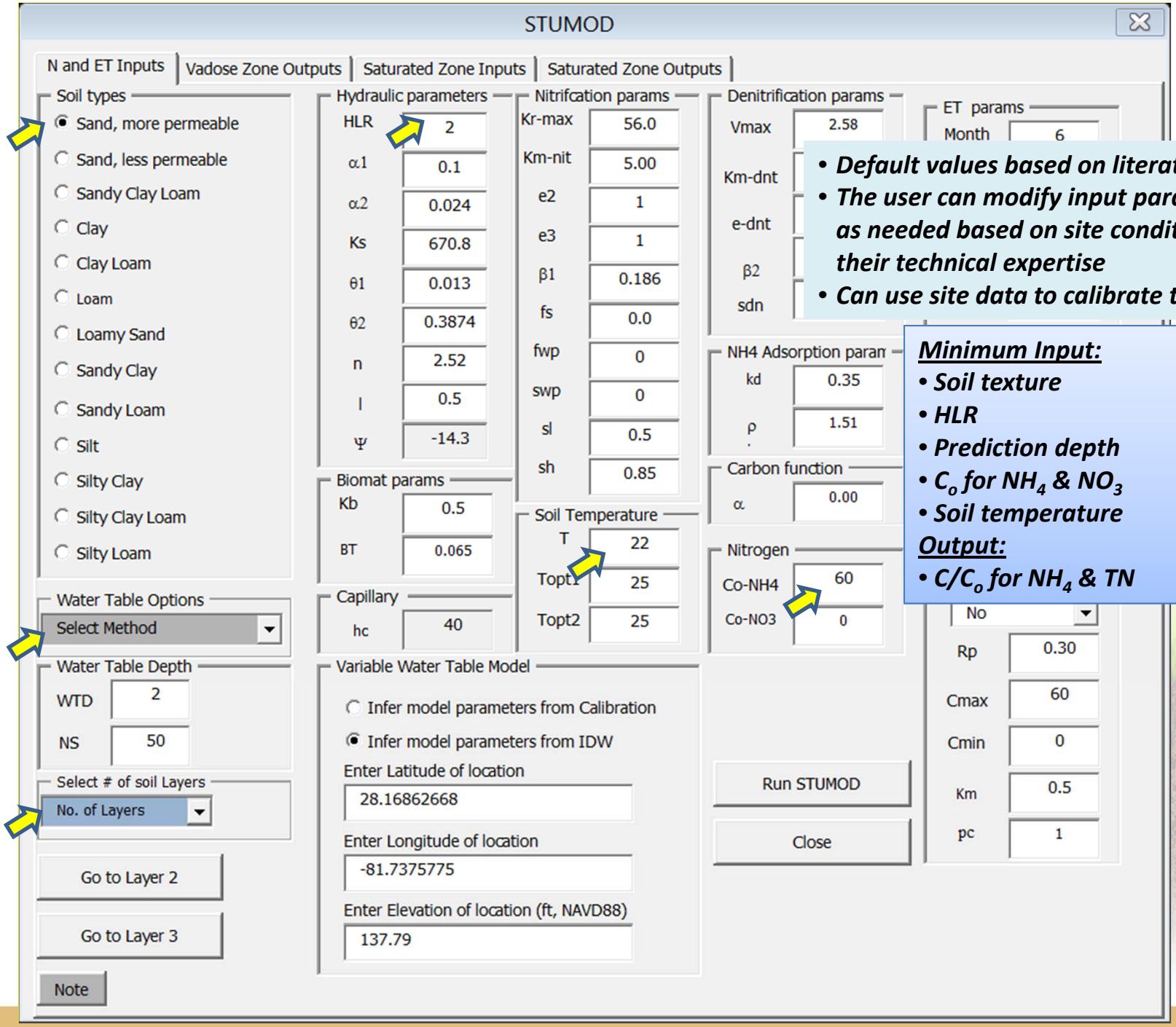
L^a =Mean, based on literature

L^m =Median, based on literature

P =Based on parameterization of soil moisture function using observed data

R^m =Schaap et al 2001. Rosetta program.

Revisions have also been made to some of the parameters for soil moisture response function in STUMOD-FL



- ***Default values based on literature***
- ***The user can modify input parameters as needed based on site conditions & their technical expertise***
- ***Can use site data to calibrate the model***

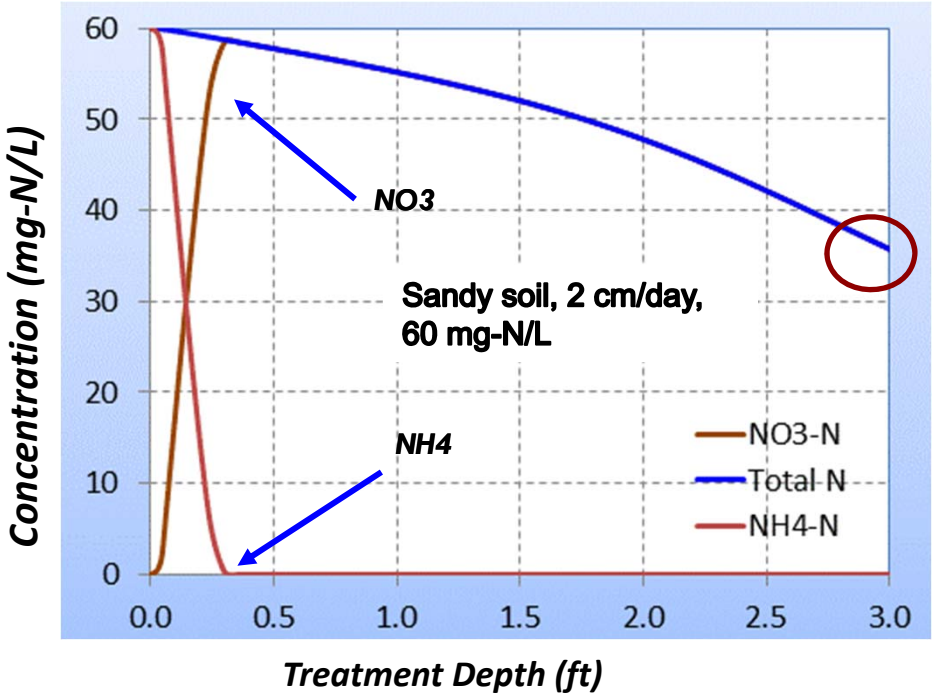
Minimum Input:

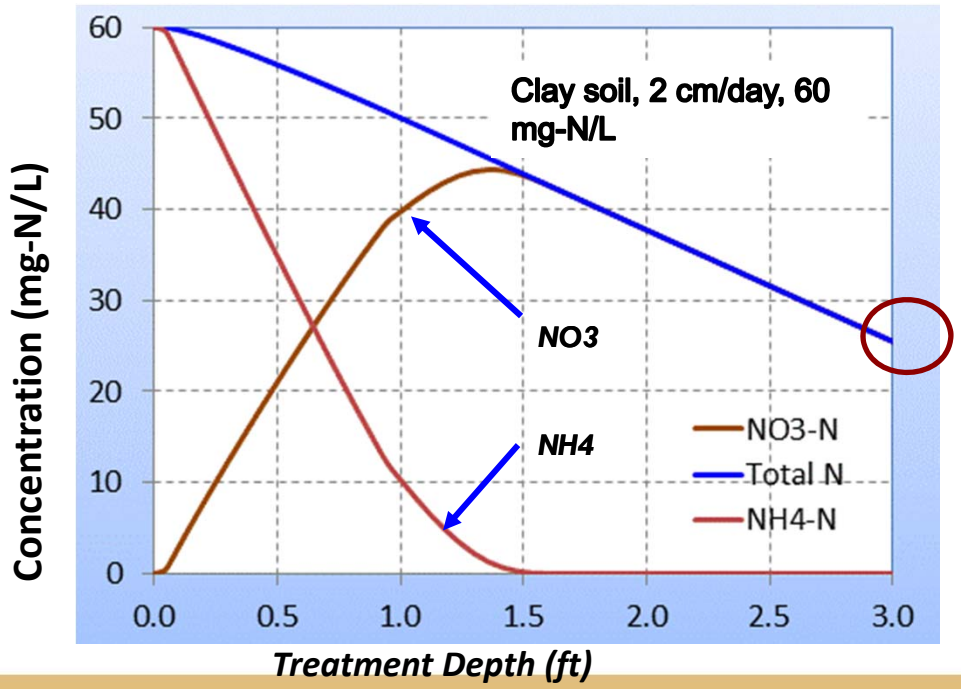
- ***Soil texture***
- ***HLR***
- ***Prediction depth***
- ***C_o for NH_4 & NO_3***
- ***Soil temperature***

Output:

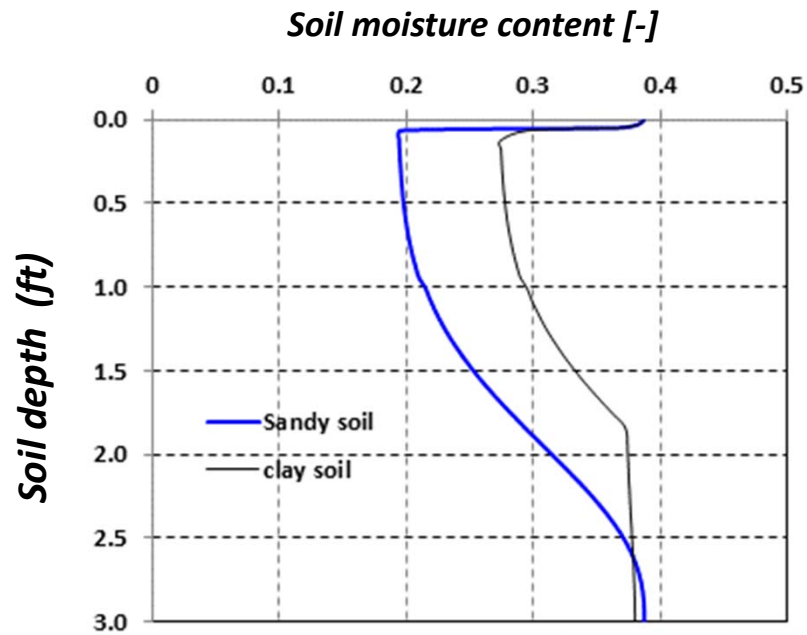
- ***C/C_o for NH_4 & TN***

STUMOD-FL outputs

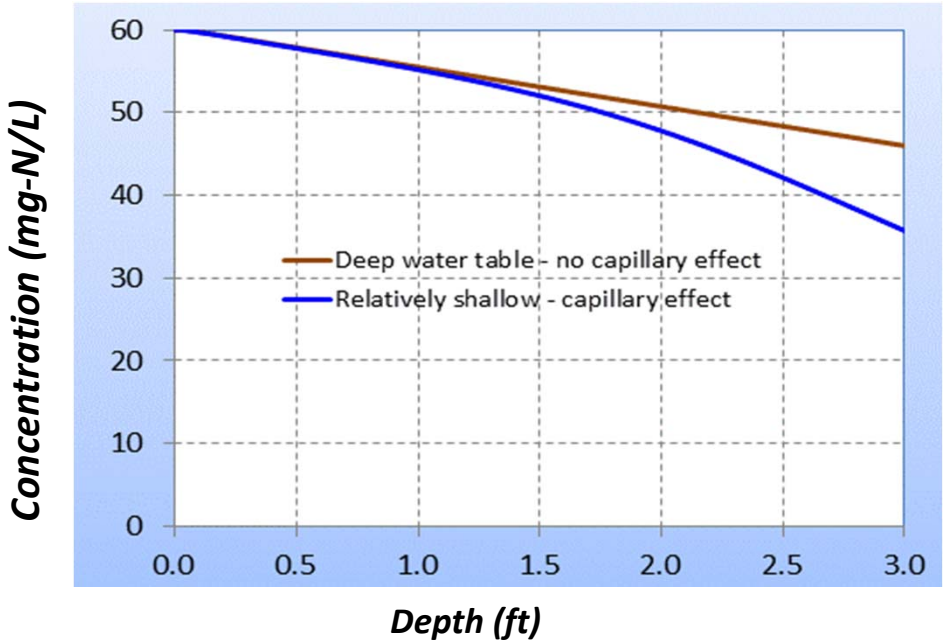




- Faster nitrification in sandy soil due to relatively low steady state moisture content

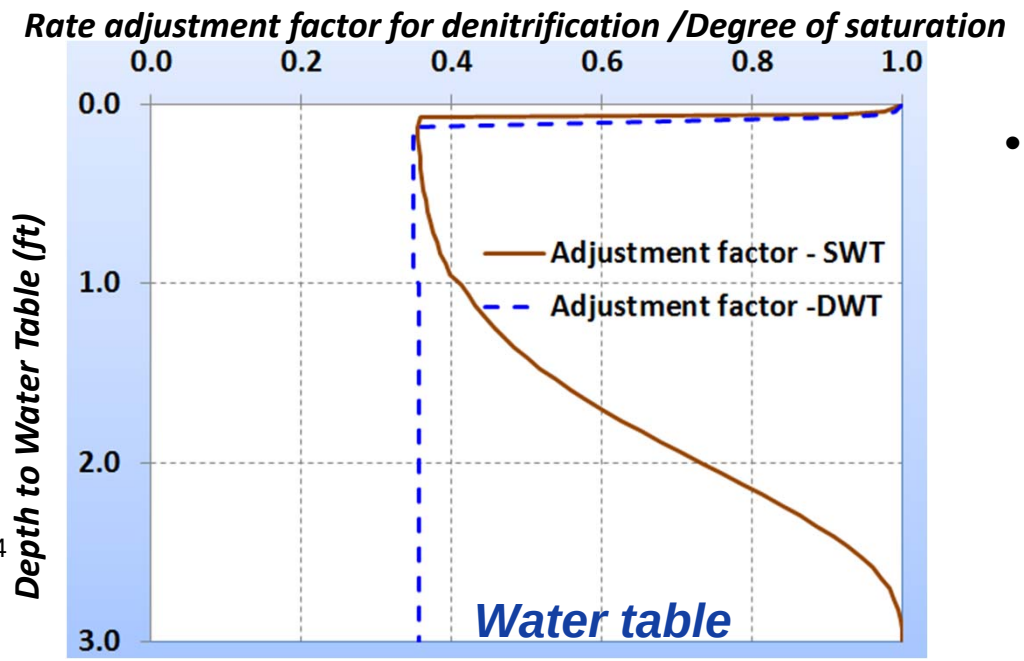


- Higher moisture content in clays slows nitrification but improves denitrification

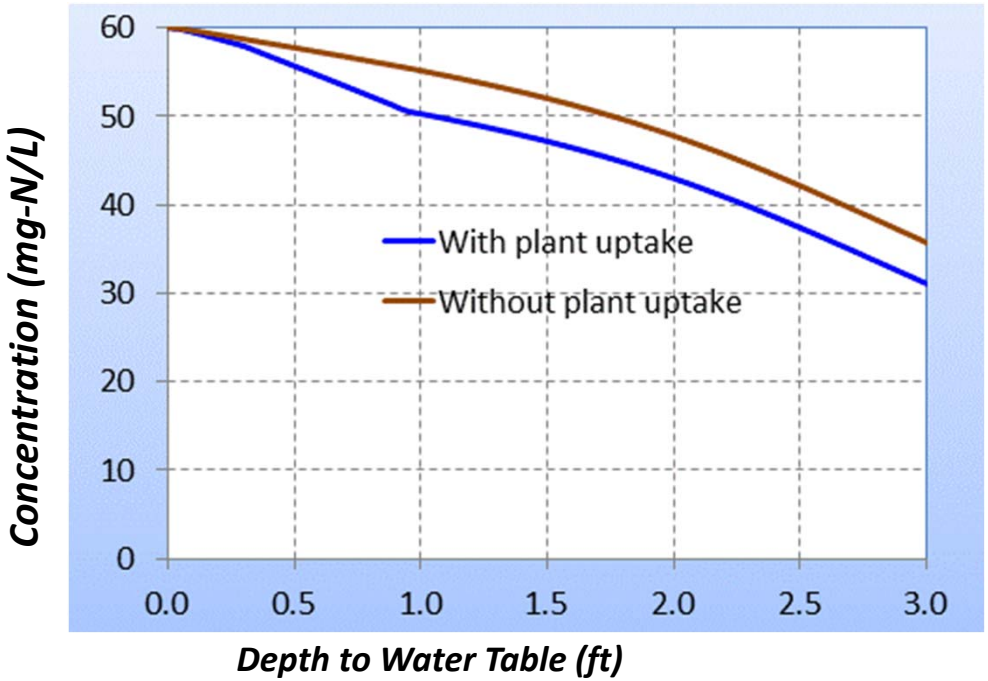


Deep and shallow water table conditions

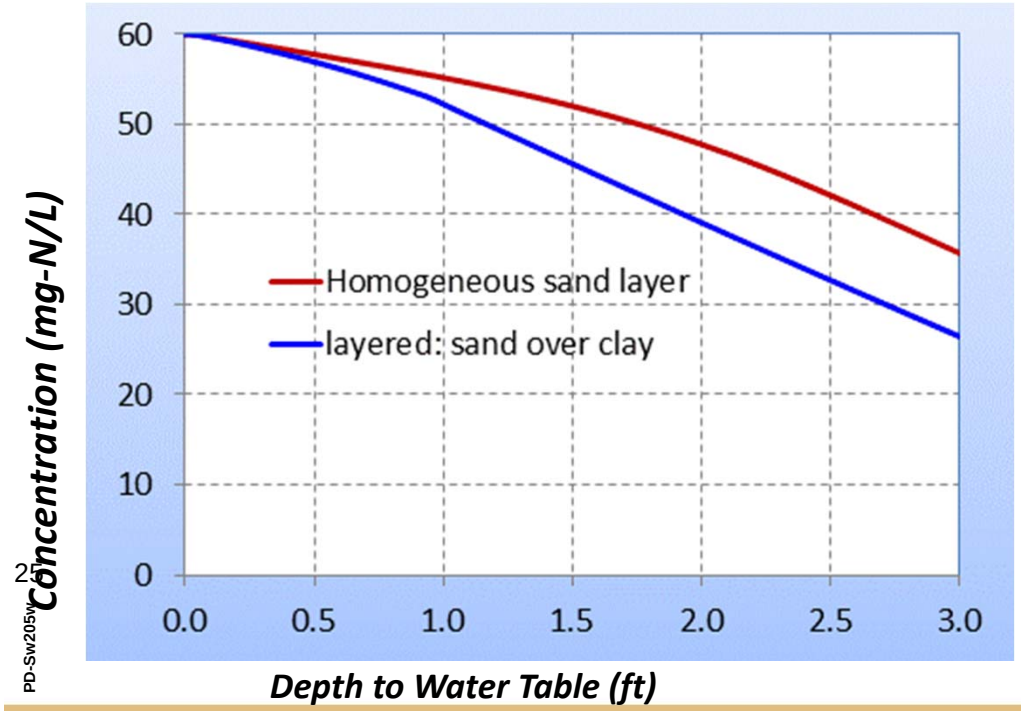
- STUMOD outputs show increased removal for shallow water table if there is sufficient depth for nitrification



- Higher water content at the capillary zone increases denitrification via the adjustment factor for degree of saturation in STUMOD



- STUMOD-FL outputs –effect of Plant nutrient uptake



- STUMOD-FL outputs –effect of heterogeneity

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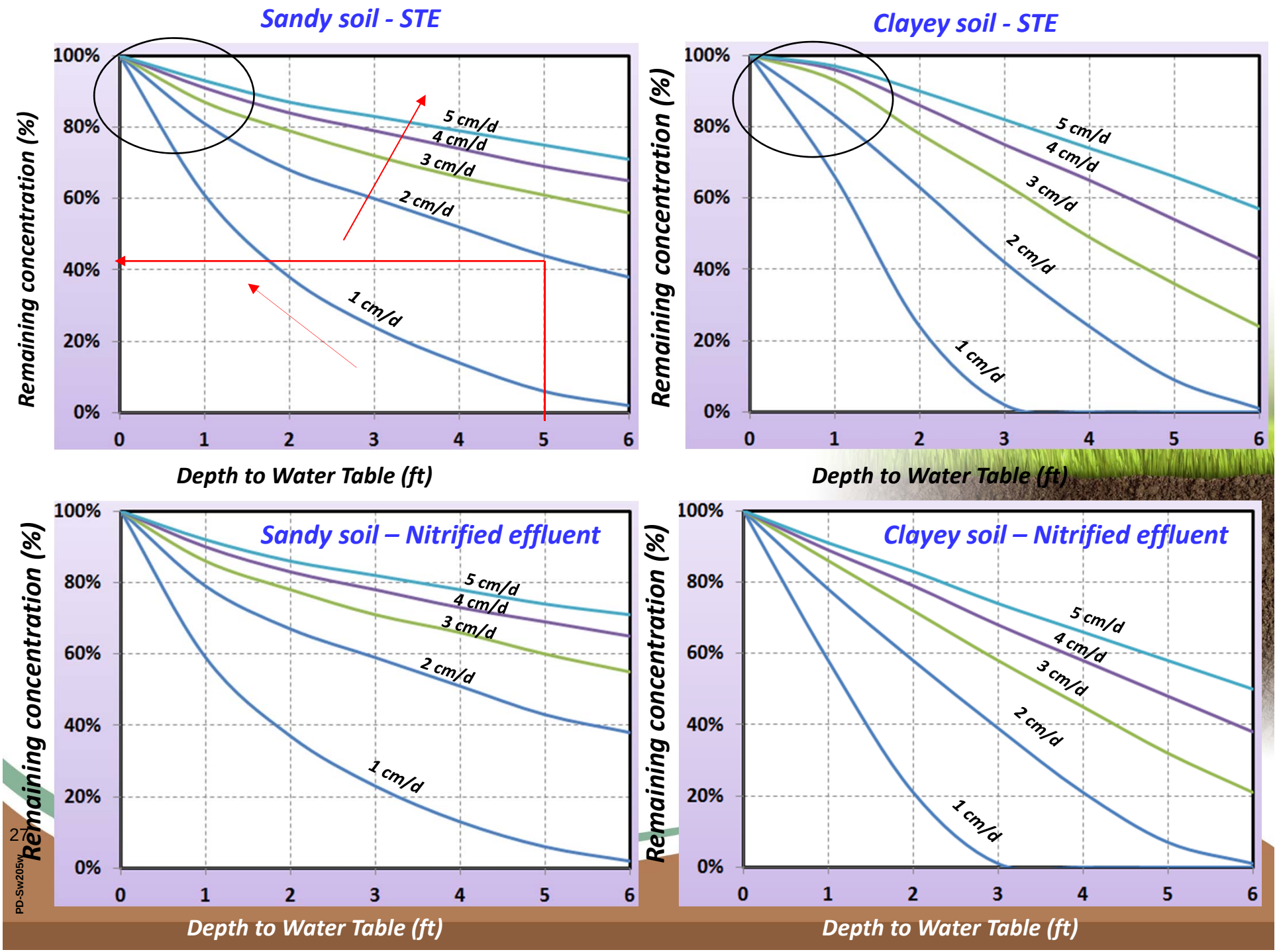
Interaction among factors affecting treatment

- **Higher hydraulic loading rate**
  - Increased in soil moisture content
  - Limits nitrification in some soil textures
  - Enhances denitrification
  - Reduces travel time limiting removal
- **Soil texture**
  - Soil moisture content differs by texture for a given loading
  - Travel times differ by texture for a given loading rate
  - Capillary rise differs by soil texture
- **Depth to water table**
  - Increased soil moisture at the capillary zone may enhance denitrification
  - Increased soil moisture due to capillary rise may limit nitrification if DWT is too shallow
- **Effluent quality STE vs Nitrified effluent**
  - Benefits from nitrifying for clayey textures and shallow water table conditions
- Nomographs demonstrating the interactions among several factors for a site can be developed using STUMOD.


Sandy soil - STE
Clayey soil - STE
Sandy soil – Nitrified effluent
Clayey soil – Nitrified effluent
Remaining concentration (%)
Depth to Water Table (ft)
100%
80%
60%
40%
20%
0%
0
1
2
3
4
5
6
5 cm/d
4 cm/d
3 cm/d
2 cm/d
1 cm/d

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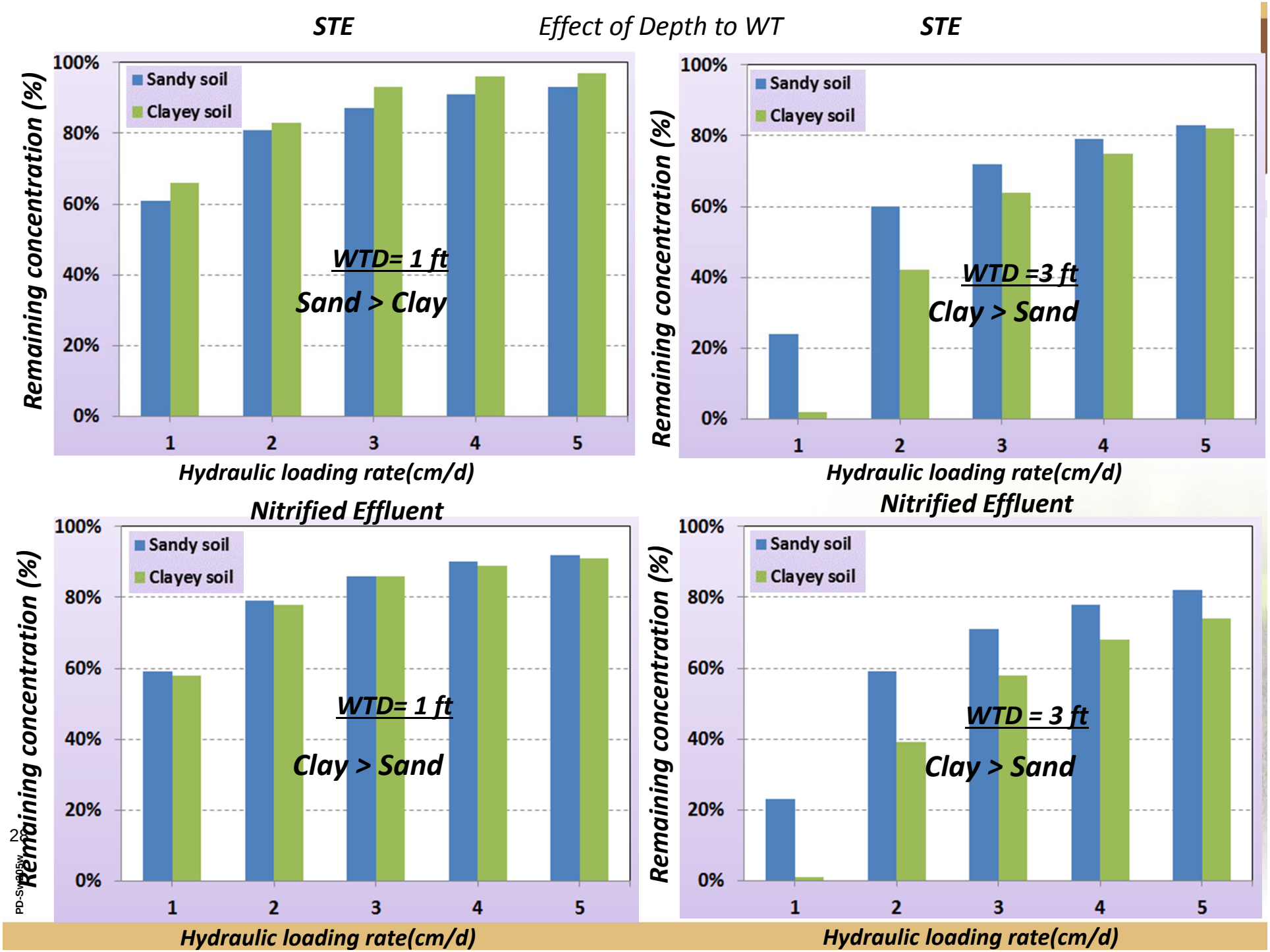
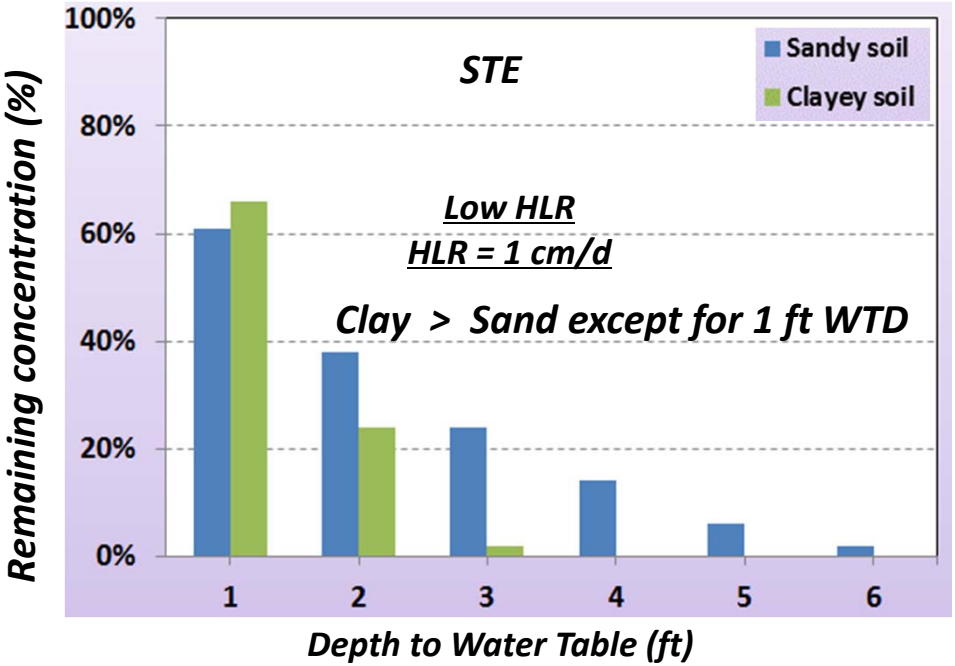
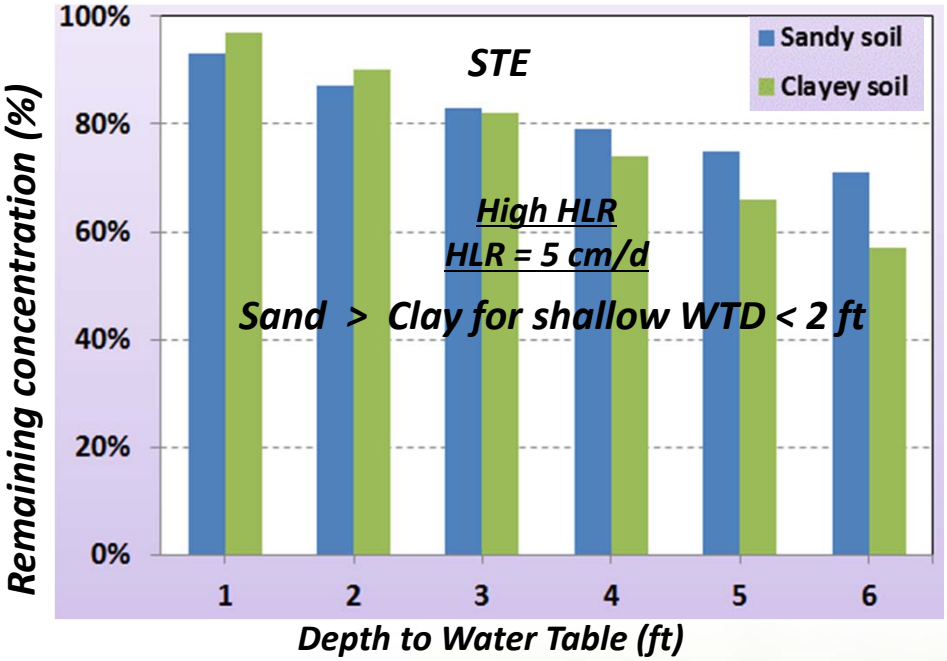
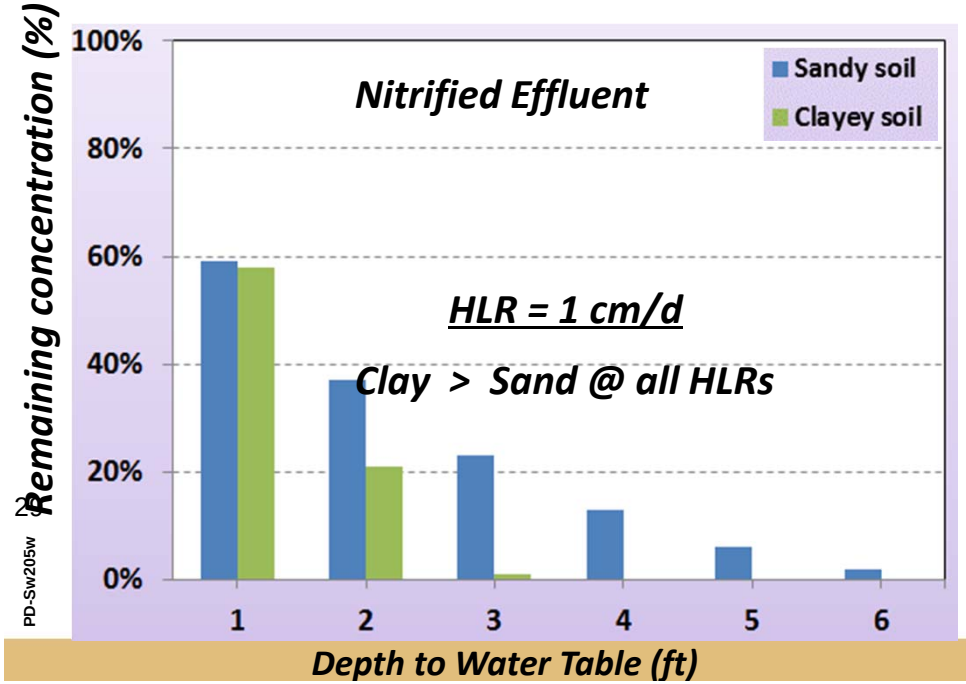
Effect of Depth to WT

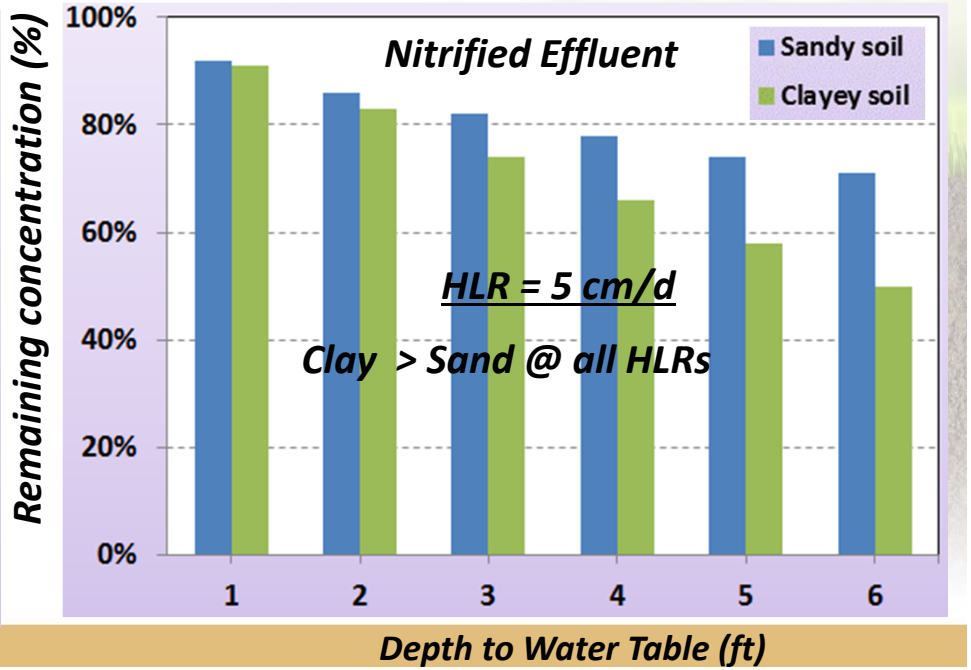


Effect of hydraulic loading rate



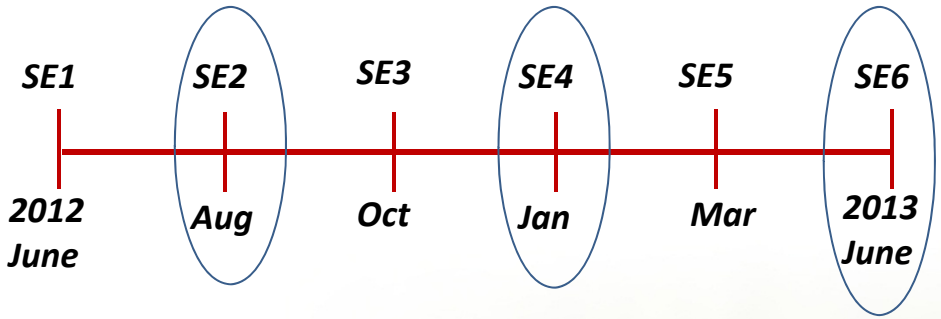






STUMOD-FL Evaluation

- Field data collected during six sample events
- Samples also collected the outflow from the septic tank
- Depths: 1, 2, 3.5 ft below infiltrative surface
- Analyzed for TN, NO_3^-, NH_4^+, Organic N
- STUMOD-FL run with default parameters

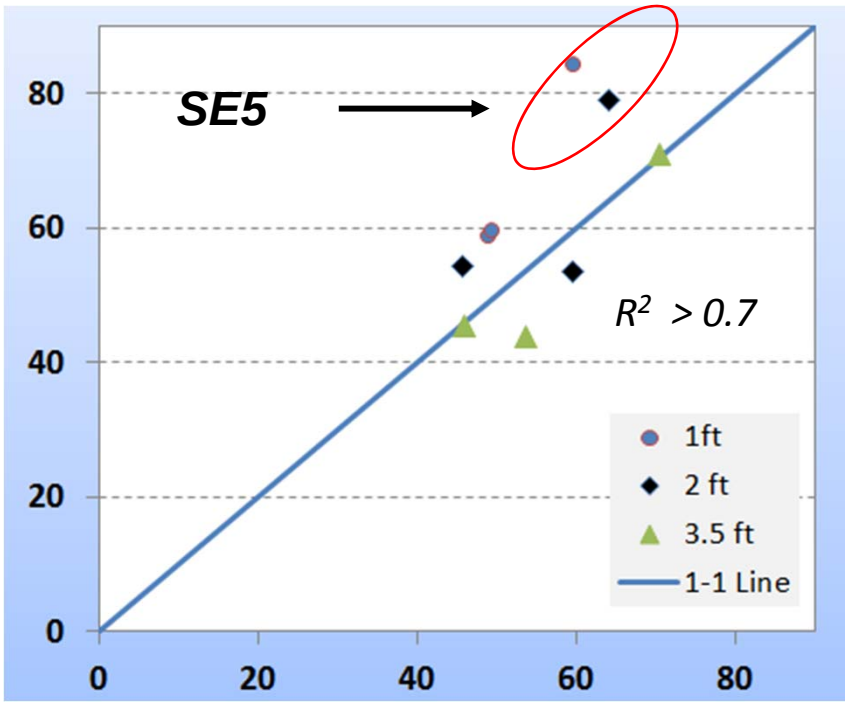


- SE2, SE4, SE6 had a considerable rainfall events in the days preceding the sampling events and were not applicable to STUMOD-FL steady state model

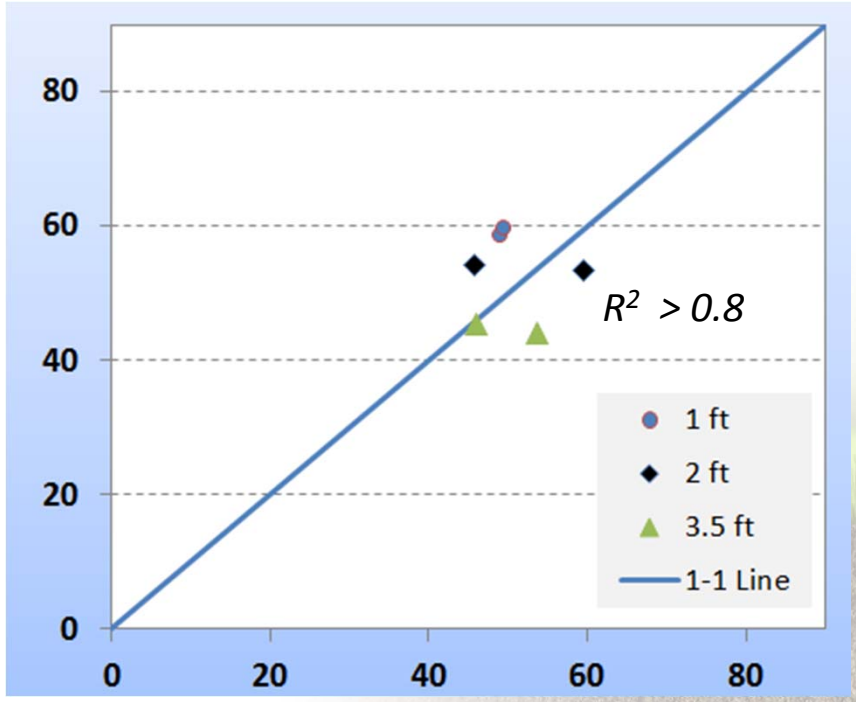
- Only sampling events 1, 3 and 5 with relatively less rainfall in the preceding days could be used

STUMOD-FL Evaluation

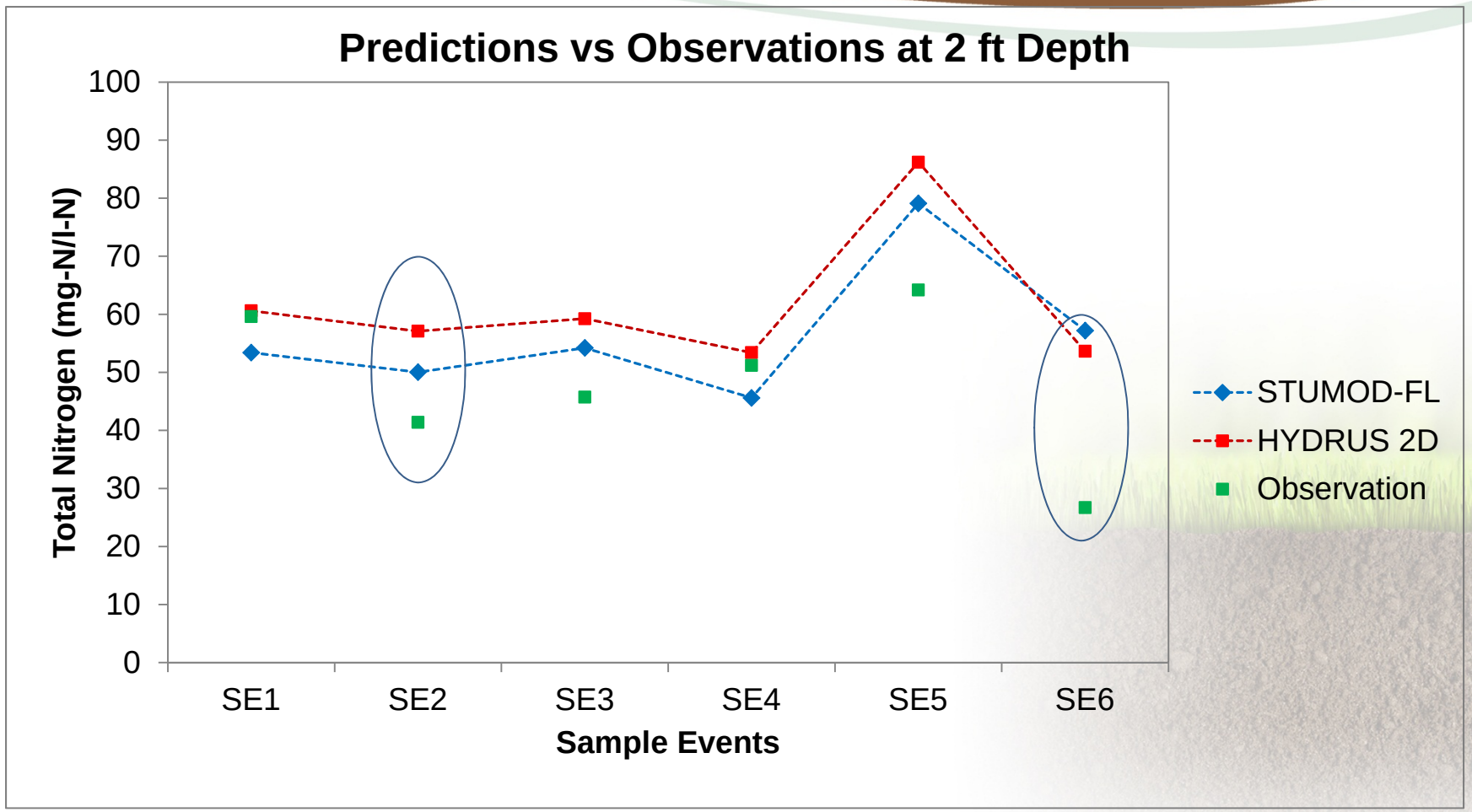
SE1, SE3 & SE5



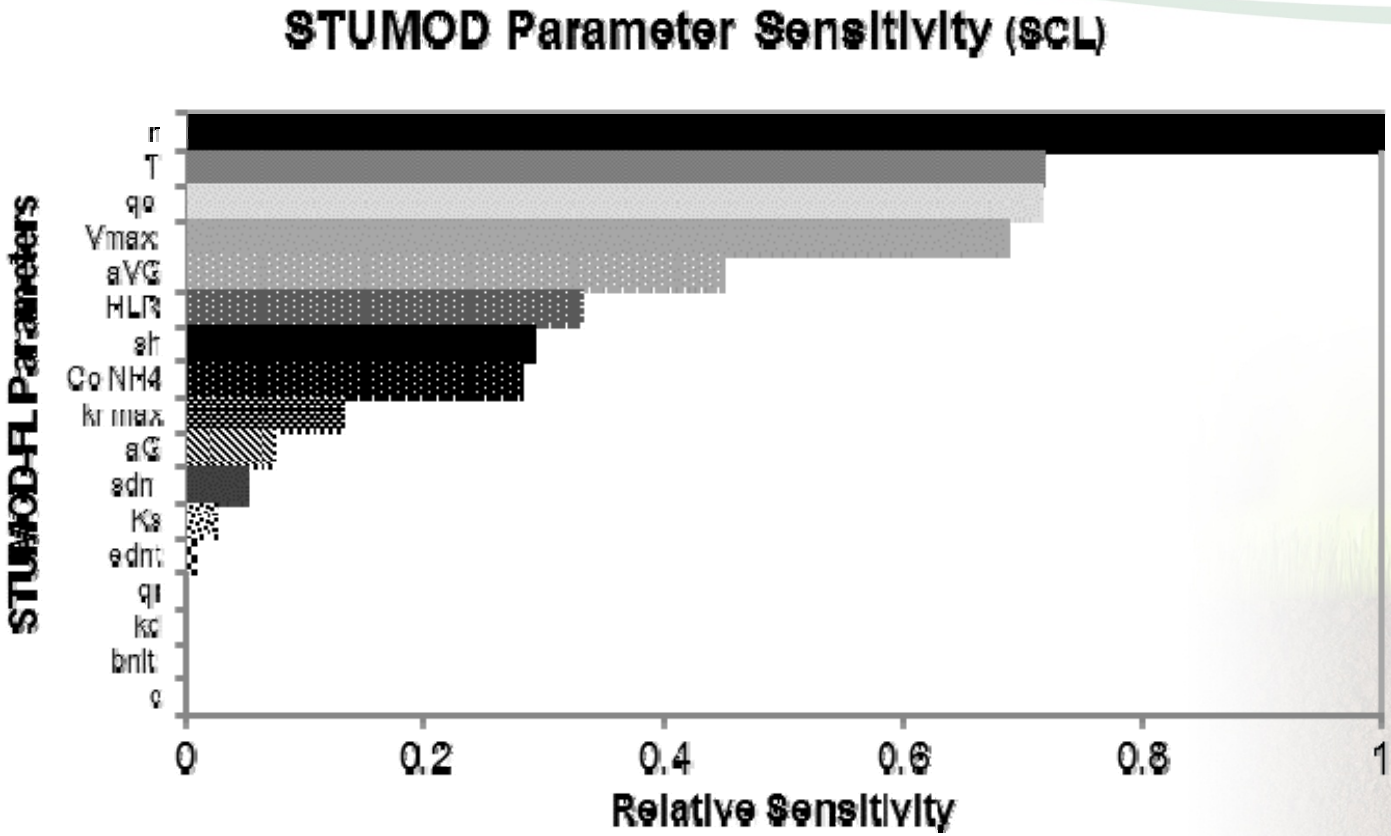
SE1 & SE3



STUMOD-FL Evaluation



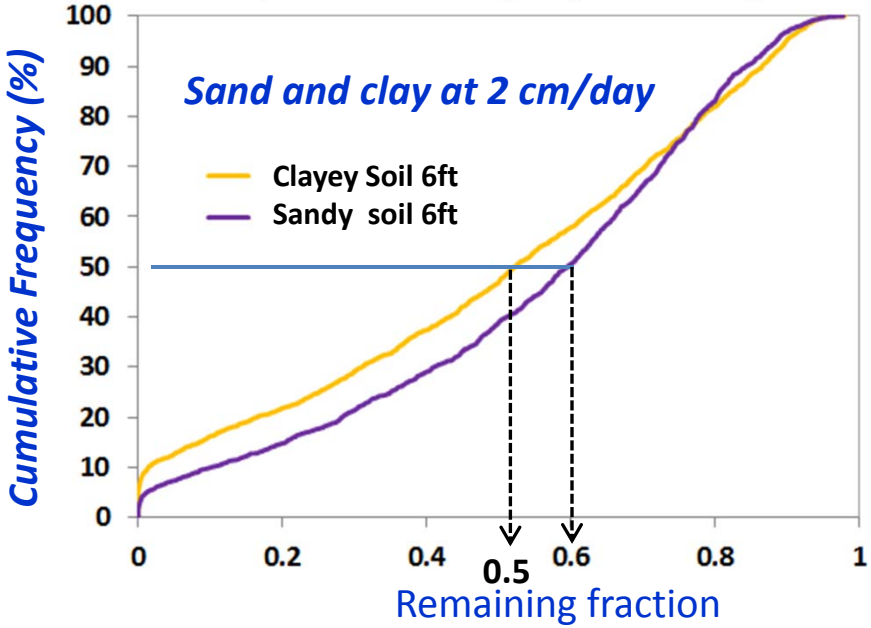
STUMOD-FL Sensitivity Analysis Results

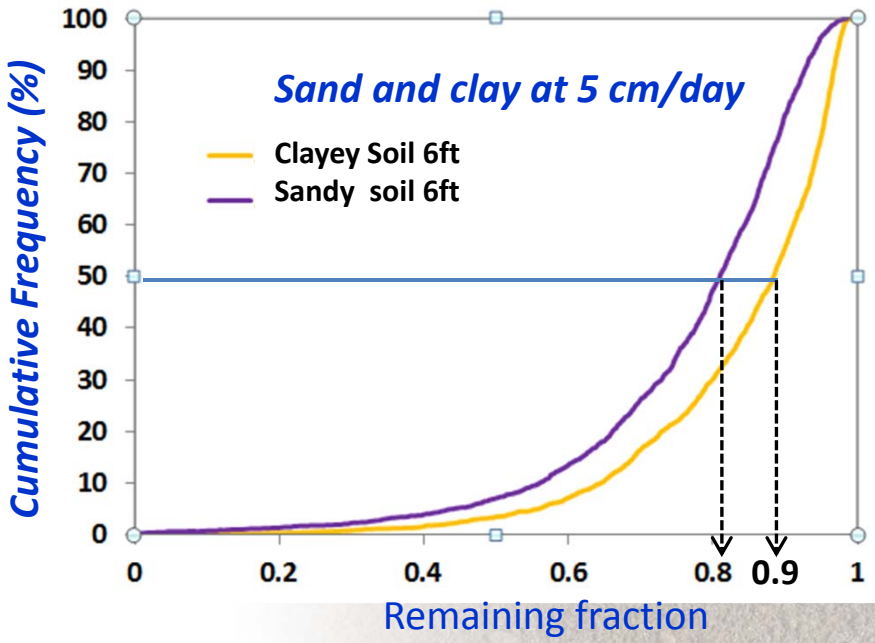


van Genuchten n
Soil Temperature
Porosity
Denitrification rate
Van Genuchten alpha
Hydraulic loading rate
Nitrification soil moisture function
Effluent concentration
Nitrirification rate
Gardner's alpha parameter
Threshold soil moisture
Ksat
Denitrification exponent
Residual moisture content
Sorption
Temperature factor

STUMOD-FL Uncertainty Analysis Results

- Run STUMOD for a range of inputs to generate a range of output and determine the probability of removing a percentage of the effluent concentration from a CFD





Soil	HLR	probability	Removed	DTW
Clay soil	2 cm/day	50%	50%	6ft
Sandy soil	2 cm/day	50%	40%	6 ft
Clay soil	5 cm/day	50%	20%	6ft
Sandy soil	5 cm/day	50%	10%	6 ft

Summary

- STUMOD-FL is simple-to-use tool that can provide cost-effective evaluations on nitrogen removal strategies in STUs
- The model is relatively simple to use but detailed enough to account for important fate and transport processes such as advection, sorption, nitrification and denitrification
- The input parameters for nitrogen transport and transformation were derived based on a thorough literature review and statistical analysis of the available data
- The model accounts for the effect of degree of saturation on nitrification and denitrification rates. It also accounts for the effect of temperature & concentration.

Summary

- Both the measured data and STUMOD-FL output show a relatively higher removal in clayey soils compared to sandy soils.
- For sandy soils STUMOD-FL predicted ammonium conversion to nitrate within the first foot below the trench infiltrative consistent with field data.
- STUMOD-FL results showed that ammonium persisted relatively deeper below the trench in finer grained soils and high loading rates due to low nitrification rates caused by high predicted water content
- Interactions between several factors including loading rate, distance to water table, effluent quality (STE vs nitrified effluent), capillary rise effects, soil texture, plant nutrient uptake can be evaluated in a relatively short time as demonstrated by the nomographs

Implications

- **Scenario Evaluation**
  - Practitioners can perform rapid evaluations of scenarios that may influence nitrogen treatment such as the influence of nitrogen concentrations in septic tank effluent, pretreatment, soil properties, loading rates, and temperature
- **System Design**
  - Hydraulic loading rates, effluent quality, trench size, or loading area can be evaluated in light of nitrogen-treatment performance goals
- **Rigorous Assessment**
  - STUMOD-FL can be calibrated to actual site and subsequently used to optimize operation of OWTS or to design new OWTS in a similar soil setting

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Future plans

- Linking STUMOD to the saturated zone module – in progress
- Additional wastewater contaminants DOC, CEC and pathogens
- Site specific parameterization- e.g. STUMOD-FL
- Integrate parameter Sensitivity and uncertainty modules
- Automate nomograph generation from multiple representative scenarios to create an understanding of STU performance under various site and operational conditions

Final report will made available through FDOH

Acknowledgment

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QUESTIONS?

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