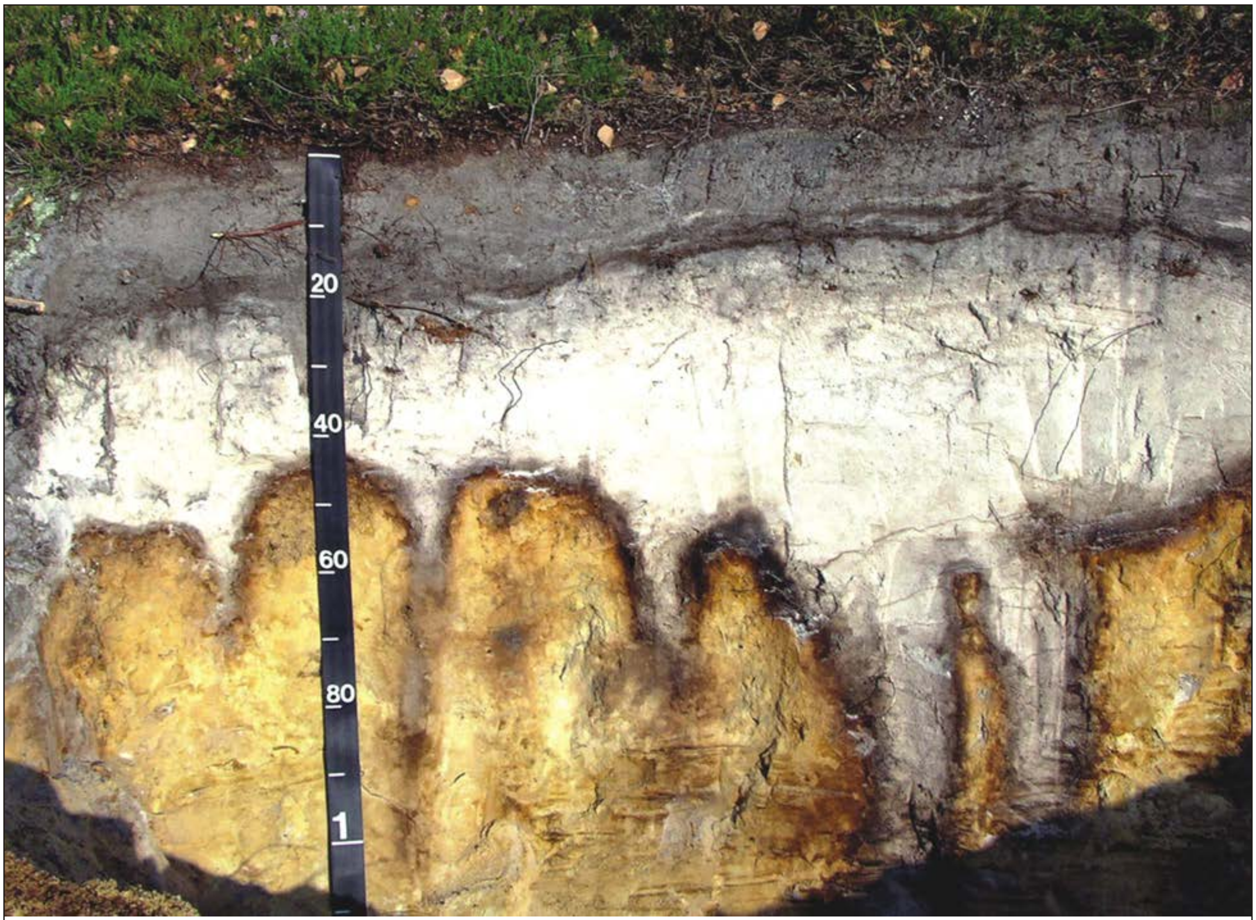

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Cumulative Saturation of Low Chroma Soil Colors and Shallower Depths: Implications for On-site Wastewater System Design

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ABSTRACT

On-site wastewater treatment systems require aerated soil beneath the disposal field trenches for adequate effluent treatment and protection of groundwater quality. Low chroma colors are used as a reference point for the depth to the seasonal high water table. The study objective was to assess the frequency of water table saturation and cumulative saturation of soil at depths typical for disposal field trenches (30 to 60 cm shallower than low chroma soil colors). Groundwater monitoring wells were installed at 11 sites with 4 different soil series in mainland Carteret County, North Carolina. Soil profile descriptions and the depth to low chroma colors were recorded during the well installation process. Automated water level loggers were placed in the wells and programmed to record water table depths every 0.5 h. The depths to low chroma soil colors and 30-60 cm shallower were compared to groundwater levels for a one year period (December 2006 to January 2008) to determine the frequency and cumulative saturation of soil at these depths. Data indicated that the soil cumulative saturation and frequency of water table inundation was greater at depths 30 cm above chroma 2 colors relative to 45 and 60 cm above chroma 2 colors. Increasing the vertical separation distance requirements from on-site wastewater system disposal field trenches to low chroma colors by 15 cm could reduce the frequency of saturation and the cumulative groundwater table saturation of disposal field trenches by 25 and 67%, respectively. Water quality could be improved by increasing separation distance requirements by 15 cm or more from the current standards.

Key words: Groundwater, soil colors, on-site wastewater, coastal, cumulative saturation

INTRODUCTION

Domestic wastewater effluent contains many constituents such as nutrients, bacteria, Biochemical Oxygen Demand (BOD), viruses and heavy metals which can become public and environmental health hazards if not properly treated and dispersed (Laghari *et al*., 2004a, b; Mensah *et al*., 2008; Al-Jlil, 2009; Daghrah and Al-Sa`ed, 2009; Momba *et al*., 2009; Al-Jlil and Alharbi, 2010). In the United States of America, typical wastewater treatment systems include centralized sewage treatment plants that collect sewage from surrounding towns and individual On-site Wastewater Systems (OWS). The centralized sewer plants either discharge treated wastewater to surface waters (point sources) and/or spray the effluent on agricultural fields or forests (non-point sources). OWS discharge effluent to the subsurface (non-point source) of the home or business it serves. Research has shown that centralized sewage treatment plants that discharge effluent directly to surface waters can impact downstream water quality (Daghrah and Al-Sa`ed, 2009; Momba *et al.*, 2009). Agricultural fields that are irrigated with high strength wastewater may build up heavy metals in the soil or may contain elevated concentrations of wastewater pollutants in shallow groundwater beneath the fields (Hussain Chattha *et al.*, 2005; Laghari *et al.*, 2004a). The nutrient concentration of the irrigation wastewater can lead to increased yields for some crops such as sorghum (Galavi *et al.*, 2009) but the heavy metals in wastewater may lead to decreased yields for other crops such as lettuce (Mensah *et al.*, 2008). OWS may also contaminate shallow groundwater with nutrients and pathogens (Carlile *et al.*, 1981; Humphrey *et al.*, 2010, 2011). Therefore, environmental and public health risks are associated with each of the most common wastewater treatment methods. More research is needed to understand the various processes associated with wastewater treatment and to develop regulatory policies that reduce risks of water and soil contamination from wastewater treatment systems.

Surface water pollution problems such as eutrophication and closure of shellfisheries due to nutrient loading and bacterial contamination have been a problem in coastal North Carolina (Fear *et al.*, 2004; Cahoon *et al.*, 2006). With approximately 60% of coastal North Carolina residences utilizing OWS for wastewater treatment and dispersal (North Carolina National Estuarine Research Reserve, 2003), it is likely that OWS are a contributing source of coastal water quality degradation. Reducing the impacts from developments that will use OWS is an important step in curbing the trend of increasing incidences of water quality impairment.

OWS typically have four components (Fig. 1) including a wastewater source, tank, drainfield trenches and soil (Lindbo *et al.*, 2005). The tank provides primary treatment and settling of solids and the drainfield trenches store the wastewater until it infiltrates the soil. Aerated soil beneath the drainfield trenches provides an environment for the physical, chemical and biological treatment of wastewater (Hoover *et al.*, 1996). Thus, vertical separation distance regulations (from trench to water table) aim to ensure aerated conditions beneath septic drainfield trenches to prevent OWS effluent (and pollutants) from discharging directly into the groundwater, causing contamination.

Current North Carolina regulations for the design and construction of OWS require that drainfield trenches are installed in aerated soils with at least 45 cm separation to the seasonal high water table for systems in sandy soils (group 1) and at least 30 cm separation for systems in loam to clay textures (group II-IV) (15A NCAC 18A. 1955 m). The seasonal high water table is assumed to be the depth at which chroma 2 or less (Munsell's Color Chart) soil colors occupy 2% or more of

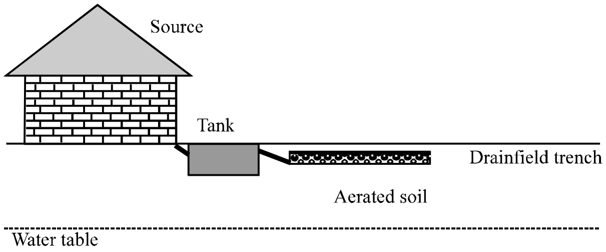

Fig. 1: On-site wastewater system components including the source (a house), tank, drainfield trench and aerated soil above the water table

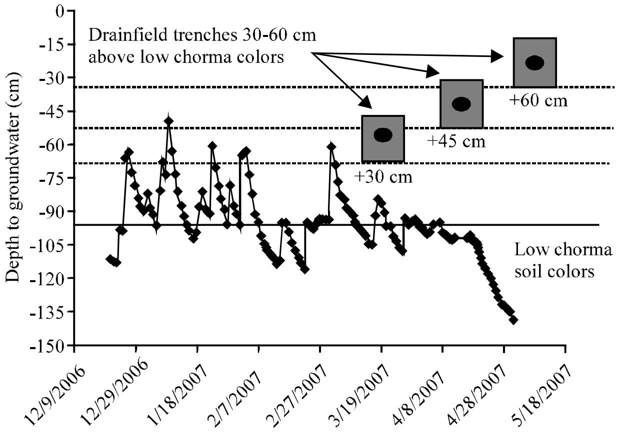

Fig. 2: Hydrograph showing the depth to low chroma soil colors (red line) relative to the water table (blue line) and potential drainfield trenches installed 30, 45 and 60 cm above the low chroma colors (green lines)

the soil (15A NCAC 18A .1942b). In soils formed from iron rich parent materials, low chroma soil mottling can be produced when soils are saturated, anaerobic, there is an available carbon source and the temperature is above 5°C (Vepraskas and Faulkner, 2000). Therefore, low chroma mottling is often used as a reference point for the seasonal high water table in many soils (Hassannezhad *et al.*, 2008; Humphrey and O`Driscoll, 2011). Research has shown that it takes on average between 15 and 21 days of continuous saturation to produce anaerobic conditions and low chroma soil colors (mottles or matrix) for many coastal plain settings (He, 2000; He *et al.*, 2003; Severson *et al.*, 2008; Humphrey and O`Driscoll, 2011). These studies reported the longest continuous saturations of soils at the depths low chroma colors were found (Severson *et al.*, 2008; Humphrey and O`Driscoll, 2011) and/or modeled the potential frequency and cumulative saturation of low chroma soil color depths by the water table (He *et al.*, 2003). However, less information is available concerning the frequency and cumulative saturation of soils 30-60 cm above the low chroma colors, representing the potential installation depths of OWS drainfield trenches for many states (Fig. 2) including: Florida, Maryland, Virginia and North Carolina (Stall, 2008).

The study objective was to assess the frequency of water table saturation and Cumulative Saturation (CS) of soil depths 30 to 60 cm shallower than low chroma soil colors (water table indicators). OWS installed in soils that have water tables that rise to the depths of OWS trenches may discharge wastewater pollutants directly into groundwater and contribute to water quality degradation (Humphrey *et al.*, 2011). Regulations that reduce or prevent direct discharge of wastewater pollutants to groundwater may help reduce the incidences of water quality impairment (Humphrey *et al.*, 2011). The frequency of saturation and CS of soils at depths 30, 45 and 60 cm above low chroma colors were compared to determine what the potential benefits would be if the current separation distance requirements from OSW trench to water table were increased by 15 cm or more.

MATERIALS AND METHODS

Study area: The study period began in December 2006 and ended in January 2008. Eleven sites with four different soil series were evaluated in mainland Carteret County, North Carolina, United

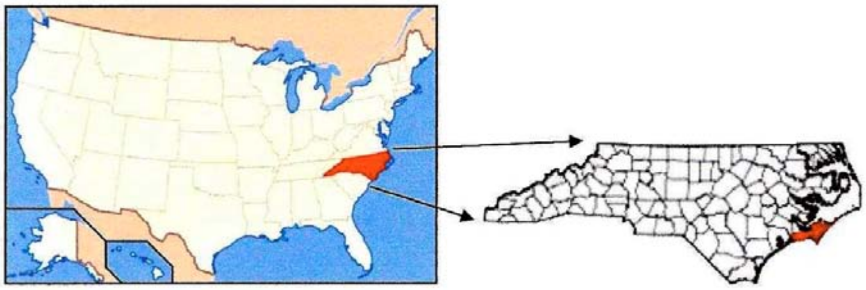

Fig. 3: Research sites were located in Carteret County, North Carolina, United States of America

States of America (Fig. 3). Detailed soil profile descriptions were performed at each site, using a soil auger, Munsell color book, measuring rod and the texture by feel method (Brady and Weil, 2004). Depth to low chroma colors was recorded during the profile descriptions. Soil samples near the low chroma soil color depths were collected and particle size distribution analysis was performed in the laboratory using the hydrometer method (Day, 1979). Soil hydraulic conductivity of the saturated zone was determined using slug tests with the Bouwer and Rice (1976). These sites were described in a previous study that focused on the accuracy of low chroma colors as predictors of the seasonal high water table depth (Humphrey and O`Driscoll, 2011).

Groundwater monitoring: Hand augers were used to install 10 cm diameter, PVC monitoring wells at each site. Monthly groundwater depths were determined manually using the Solinst Model 107 Temperature Level and Conductivity (TLC) meter (Solinst Canada Ltd., 2007) and automated water level loggers (Onset Computer Corporation, 2007) were in the wells and programmed to recorded one-half hourly water levels in groundwater wells during the study period. Atmospheric pressure loggers and correction software were used with the groundwater level loggers to correct for atmospheric pressure changes and determine true water table depths. Hourly precipitation data from nearby weather stations were used for the sites in this study (North Carolina Climate Office, 2008).

Statistical analyses: Spreadsheets and hydrographs (groundwater level over time) were produced for each site from the half hour water level data using Hoboware Pro Software (Onset Computer Corporation, 2007) and Microsoft Office Excel (Microsoft Corporation, 2007). The water level data was compared to the soil profile descriptions and low chroma color depths (Fig. 2). Using the spreadsheets, hydrographs and profile descriptions, the total number of times the water table rose 30, 45 and 60 cm above the low chroma colors was manually recorded as frequency of saturation for each soil at these depths. The cumulative duration of time the water table was 30, 45 and 60 cm above low chroma colors was recorded as Cumulative Saturation (CS). The spreadsheets were used to manually calculate the total number of hours of water table monitoring, the cumulative duration of saturation at various depths and the % Cumulative Saturation (CS). Cumulative saturation at 30, 45 and 60 cm above the low chroma colors represents the duration of time wastewater would discharge directly into the groundwater (no vertical separation) if OWS were installed 30-60 cm above chroma 2 colors, as required by many states (Fig. 2). The frequency of saturation and CS of soil 30-60 cm above low chroma colors were compared to determine the potential benefits of increasing the North Carolina separation distance requirements by 15 cm from 30 to 45 cm for soils groups II-IV and from 45 to 60 cm for soil group I.

RESULTS AND DISCUSSION

Soil and site data: Three sites contained group I soils (sand/loamy sand) including 2 in the Baymeade series (loamy, semiactive, thermic arenic hapludults) and 1 in the Mandarin Series (sandy, siliceous, thermic, oxyaquic alorthod). Four sites contained the group II Goldsboro series (fine-loamy, siliceous, subactive, thermic aquic paleudults) and four sites contained the group III Alatavista series (fine-loamy, mixed, semiactive, thermic aquic hapludults). The Baymeade and Mandarin soil series both contained more than 90% sand by weight, the Goldsboro series soils had on average 77% sand and the Altavista series contained an average of 67% sand (Table 1). The Group I soils (Mandarin and Baymeade), had the highest average hydraulic conductivities (0.98 and 1.74 m day^{-1}, respectively), followed by the group II (0.32 m day^{-1}) and group III soils (0.19 m day^{-1}) (Table 1).

Rainfall for the study period was within 7% of the long term annual average as reported at Morehead City, North Carolina (Humphrey and O`Driscoll, 2011). The water table was monitored for an average of more than 8500 h (355 days) for each soil series (Table 2), although there was some variability due to data logger transfer errors.

Saturation frequency and cumulative saturation: The mean depth (cm) to chroma 2 colors for the Mandarin, Baymeade, Goldsboro and Altavista soils were 86, 140, 57 and 86 cm, respectively (Table 1). The water table rose above the chroma 2 depth more frequently for the Baymeade series (33 times on average), than for the Altavista (31), Mandarin (29) or the Goldsboro series (14) (Table 2).The average Cumulative Saturation (CS) of the depth to chroma 2 colors (expressed as total hours the water table was elevated above the depth to chroma 2 colors and %

Table 1: Site, soil and water table data including United State Department of Agriculture soil series, North Carolina Department of Environment and Natural Resources soil group, particle size analysis, saturated hydraulic conductivity, depth to low chroma colors and the total range (high to low) of water table fluctuation below the soil surface

Site	*USDA soil series	NC DENR soil group	Sand/silt/clay %	**Ks (m day^{-1})	Chroma 2 depth (cm)	Water table depth (cm)
GI-A	Mandarin	Group I	90.3/4.6/5.1	0.98	86	61-134
GI-B	Baymeade	Group I	94.6/2/3.4	2.47	140	87-165
GI-C	Baymeade	Group I	90.7/3.9/5.3	1.01	140	91-182
Mean			92.7/3/4.3	1.74	140	89-178
GII-A	Goldsboro	Group II	74.2/9.6/16.2	0.18	58	10-210
GII-B	Goldsboro	Group II	80.7/10.1/9.2	0.52	56	1-154
GII-C	Goldsboro	Group II	79/7.5/13.4	0.49	56	39-180
GII-D	Goldsboro	Group II	75.4/11.1/13.5	0.09	58	9-173
Mean			77.3/9.6/13.1	0.32	57	15-179
GIII-A	Altavista	Group III	66.8/12.3/20.9	0.15	91	2-149
GIII-B	Altavista	Group III	71.2/5.2/23.6	0.18	79	0-120
GIII-C	Altavista	Group III	67/8.2/24.7	0.09	84	2-135
GIII-D	Altavista	Group III	64.9/9.7/25.4	0.34	89	9-160
Mean			67.5/8.9/23.7	0.19	86	3-141

*United States Department of Agriculture (USDA) **Saturated hydraulic conductivity (Ks)

Table 2: Frequency of soil saturation and cumulative saturation of soil at low chroma soil color depths and 30, 45 and 60 cm above the depth to low chroma colors

			Saturation frequency				Cumulative saturation (h/%total time)			
Site	USDA soil series	Monitoring duration (h)	Chroma 2	Chroma 2 + 30 cm	Chroma 2 + 45 cm	Chroma 2 + 60 cm	Chroma 2	Chroma 2 + 30 cm	Chroma 2 + 45 cm	Chroma 2 + 60 cm
GI-A	Mandarin	8889	29	0	0	0	587/6.6	0	0	0
GI-B	Baymeade	8933	28	14	3	0	4776/53.5	704/7.9	58/0.6	0
GI-C	Baymeade	8933	37	11	1	0	3040/34	352/3.9	32/0.4	0
Avg		8933	33	13	2	0	3908/43.7	528/5.9	45/0.5	0
GII-A	Goldsboro	9070	9	2	2	0	146/1.6	28/0.3	3/0.0	0
GII-B	Goldsboro	9066	27	10	7	0	2457/27.1	354/3.9	93/1.0	0
GII-C	Goldsboro	9051	4	0	0	0	58/0.6	0	0	0
GII-D	Goldsboro	9023	17	3	1	0	428/4.7	6/0.1	2/0	0
Avg		9052	14	4	3	0	772/8.5	97/1.1	24/.3	0
GIII-A	Altavista	9024	38	15	11	9	3876/43	1101/12.2	428/4.7	188/2.1
GIII-B	Altavista	9058	31	15	11	6	3804/42	633/7	223/2.5	37/0.4
GIII-C	Altavista	8062	22	13	4	3	2728/33.9	496/6.2	125/1.6	34/0.4
GIII-D	Altavista	8113	32	13	9	1	2070/25.5	341/4.2	66/0.8	3/0
Avg		8564	31	14	9	5	3120/36.4	643/7.5	211/2.5	66/0.8

of total time monitored) was highest for the Baymeade series (3908 hours and 43.7%) and the Altavista series (3120 h and 36.4%). The Goldsboro series (772 h and 8.5%) and the Mandarin series (587 h and 6.6%) had relatively lower average CS (Table 2).

The average CS of soil 30 cm above the depth to chroma 2 colors was longest for the Altavista series (643 h and 7.5%) followed by the Baymeade series (528 h and 5.9%) and the Goldsboro series (97 h and 1.1%) (Table 2). The water table for the Manadarin series did not rise 30 cm above the depth to chroma 2 colors. The frequency of saturation 30 cm above chroma 2 depths was highest for the Alatavista (14 times) and Baymeade (13) series, followed by the Goldsboro (4) and Mandarin (0) (Table 2).

The average CS of soil 45 cm above chroma 2 colors depths was longest for the Altavista series (211 h and 2.5%) followed by the Baymeade (45 h and 0.5%) and Goldsboro (24 h and 0.3%) series (Table 2). The Frequency of saturation 45 cm above chroma 2 depths was highest for the Altavista series (9 times) followed by the Goldsboro series (3) and Baymeade series (2) (Table 2). The water table rose 60 cm above the depth to chroma 2 colors only for the Altavista series (average frequency of saturation was 5 times and the average cumulative saturation was 66 h or 0.81%) (Table 2).

After log transformation of the CS data, strong inverse relationships ($R^2 = 0.77$ to 0.98) were found between vertical separation distances from chroma 2 colors and CS durations (Fig. 4, 5). The inverse relationships between separation distances from chroma 2 colors and log of CS were highest for the soils with the most clay and lowest hydraulic conductivities (Altavista and Goldsboro) in comparison to the more permeable, sandy series (Mandarin and Baymeade) (Fig. 4, 5, Table 1). For each series, increasing separation distance requirements from chroma 2 colors could reduce CS, trench ponding durations and discharge of wastewater directly to groundwater.

Water table dynamics: The Mandarin and Baymeade soils had the smallest mean water table ranges (73 and 89 cm, respectively) in relation to 165 cm for the Goldsboro sites and 138 cm

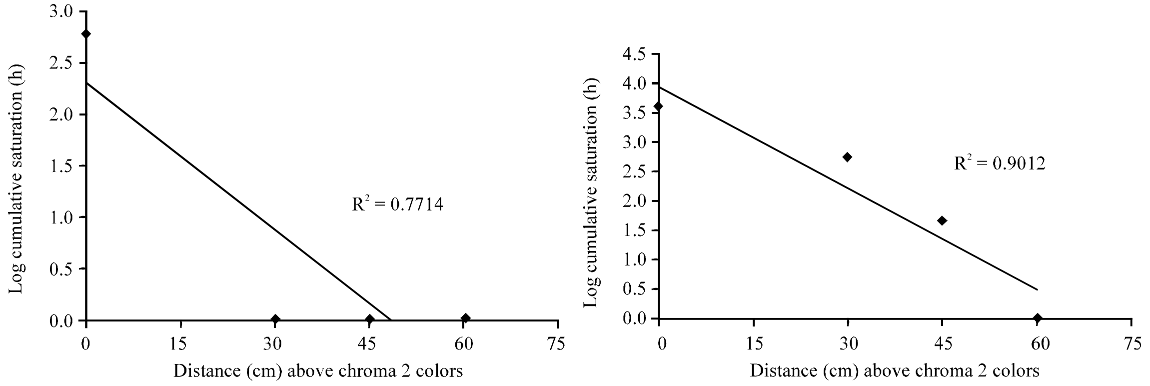

Fig. 4 (a-b): Log of the cumulative saturation duration (h) at the chroma 2 depth and 30, 45 and 60 cm above the chroma 2 depths. (a) The Mandarin series and (b) Baymeade series

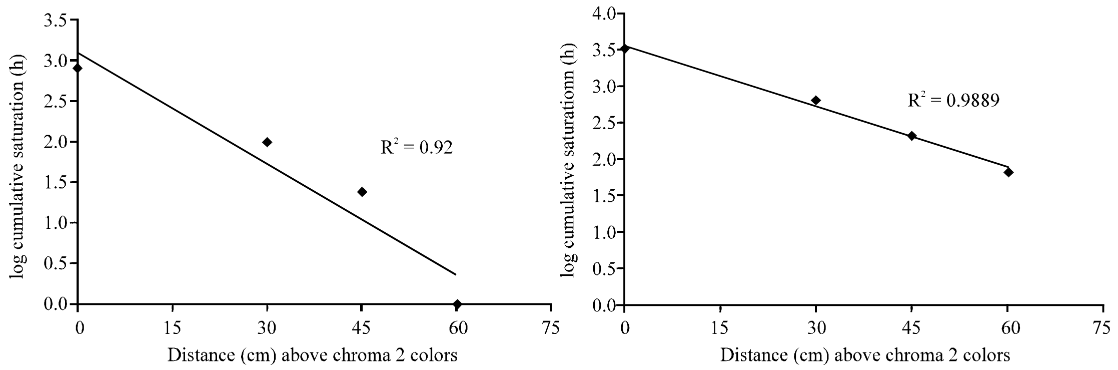

Fig. 5: Log of the cumulative saturation duration (h) at the chroma 2 depth and 30, 45 and 60 cm above the chroma 2 depths. Top is the Goldsboro series and bottom is the Altavista series

Altavista sites (Table 2). The relatively high water table ranges for the Altavista and Goldsboro series may be linked to the hydraulic properties of fine and coarse loamy soils in relation to sandy soils. Darcy's law ($Q = KA*dh/dl$) relates groundwater discharge (Q) directly to the hydraulic conductivity (K), the affected area (A) and the hydraulic gradient (dh/dl) (Heath, 1998). The Altavista and Goldsboro soils in this study had the smallest mean hydraulic conductivities (Ks of 0.19 and 0.32 m day^{-1}, respectively) in comparison to the Mandarin and Baymeade soils (0.98 and 1.74 m day^{-1}, respectively) (Table 1), indicating that to move similar volumes of water away from the soils, larger hydraulic gradients would be necessary. Therefore, water tables must rise higher in loamy soils and/or remain higher for longer durations to increase the hydraulic gradient in order to transmit similar volumes of water as a more course textured, permeable sand. The water table rose was within 11 cm of the surface for all four Altavista sites and three of four Goldsboro sites (Table 2). Furthermore the high water table nearly reached the surface (within 2 cm) in three of the four Altavista sites and 1 on the Goldsboro sites in group III soils (Table 2).

DISCUSSION

In general, the soil series with the deepest depths to low chroma colors had longer durations of CS at those depths. For example, the Baymeade series had the longest average CS of low chroma colors and the deepest average depth to low chroma colors (43.7% and 140 cm) followed by the Altavista series (36.4% and 86 cm) (Table 1 and 2). These findings are in agreement with prior research that has indicated soils with relatively deep seasonal high water tables had longer CS at the low chroma color depths because the groundwater was further from organic carbon sources typically found in surface horizons of soil (Genthner *et al.*, 1998; Vepreskas and Wilding, 1983; Humphrey and O`Driscoll, 2011; He *et al.*, 2003). While the Goldsboro series evaluated in this study had the shallowest average depth to low chroma colors (56 cm) but similar CS (8.5%) as the Mandarin series (6.6%), the Mandarin had a deeper depth to low chroma colors (86 cm) (Table 1, 2). However, the Mandarin series had an organic rich subsurface horizon (Bh) at the water table depth which may have influenced the duration of saturation necessary to create low chroma colors. Soil layers with high organic carbon contents typically form redoximorphic features sooner than horizons with less organic carbon (He *et al.*, 2003) but research has also shown that low chroma colors indicate different saturation durations for different soils (Severson *et al.*, 2008).

Increasing the North Carolina separation distance requirements from OWS to low chroma colors by 15 to 30 cm could help reduce the frequency and cumulative saturation (and duration of trench ponding), especially for systems in group II and III soils like the Goldsboro and Altavista series, that currently only require a 30 cm vertical separation distance. There was an average 67% decrease in cumulative saturation duration at a depth 45 cm above chroma 2 colors (211 h) in comparison to 30 cm above chroma 2 colors (643 h) for the Altavista series (Table 2). A 45 cm separation distance requirement for the group II Goldsboro soils would have reduced cumulative saturation duration by an average of 75% in comparison to a 30 cm separation from chroma 2 colors and increasing the separation distance requirement for group I soils to 60 cm would have eliminated saturation for the Baymeade series (Table 2). Many states already require a 60 cm separation from OWS trenches to the seasonal high water table for all soil groups (Stall, 2008).

CONCLUSIONS

Reducing or eliminating trench ponding frequency and duration should improve shallow groundwater quality by reducing the time that septic tank effluent directly discharges into the groundwater without being filtered by aerated soil. Because the soil cumulative saturation and frequency of inundation is greater at depths 30 cm above chroma 2 colors relative to 45 and 60 cm above chroma 2 colors, water quality could be improved by increasing separation distance requirements by 15 cm or more from the current standard.

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