



Hydraulic management of a soil moisture controlled SDI wastewater dispersal system in an Alabama Black Belt soil

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ABSTRACT

Rural areas represent approximately 95% of the 14000 km² Alabama Black Belt, an area of widespread Vertisols dominated by clayey, smectitic, shrink–swell soils. These soils are unsuitable for conventional onsite wastewater treatment systems (OWTS) which are nevertheless widely used in this region. In order to provide an alternative wastewater dosing system, an experimental field moisture controlled subsurface drip irrigation (SDI) system was designed and installed as a field trial. The experimental system that integrates a seasonal cropping system was evaluated for two years on a 500 m² Houston clay site in west central Alabama from August 2006 to June 2008. The SDI system was designed to start hydraulic dosing only when field moisture was below field capacity. Hydraulic dosing rates fluctuated as expected with higher dosing rates during warm seasons with near zero or zero dosing rates during cold seasons. Lower hydraulic dosing in winter creates the need for at least a two month waste storage structure which is an insurmountable challenge for rural homeowners. An estimated 30% of dosed water percolated below 45 cm depth during the first summer which included a 30 year historic drought. This massive volume of percolation was presumably the result of preferential flow stimulated by dry weather clay soil cracking. Although water percolation is necessary for OWTS, this massive water percolation loss indicated that this experimental system is not able to effectively control soil moisture within its monitoring zone as designed. Overall findings of this study indicated that soil moisture controlled SDI wastewater dosing is not suitable as a standalone system in these Vertisols. However, the experimental soil moisture control system functioned as designed, demonstrating that soil moisture controlled SDI wastewater dosing may find application as a supplement to other wastewater disposal methods that can function during cold seasons.

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1. Introduction

The Alabama Black Belt is a 14,000 km² area of widespread clayey soils that make up part of the larger Blackland Prairie soil area in central Alabama and eastern Mississippi. This area influences 14 Alabama counties and a total population of 40,000 (US Census, 2000). Conventional onsite wastewater treatment systems (OWTS), are the most common decentralized wastewater dispersal method in this region because of the relatively low cost of installation, operation, and maintenance (Alabama Department of Public Health (ADPH), 2006; Kruzic 1997). The environmental challenge for conventional OWTS comes from the almost complete

reliance on soil properties for proper waste treatment (Oron, 1996). Soils having too high or too low a percolation rate are generally not suitable for conventional onsite septic systems (US EPA, 2002). In the shrink–swell clay soils that dominate the Black Belt region of Alabama, conventional OWTS can pose a genuine environmental and health threat if not designed and operated properly (McCoy et al., 2004).

According to the Geographical Survey of Alabama (Geographical Survey of Alabama, 1993), Alabama Black Belt soils are underlain at a general depth of approximately 6 m by a relatively impermeable layer of fossiliferous clayey chalk and chalky marl to a depth of approximately 122 m. Below that are the Eutaw and Tuscaloosa aquifers, the only significant groundwater sources in the Alabama Black Belt region. When top soil layers become saturated, the low permeability of the underlying chalk limits deep percolation to underground aquifers. Thus, surface ponding and runoff from

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conventional OWTS drain fields is the more common environmental and health concern from malfunctioning OWTS in the Alabama Black Belt.

A series of GIS analyses conducted by He et al. (in press) evaluated environmental and health risk to ground and surface water from conventional onsite septic systems in the Alabama Black Belt soil area. In 2000, more than 97% of the rural census block groups in this region had onsite systems with an average age of over 20 years. This data confirms the widespread use and aging of conventional onsite septic systems in the area. Subsequent risk analysis and ranking revealed that in absence of centralized municipal wastewater collection, ground and surface water resources immediately surrounding city fringes are at higher risk of being impaired by high OWTS densities.

In order to provide an alternative wastewater dispersal system for the Black Belt area, a pilot scale SDI wastewater dispersal system, integrated with a cropping system rotation over the drain field, was designed. The system was controlled by volumetric soil moisture content to allow dosing of wastewater only when the drain field was at a moisture content below field capacity, while field capacity is interpreted by Soil Science Society of America (SSSA, 2002) as the soil moisture content when water drainage is negligible. The whole system design idea was to integrate the merits of: 1) a more uniform distribution of wastewater throughout the drain field by SDI that might reduce the risk of ground and surface water contamination (Ruskin, 1992; Phene and Ruskin, 1995; Jnad et al., 2001); 2) a drain field soil moisture content based hydraulic dosing timing which might limit water and nutrient loss through deep percolation or surface runoffs (Phene and Howell, 1984; Meron et al., 1996; Muñoz Carpena et al., 2003; Dukes and Scholberg, 2005; Blonquist et al., 2006; Duan and Fedler, 2009; Duan et al., 2010; McCready and Dukes, 2011); 3) a proper managed cropping systems that can provide an increase field evapotranspiration (ET) and a reduce drainage loss of the dosed water (Colomb et al., 2007; Askegaard and Eriksen, 2008; Wang et al., 2008).

The experimental system was field tested with respect to hydraulic management over a two year period. The objective of the study was to evaluate the application of soil moisture controlled hydraulic dosing at a field site in the Alabama Black Belt region. Field nutrient movement was not studied at this phase of the study. Although the experimental system may not be cost effective for all rural home owners in the Alabama Black Belt, system hydraulic capabilities reported in this manuscript provide important information regarding system feasibility.

2. Materials and methods

2.1. Site selection and characterization

The site selected for the field study is in Marion Junction, Dallas County, Alabama, at the Alabama Black Belt Research and Extension Center (ABBREC), approximately 10 miles west of Selma, Alabama. A Houston clay soil site with 1% slope was selected. Five soil horizons were identified to a depth of 1.52 m (data not shown). Dark clay was prominent at the surface to approximately 42 cm depth, with redoximorphic features at 88 cm indicating significant periods of saturated or anaerobic conditions during most years, typical in these soils. Particle size distribution indicates increasing clay content with depth, up to 71% at 152 cm.

2.2. Field experiment design and operation

The SDI system consists of 30 drip tubes rated for wastewater application, WFPC16–2–24, 16 mm diameter (Geoflow, CA), 27 m long with 1.9 LPH emitters every 0.61 m along the row and 0.61 m

lateral spacing installed approximately 20–25 cm deep (Fig. 1). The design flow rate of the experimental system was 1022 L per day, equivalent to the daily wastewater flow of a 3 person home in a decentralized subdivision system (Alabama Department of Public Health, June 14, 2005, personal communication). The SDI system was supplied by well water (Total Organic Carbon, (TOC) < 1.0 mg/L, Total Kjeldahl Nitrogen, TKN and $\text{NO}_3\text{-N}$ were not detectable, pH varied between 6.1 and 6.5) stored in a 7600 L above ground plastic septic tank (Fralo, NY). A 0.37 kW submersible pump installed inside the plastic septic tank served as the SDI dosing pump controlled by a GEO1 SDI controller (GEO1, Geoflow, CA). The two soil moisture sensors were buried at two depths (20 cm and 45 cm) at one location in the middle of the SDI site to provide monitoring of the drain field moisture content for subsequent control of the SDI dosing pump. A GP1 data logger/controller (GP1, Delta T, UK) was programmed to record data from the following instruments every 15 min; two soil moisture sensors, one soil temperature sensor buried at 10 cm with the soil moisture sensors, one tipping bucket rain gauge, and one inline vortex flow meter on the main water line from the SDI dosing pump. Once the soil moisture system was operational, dosing was initiated for a 5 min period every 55 min.

Based on the NRCS Web Soil Survey (NRCS, 2008), the field capacity (1/3 bar) at the 45 cm of the experimental site is approximately $0.42 \text{ m}^3 \text{ m}^{-3}$, which was subsequently field verified at between 0.37 and $0.44 \text{ m}^3 \text{ m}^{-3}$. Soil moisture ($\text{m}^3 \text{ m}^{-3}$) thresholds used for SDI control were set at 0.40 (on) and 0.45 (off) with the intent to avoid hydraulic overloading of the experimental site beyond field capacity. As long as there was sufficient water in the dosing tank, system hydraulic dosing occurred on the pre programmed 55 min schedule when either of the two soil moisture sensors read $< 0.40 \text{ m}^3 \text{ m}^{-3}$. System hydraulic dosing was not enabled when either of the two soil moisture sensors read above $0.45 \text{ m}^3 \text{ m}^{-3}$ or when there was insufficient water in the SDI dosing tank.

The experiment was conducted for approximately two years, from August 2006 to June 2007 (year one) and from June 2007 to June 2008 (year two). Crops grown over the field site during the study period included sorghum sudangrass (*Sorghum bicolor* (L.)) from June–November and a mixture of winter wheat (*Triticum aestivum*) and rye (*Secale cereale*) from November to the following June. Sorghum sudangrass was planted with a grain drill at 33.6 kg seed per hectare on 18 cm row spacing. Winter wheat was planted with a grain drill on 18 cm row spacing at 67.2 kg per hectare; and ryegrass was broadcast at 22.4 kg per hectare.

2.3. Soil moisture control and testing

The GEO 1 wastewater SDI controller was wired to the GP1 data logger/controller to provide both real time soil moisture control and data logging capabilities for the experimental system. The GP1 data logger/controller controlled an intermediate relay based on the readings from two capacitance type volumetric soil moisture sensors (ML2 ThetaProbe, Delta T, UK). The two sensors have typical errors of $\pm 0.01 \text{ m}^3 \text{ m}^{-3}$ after validation with intact soil cores. The intermediate relay was wired in series to a low reservoir water level switch used by the GEO1 to actuate the SDI dosing pump. With this electrical design, the SDI dosing sequence is activated only when both 1) the intermediate relay is closed, indicating that soil moisture readings are within the designated range, and 2) the circuit for low reservoir water level switch is closed, indicating an adequate water level for pumping.

2.4. System hydraulic performance evaluation

A monthly water balance was developed for the drain field from September 2006 to June 2007 to evaluate the impact of automatic

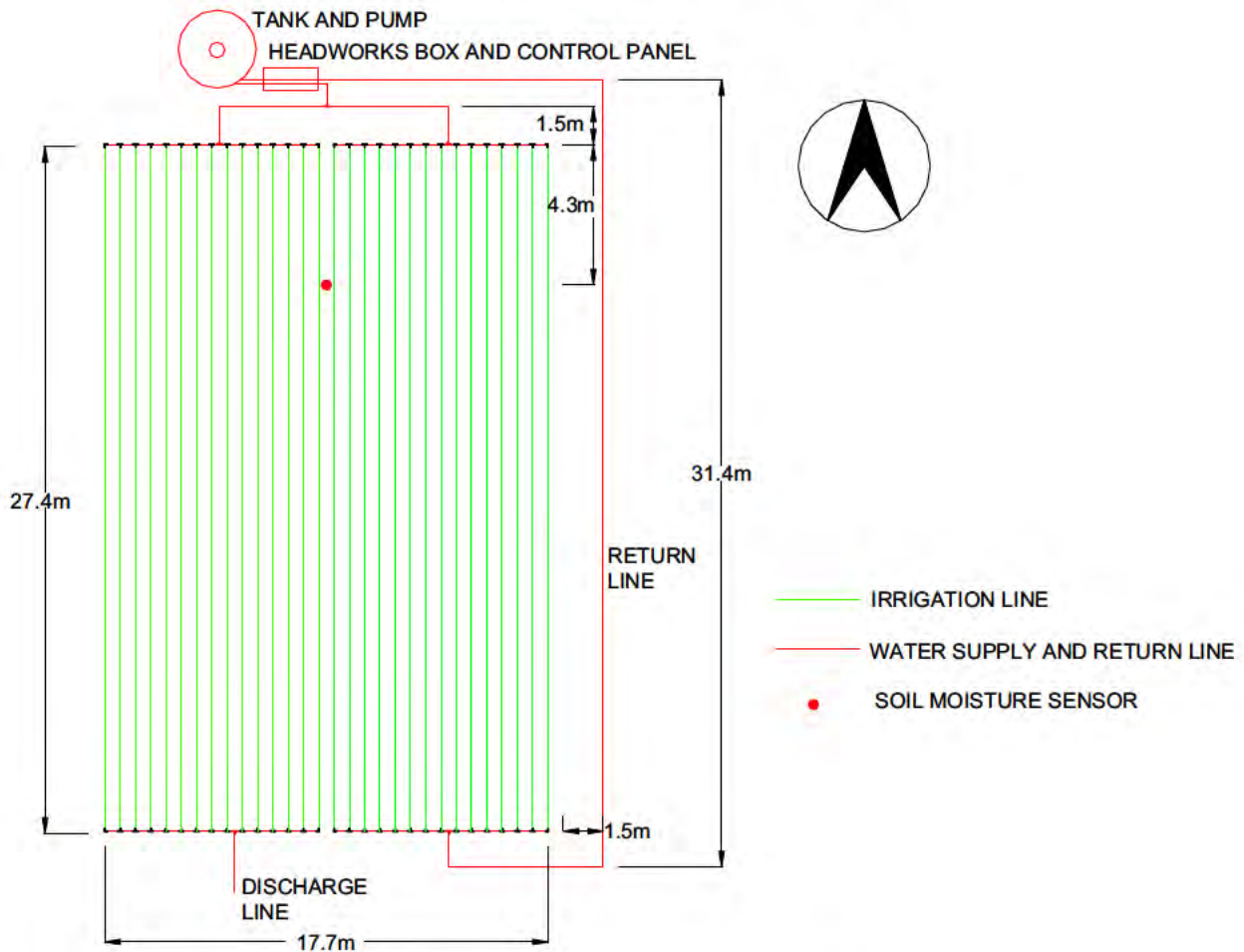


Fig. 1. Design layout of the experimental wastewater SDI system.

system control on soil water. Components of the water balance included depth of disposed water (D , cm month^{-1}), precipitation (P , cm month^{-1}), evapotranspiration (ET , cm month^{-1}), percolation below 45 cm depth (G , cm month^{-1}), and water content change in the upper 45 cm ($\Delta\theta$, cm month^{-1}).

Drain field surface runoff and soil lateral flow was neglected because the experimental site was relatively level and no runoff or ponding was observed throughout the study. Percolation below 45 cm depth was estimated by mass balance difference between water balance components, including dosed and rainwater inputs, estimated monthly drain field soil moisture change, and calculated field ET (Eq. (1)). If calculated net monthly percolation, G (Eq. (1)), indicated a positive moisture gain to the soil control volume above 45 cm depth, then this value was identified as an error term to properly balance water input and outputs.

$$G = D + P - ET - \Delta\theta \quad (1)$$

The data, one tipping bucket rain gauge, and one inline vortex flow meter on the main water line from the SDI dosing pump, recorded by the GPI data logger/controller were used to estimate the disposed water (D) and precipitation (P). The change in monthly soil moisture content within the upper 45 cm of the soil ($\Delta\theta$) was estimated as the difference between weighted field water content (Eq. (2)) at the beginning and ending dates of each month based on in situ soil moisture readings. Since volumetric soil moisture content was only measured at 20 and 45 cm depth, the

assumption was made, although there could be other possibilities, that 1) soil moisture content varied linearly between 20 and 45 cm depth, and 2) soil moisture content in the upper 20 cm depth was represented by the volumetric soil moisture reading at 20 cm.

$$\theta_{\text{upper 45 cm}} = (\theta_{20 \text{ cm}} \times 20 \text{ cm}) + [(\theta_{20 \text{ cm}} + \theta_{45 \text{ cm}})/25 \text{ cm}] \quad (2)$$

Field evapotranspiration (ET) was estimated by the Penman–Monteith method (FAO, 2006) corrected by the single crop coefficient method (K_c) referenced from the FAO Irrigation and drainage paper 56 (FAO, 2006). Meteorological data for ET calculation was obtained from the Alabama Agricultural Weather Information Service (Agricultural Weather Information Service, 2008).

2.5. Site K_{sat} and field capacity verification

At the end of the two year study, site uniformity was quantified in terms of field capacity and soil saturated hydraulic conductivity (K_{sat}) to determine how closely field conditions conformed to original system design parameters. Field capacity was measured on June 24, 2008 by taking intact soil cores at 20 cm depth from nine uniformly distributed locations. Volumetric soil moisture at field capacity (1/3 bar) was measured using the laboratory pressure plate method (SSSA, 2002). K_{sat} was also measured onsite during June–July, 2008 using a permeameter (Ksat Inc., CA) at six

uniformly distributed locations at 45 cm depth. Resulting site maps of field capacity and K_{sat} distribution were generated using inverse distance weight (IDW) method within a GIS (ArcMap9.2, ESRI, CA). The Christiansen uniformity coefficient (Cu) (Soil Conservation Service, 1970) was calculated for both field capacity and K_{sat} to quantify site uniformity for these two important hydraulic parameters.

3. Field testing results

3.1. System hydraulic dosing control

Hydraulic dosing rates and soil moisture at two sampled depths from years one and two, September 6, 2006 to June, 2008, are presented in Fig. 2a. Soil temperature at 10 cm, field ET, and daily precipitation for the same period are illustrated in Fig. 2b. The experimental SDI dosing system became nonfunctional due to an onsite power outage and water supply cutoff from October 2006 to January 2007 (Fig. 2a). In addition, the experimental system was cut off manually for approximately one month during each May and October to facilitate field crop harvesting and planting. For the remainder of the 2 year study period, SDI dosing was successfully controlled by the automatic soil moisture feedback system. Dosing system response to changing soil moisture was consistent

throughout years one and two indicating successful incorporation of soil moisture control into a manufacturer's regular dosing control system.

Throughout years one and two, relatively higher dosing rates and frequencies were observed from late spring to late autumn as expected, with consistent near zero dosing periods during wet, winter months (Fig. 2a). System hydraulic dosing in year one had a higher magnitude and frequency than year two due to the occurrence of a 30 year drought during 2006/2007 (mid 2006 to mid 2007). The highest hydraulic dosing rate, 1.18 cm d^{-1} occurred in April 2006. The average hydraulic dosing rate during the period from February 2007 to June 2007 was approximately 0.40 cm d^{-1} . However, there were almost 3 months during the same period in 2008 when there was almost no dosing, suggesting the need of a 3 month wastewater withholding requirement if the system was applied standalone. Soil moisture readings from Fig. 2a indicate that the experimental system successfully shut down and did not aggravate drain field moisture content during wet winter when the drain field was naturally saturated during winter times.

Demonstrated advantages of soil moisture controlled hydraulic dosing observed in this study include: 1) avoidance of ponded drain field conditions by withholding wastewater dosing until field moisture content drops to a pre determined "operational" window; and 2) temporarily increased wastewater hydraulic dosing rates

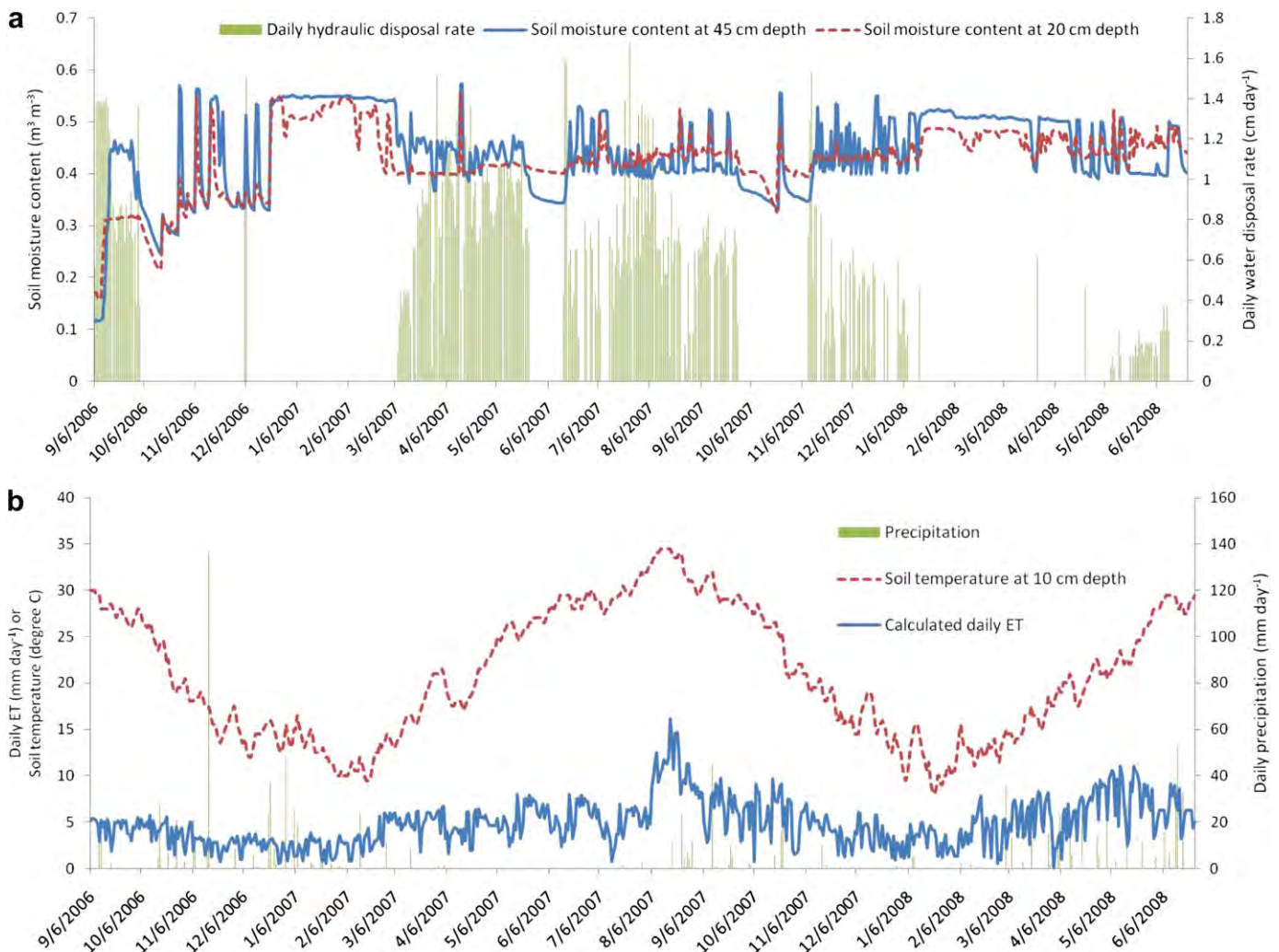


Fig. 2. Recorded field data for years one and two, September 2006 to June 2008. (a. soil moisture content and daily hydraulic dosing rate; b. daily precipitation, soil temperature at 10 cm depth, and calculated daily ET).

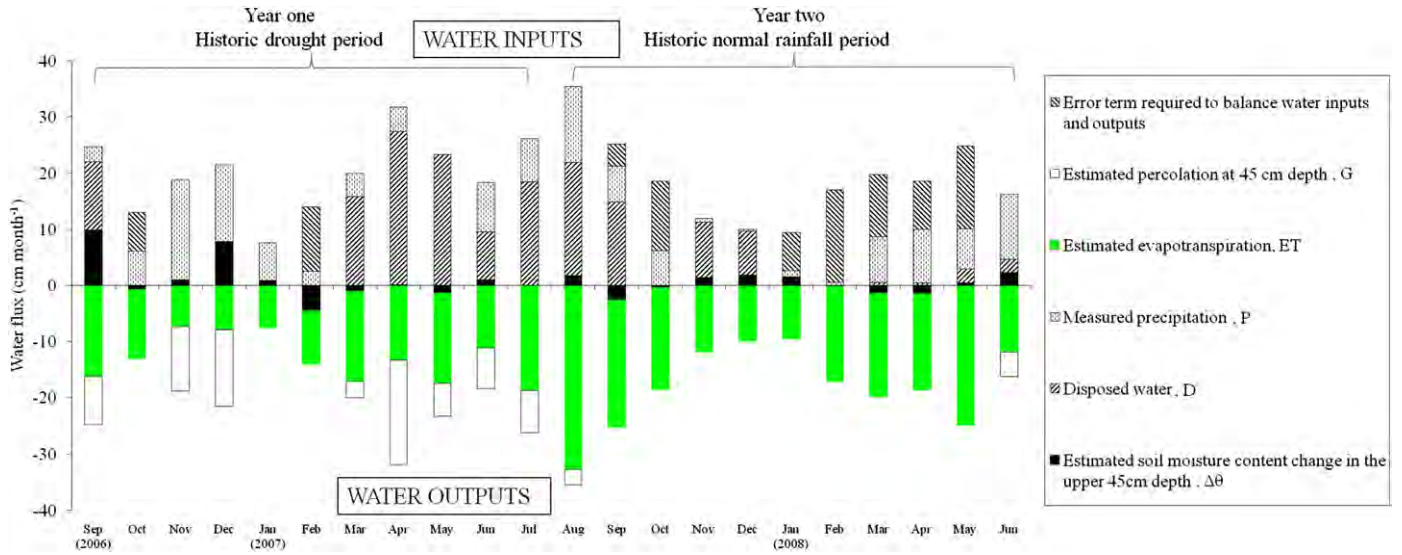


Fig. 3. Estimated monthly drain field (treatment I) water balance from September 2006 to June 2008.

under favorable field conditions based on seasonal soil moisture conditions. The two month zero dosing period in winter 2006/2007 indicates that to avoid direct discharge to surface or ground water, at least a two month waste storage is required. This constraint likely creates an insurmountable challenge for application of this system by individual rural homeowners.

3.2. Drain field monthly water balance

The estimated monthly water balance presented in Fig. 3 indicates that more than 30% of dosed water percolated below 45 cm depth during year one (September 2006, winter of 2006/2007, and March to June 2007). This high percolation fraction was unexpected since water dosing was allowed only when drain field soil moisture content was close to field capacity. Except for June 2008, the large percolation loss during the drought of year one was not indicated during the same period in year two.

The period from March 2007 to June 2007 (year one) coincided with a historic drought with total March through June precipitation equal to 248 mm versus 492 mm in an average year. It is recognized that shrinking and swelling of clay rich smectitic soils create dynamic crack formations that change soil physical and hydraulic properties (Bouma et al., 1981). Cracking development to a depth of around 50 cm is normal for Vertisols (Amidu and Dunbar, 2007) and more than 100 cm depth crack development has been reported in Houston clays (Kishne et al., 2009). Preferential channels can form which alter the landscape hydrology and facilitate rapid transport of water into the soil (Bouma et al., 1981; Youngs, 1995; Kishne et al., 2009). Although the cracking extent of the clay soil at the test site was not quantified during this study, surface cracking was consistently observed during summer months, more so in year one (data not shown).

Since the test site is a low permeable Houston clay soil, a likely explanation for the estimated percolation loss during the dry late

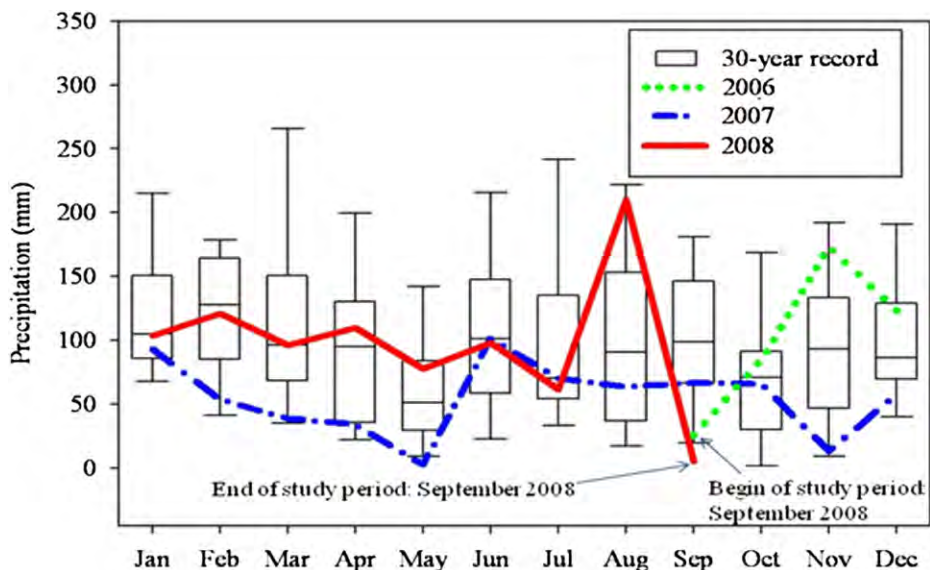


Fig. 4. Observed monthly precipitation at experimental site versus 30-year precipitation record.

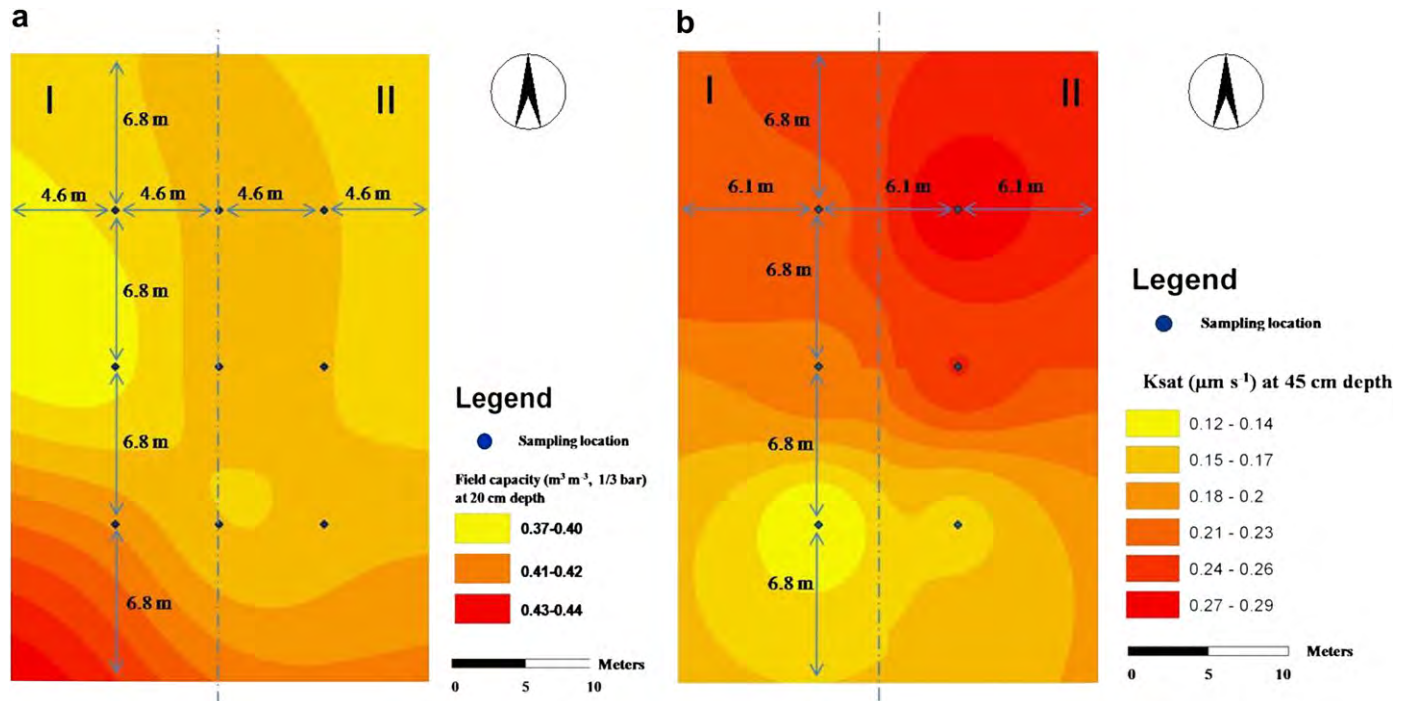


Fig. 5. Spatial variation of (a) field capacity and (b) saturated hydraulic conductivity, K_{sat} , in the SDI drain field.

spring and early summer months of 2007 is that dosed water did not adequately curtail soil crack development. Presumably, much of the dosed water moved by preferential flow away from soil moisture sensors, draining the soil profile at a higher rate than would have occurred in a more structurally homogenized soil.

The different hydraulic dosing rate and water percolation loss between years one and year two requires an explanation. There was a significant difference in precipitation between years one and two (Fig. 4). The period from March 2007 to June 2007 coincided with a historic drought; 248 mm precipitation versus 492 mm in an average year. The same period in 2008 had a total of 382 mm. Since multi year rainfall variability is expected to impact soil cracking on Vertisols (Kishne et al., 2009), the difference in rainfall suggests that soil cracking in 2008 would not be as severe as during the drought of 2007. The result, which matches observed data, would be higher hydraulic dosing rates during a warm season drought in these soils with lower dosing rates during years of normal warm season rainfall.

Measured field capacity of the SDI site varied from 0.37 to 0.44 ($\text{m}^3 \text{m}^{-3}$) (Fig. 5a), close to system operational thresholds (0.40–0.45 $\text{m}^3 \text{m}^{-3}$). The Christiansen uniformity coefficient for field capacity measurements was 96.9%, indicating a high uniformity for this texture dependent soil parameter. Measured K_{sat} of the experimental site varied from 0.12 to 0.29 $\mu\text{m s}^{-1}$ with relatively higher values in the upper slope section (Fig. 5b). The Christiansen uniformity coefficient for K_{sat} was 76.2%, indicating a uniformly low permeability. This field soil testing indicated that permeability and field capacity corresponded well to system design and operational thresholds, suggesting that inherent limitations of the soil rather than designed control system deficiencies most likely limited the effectiveness of the experimental dosing system.

If soil cracking caused the unexpected water percolation during dry summer conditions, then the soil moisture controlled waste water dosing was ineffective in preventing clay soil shrinking during dry soil conditions. One explanation for the experimental system's ineffectiveness in limiting soil cracking is the 0.61 m

spacing between emitters and drip lines, which may have resulted in dry areas between emitter wetting fronts. It is possible that reduced emitter and drip line spacing can enhance water distribution and limit soil cracking, but only if spacing is reduced to within the range of the expected wetting fronts for each emitter in these soils. Also, by putting soil moisture sensors more close to the emitters might increase the chances for the soil moisture sensors to capture the wetting front before it reaches soil cracks, thus calling off water dosing that might contribute to water percolation loss.

4. Conclusions

Over a two year field study, an experimental wastewater SDI system that incorporates real time soil moisture control and a seasonal cropping system was evaluated for its hydraulic management in an Alabama Black Belt clay soil. Soil moisture controlled hydraulic dosing rates in the drain field varied between 1.18 cm day^{-1} in April 2007 to a nearly two month zero dosing period (0.0 cm day^{-1}) during the preceding and succeeding winter seasons. Demonstrated advantages of the water management strategy of this experimental system include 1) avoidance of soil moisture conditions above field capacity in the absence of consistent rainfall events and 2) seasonally increased wastewater dosing rates under favorable dry field conditions. Unfortunately, the consistently low winter dosing period created a demand for wastewater storage that exceeds the capabilities of most rural home owners in this region.

Observed water management of the experimental system indicated that more than 30% of applied water was lost to percolation below 45 cm during dry soil conditions, most likely a result of soil cracking. Although water percolation is necessary for OWTS and may be favorably exploited for wastewater dispersal in the Alabama Black Belt region due to its unique geographical status that segregate underground water aquifer to top soil layers, this observed massive water percolation loss further indicates that the experimental system, including lateral and emitter spacing configurations

and soil moisture monitoring and feedback control, is not able to effectively limit water percolation during dry soil conditions. This finding suggests that the automated dosing system was unable to limit soil cracking and the accompanying severe hydraulic limitations inherent in the Houston clay soil. This study suggested that soil moisture controlled SDI dispersal of wastewater in native clay soils of the Alabama Black Belt is not suitable as a standalone method. Nevertheless, the system as designed and installed has potential as a supplement to existing municipal or decentralized community wastewater treatment facilities that have access to adequate land, machinery, and labor.

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