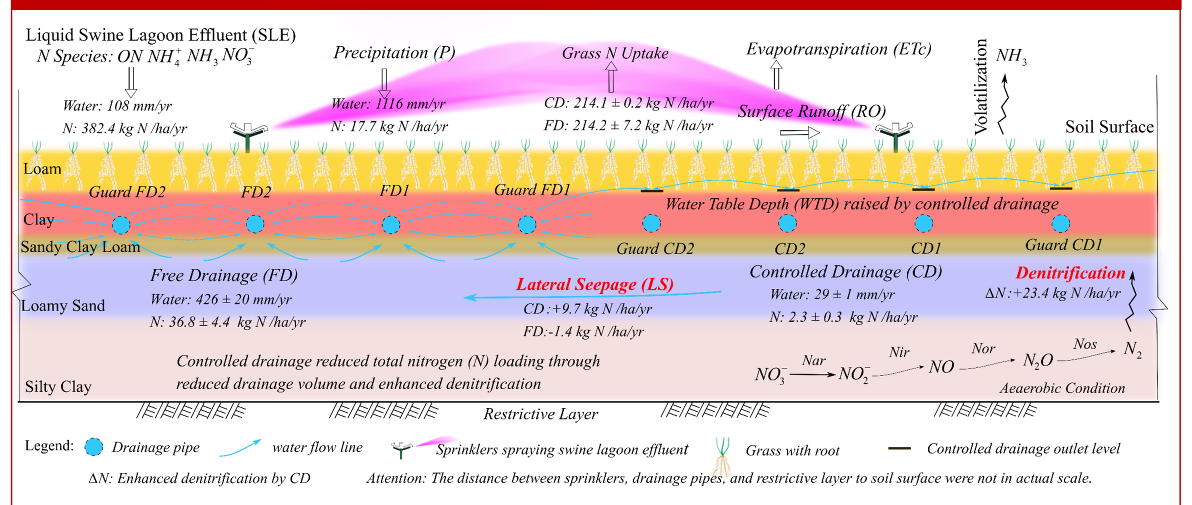
Modeling the Hydrology of an Artificially Drained Field Irrigated with Swine Lagoon Effluent

Yu Liu[1]; Mohamed Youssef[1]; George Chescheir[1]; R. Wayne Skaggs[1]; Timothy W. Appelboom[1]; Chad Poole[1]
[1]Department of Biological and Agricultural Engineering, North Carolina State University

1. Graphic Abstract



2. Introduction

• Artificially drained fields receiving liquid animal waste have the potential to export large amounts of nitrogen (N) to receiving surface waters.

• Controlled drainage has been proposed to reduce N loss from artificially drained agricultural land.

• The effect of CD on field hydrology has not been well investigated and an important question "where did the water, normally drained via continuously opened subsurface drains (conventional drainage), go when the system is operated in CD mode?" has not yet been answered.

• Computer simulation models such as DRAINMOD can be used in conjunction with field experimental data to investigate the effect of CD on field hydrology.

3. Objectives

• Simulate the hydrology of an artificially drained pasture field receiving swine lagoon effluent in eastern North Carolina during a four-year (2011 to 2014) experiment using DRAINMOD;

• Investigate the effect of CD on field water balance and estimate the fate of the water that did not leave the field via subsurface drainage because of CD implementation.

4. Water Balance Equation

$$P + Irr - D + \Delta V_a = ET + DLS + RO + \Delta SS$$

where P: precipitation; Irr: irrigation; RO: surface runoff, ΔSS: the change in surface water storage; ΔV_a: the change in the water-free pore space in the soil section; D: subsurface drainage; ET: evapotranspiration; DLS: deep and/or lateral seepage.

5. DRAINMOD Simulation

• Model modification:
DRAINMOD code was modified to read in measured daily water table depth and use it as a dynamic head that drives seepage flux.

• Statistical performance measures:
Mean absolute error (MAE), Nash-Sutcliffe modeling efficiency (NSE), and percent bias (PBIAS) were used to statistically compare measured and predicted water table depth and drainage flow

• Model calibration strategy:

a. The model was first calibrated for FD without considering seepage (FDN scenario) by adjusting the WTD-volume drained and WTD-Upflux relationships, effective rooting depth, and lower limit of water content in root zone.
b. The calibrated model for the FDN scenario was used to simulate the field hydrology under CD conditions without considering seepage (CDN scenario). However, seepage was found an important water balance component in CD plots.
c. Lateral seepage parameters were calibrated with constant head (Hr) for CD (CDL_ConHr) and FD (FDL_ConHr).
d. Lateral seepage parameters were calibrated with dynamic head (Hr) for FD (FDL_DynHr) and CD (CDL_DynHr).

Table 1. DRAINMOD model input parameters

(a) Drainage system design parameters

parameters	Value
Drain depth, B (cm)	100
Effective drain radius, Re (cm)	1.5
Depth to impermeable Layer, H (cm)	300
Drainage coefficient, D (cm day^{-1})	2.5
Maximum surface storage, Sm (cm)	1
Kirkham's Depth, SI (cm)	0.5

(d) Green-Ampt infiltration parameters

Water Table (cm)	A Coefficient	B Coefficient
0	0	3
20	0.42	3
40	0.59	2.5
100	1.25	2.5
150	2.21	2.5
1000	2.21	2.5

(b) Soil layers and saturated hydraulic conductivity (Ks)

Bottom depth of soil layers (cm)	Ks (cm hr^{-1})
0-20	16
20-36	4.5
36-75	3.2
75-100	0.4
100-175*	0.6

(c) Soil water characteristic relationship

Soil water content, θ (cm^3 cm^{-3})	Head (cm)
0.493	0
0.488	-4
0.482	-14
0.472	-34
0.457	-64
0.438	-104
0.428	-204
0.4	-2000

(e) Relationship between water table depth (WTD), volume drained (Vd), and upward Flux (Upflux)

WTD (cm)	Vd (cm)	Upward flux (cm hr^{-1})
0	0	0.5
9	0.18	0.5
12	0.24	0.5
20	0.4	0.1218
25	0.5	0.0612
30	0.686	0.0323
35	0.981	0.0182
40	1.311	0.0101
45	1.7	0.0059
60	2.55	0.0016
105	4.9	0.0006
150	6.5	0.0003
200	7	0
500	71.088	0
1000	100	0

(f) Input parameters for lateral seepage settings in controlled drainage (CD) and free drainage (FD) plots

Input parameters	CD	FD
Thickness of transmissive layer, Hd (cm)	0	0
Constant hydraulic head of receiving/source waters, Con_Hr (cm)	200	215
Distance to receiving/source waters, Lr (cm)	2500	2500
Horizontal hydraulic conductivity of transmissive layer, Kl (cm hr^{-1})	4.2	4.2

(g) The effective rooting depth function

Date	Effective rooting depth (cm)
12/1-3/1	5
3/1-3/15, 11/1-12/1	10
3/15-10/1	15

(h) Dynamic hydraulic head of receiving/source waters, Dyn_Hr (cm)

FD	*H-CDWTD-DIFF*
CD	*If (H-FDWTD)>=200 cm, 200 cm*
	If (H-FDWTD)<200 cm, H-FDWTD

* 175 cm is the effective depth of the soil profile
CDWTD and FDWTD are the WTD from CD and FD plots, respectively (cm);
DIFF is a constant term that represent impact of external factors such as the intercept of lateral seepage by guard drains and the drawdown of water table depth in surrounding area. DIFF value was calibrated as 15 cm.

6. Predicted vs. Measured

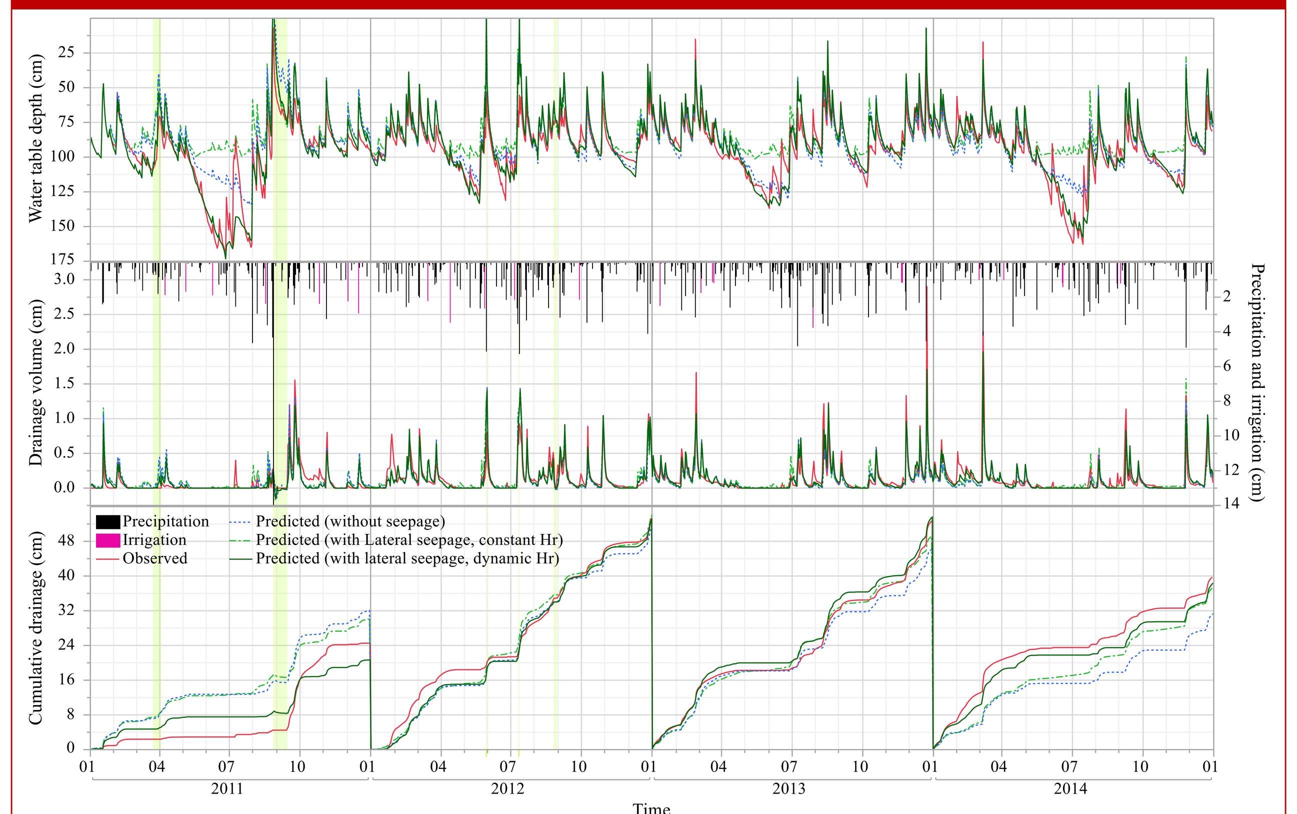


Fig. 1 Observed and predicted water table depth (WTD), daily drainage, and cumulative drainage for conventional drainage (FD) plots during 2011-2014.

Table 2 Water table depth (WTD) and daily drainage flow for FDL_DynHr scenario

Year	Mean water table depth (cm)				MAE (cm)	PBIAS (cm)	NSE
	Predicted	Observed					
2011	99.7	100.7	-	-	7.8	1.0	0.806
2012	87.8	91.6	-	-	6.7	4.1	0.579
2013	88.6	91.1	-	-	6.6	2.8	0.779
2014	95.3	98.8	-	-	6.5	3.6	0.834
4 year total	92.7	95.4	-	-	6.9	2.9	0.789
Year	**Mean daily drainage flow (cm)**		**Accumulated drainage (cm)**		**MAE (cm)**	**PBIAS (cm)**	**NSE**
	Predicted	Observed	Predicted	Observed			
2011	0.057	0.067	20.7	24.5	0.049	15.8	0.717
2012	0.145	0.146	53.1	53.4	0.060	0.4	0.660
2013	0.147	0.145	53.6	52.8	0.051	-1.6	0.793
2014	0.105	0.109	38.4	39.8	0.048	3.6	0.809
4 year total	0.114	0.117	165.8	170.5	0.052	2.7	0.758

- : Numbers in above two columns reversed

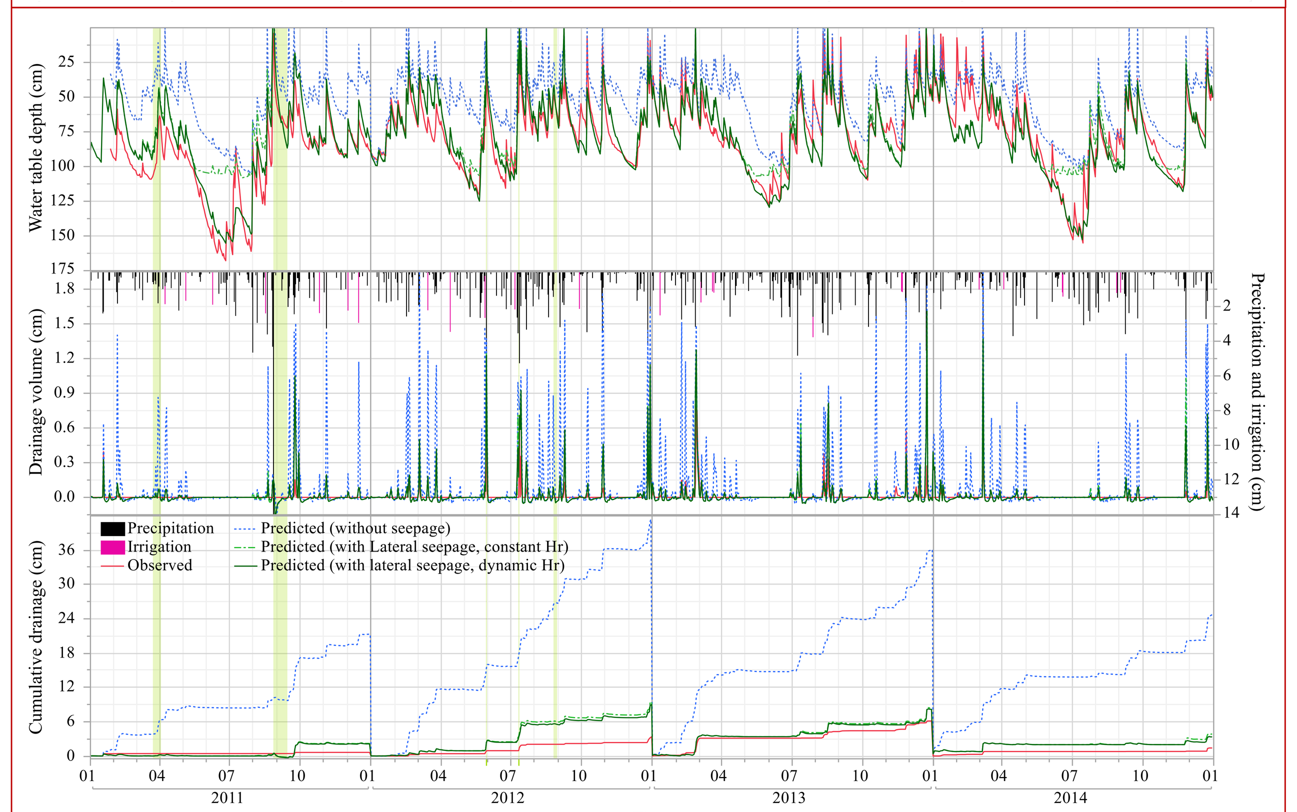


Fig. 2 Observed and predicted water table depth (WTD), daily drainage, and cumulative drainage for controlled drainage (CD) plots during 2011-2014.

Table 3 Water table depth (WTD) and daily drainage flow for CDL_DynHr scenario

Year	Water table depth					Accumulated drainage (cm)	
	Predicted mean (cm)	Observed mean (cm)	MAE (cm)	PBIAS (cm)	NSE	Predicted	Observed
2011	87.0	96.8	12.586	10.2	0.731	2.1	0.6
2012	72.2	75.5	8.052	4.4	0.750	9.0	3.4
2013	75.8	72.0	8.122	-5.2	0.810	8.1	6.1
2014	84.8	78.4	9.428	-8.1	0.794	3.3	1.4
4 year Total	79.8	80.4	9.491	0.8	0.798	22.5	11.5

7. Water Balance

Table 4 Predicted and observed water balance components for conventional drainage (FD) and controlled drainage (CD) plots, with and without seepage.

Year	(Observed) P (cm)	(Observed) Irr (cm)	ET (cm)	D (cm)	(Observed) D (cm)	RO (cm)	LS (cm)
Free drainage (FD) plots, FDL_DynHr scenario							
2011	108.0	14.5	71.7	20.7	24.5	17.9	12.8
2012	124.5	12.4	80.0	53.2	53.4	2.8	-1.4
2013	114.7	9.5	77.8	53.6	52.8	0.0	-7.6
2014	99.2	6.9	74.6	38.4	39.8	0.0	-7.2
Total	446.4	43.3	304.0	165.8	170.5	20.7	-3.4
Average	111.6	10.8	76.0	41.5	42.6	5.2	-0.9
Controlled drainage (CD) plots, CDL_DynHr scenario							
2011	108.0	14.5	72.8	2.1	0.6	18.3	29.5
2012	124.5	12.4	80.8	9.0	3.4	4.2	39.4
2013	114.7	9.5	79.3	8.1	6.1	0.3	36.0
2014	99.2	6.9	75.3	3.3	1.4	0.0	29.3
Total	446.4	43.3	308.2	22.5	11.5	22.8	134.2
Average	111.6	10.8	77.1	5.6	2.9	5.7	33.5

P is precipitation; Irr is irrigation, ET is evapotranspiration, D is subsurface drainage, RO is surface runoff, LS is lateral seepage.

8. Water Balance Conclusions

• Results of the simulations strongly suggested that lateral seepage was an important component of the water balance when CD is implemented on this site.

• DRAINMOD simulation result with seepage under dynamic hydraulic head of receiving/source waters (Hr) shows the best agreement between predicted and measured daily WTD and drainage volume.

• Simulation results showed that 96% of the reduction in subsurface drainage volume due to CD attributed to lateral seepage.

• A sandy layer at the 135 to 210 cm depth may be the major pathway for lateral seepage from CD plots to the unmanaged adjacent potion of the field.

9. Nitrogen Balance Implications

Table 5 Total nitrogen input, grass uptake, loss from subsurface drainage, and estimated enhanced TN loss through denitrification in CD plots. (Liu et al., 2018)

Time	N_I	N_P	N_D			N_{UP}			N_{LS}			ΔN_{DEN}
			FD	CD	Δ	FD	CD	Δ	FD	CD	Δ	
	kg N ha^{-1}											
2011	295.8	17.1	15.1 ± 4.7	0.7 ± 0.2	-14.3	126.2 ± 5.1	121.9 ± 0.2	-4.3	18.8	10.5	-8.3	26.9
2012	498.3	19.7	28.2 ± 0.8	3.7 ± 1.4	-24.4	404.6 ± 18.7	370.3 ± 13.9	-34.3	-3.2	15.2	18.5	40.3
2013	460.3	18.1	55.3 ± 10.4	3.9 ± 0.9	-51.4	154.3 ± 4.3	172.1 ± 3.3	17.8	-12.8	8.0	20.8	12.7
2014	275.2	15.7	48.7 ± 3.3	0.8 ± 0.3	-47.9	171.5 ± 0.7	192.1 ± 11.5	20.6	-8.3	5.2	13.5	13.9
Total	1529.5	70.6	147.3 ± 17.7	9.2 ± 1	-138.1	856.6 ± 28.7	856.4 ± 0.6	-0.2	-5.6	38.9	44.5	93.8
Mean	382.4	17.7	36.8 ± 4.4	2.3 ± 0.3	-34.5	214.2 ± 7.2	214.1 ± 0.2	-0.1	-1.4	9.7	11.1	23.4
2012 [1]	260.7	5.2	3.3 ± 0.6	0.05 ± 0	-3.3	222.1 ± 17.5	209.9 ± 3	-12.2	-0.4	3.4	3.8	11.7
2012 [2]	237.6	14.5	24.8 ± 1.4	3.7 ± 1.4	-21.2	182.6 ± 1.2	160.4 ± 11	-22.1	-2.8	11.8	14.6	28.6

N_I, N input from irrigation; N_P, N input from precipitation; N_D, N loss via subsurface drainage; N_{UP}, N uptake by grass; N_{LS}, N loss through lateral seepage; Δ, the difference of N loss between FD and CD plots; ΔN_{DEN}, enhanced denitrification by CD treatment.
[1]: Period from January 1 to May 11, 2012; [2] Period from May 11 to December 31, 2012.
The nitrogen uptake by grass in 2011 and 2012 [1] were estimated value.

• The nitrogen that did not leave the field via the subsurface drainage system under CD was lost via enhanced denitrification (68%) and lateral seepage to adjacent fields (32%).

• Considering N transported via LS, the 94% "apparent" N reduction efficiency of CD is reduced to 66%.

NC STATE UNIVERSITY
College of Agriculture and Life Sciences

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Contact information:
Yu Liu
E-mail: yliu47@ncsu.edu,
yu.liu.ncsu@gmail.com
Mobile: 919-592-7340