

Soil property changes after four decades of wastewater irrigation: A landscape perspective

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Abstract

For over 40 years, The Pennsylvania State University (PSU) has irrigated its wastewater onto both cropped and forested lands. Despite local weather conditions, approximately 50 mm/week of wastewater have been spray-irrigated onto the land since 1962. This irrigation, combined with the natural precipitation, amounts to approximately 3550 mm of water per year. The objective of this study was to investigate the morphological and functional changes in soils of this area as a result of this significantly-increased water load. The research area has a karst geology and is dominated by rolling hills with many small depressions that act as sinks for water and sediments. Together with six soil trenches, 47 soil cores were taken across a 6.5-ha field. Previous studies conducted at this site provided a reference for interpreting the changes in soil properties over time. Soil morphological properties, including structure, horizonation, and redoximorphic features, were evaluated from the soil cores and *in situ* soil pits. In addition, soil functional parameters, including saturated hydraulic conductivity (K_{sat}), bulk density, organic matter content, and soil pH, were evaluated to determine the soil functional changes. Results indicate that the soils have experienced periods of local saturation and soil transport, which are reflected by the distribution of redoximorphic features and A-horizon thickness across the study area. Sample locations were grouped into three landscape positions (summit, midslope, and depression) that exhibited similar soil properties. The depth of the A-horizon was significantly greater in the depressions, while the midslope position had the highest manganese oxide coating percentage, and the summit position had the highest bulk density. This reflects the likely hydrologic path from the summit to the depression. The depression areas had the highest mean surface K_{sat} (10.2 cm/h), while the summit areas had the lowest mean surface K_{sat} (1.2 cm/h). Both organic matter content and soil pH have increased considerably since 1971. Overall, although soil properties have changed through the decades of irrigation, the wastewater spray irrigation system remains functional in this area and the soils are still performing reasonably well; however, some concerns about reduced soil functionality need to be addressed from a landscape perspective in order to sustain this system.

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1. Introduction

Using large-scale wastewater irrigation on agricultural lands can be a synergistic management practice. The wastewater will have a different fate than being pumped into a river, agricultural crops can make use of the extra water and nutrients (Toze, 2006), and groundwater recharge is yet another positive outcome of wastewater irrigation. However, in a climate that typically receives 1000 mm of precipitation a year, wastewater irrigation systems have many uncertainties with respect to the

capabilities of soils to handle the increased load of water (2500 mm/year).

Previous research indicates that wastewater irrigation has the potential to alter soil properties (Vinten et al., 1983; Filip et al., 1999; Tarchitzky et al., 1999; Magesan et al., 2000; Wang et al., 2003; Coppola et al., 2004; Wallach et al., 2005; Toze, 2006). However, few studies have investigated wastewater irrigated soils by taking a landscape perspective. A landscape approach would not only evaluate how soils are reacting at a particular point, but also link point observations to their landscape position. In turn, sound management decisions can be better achieved based on a landscape approach.

Method of irrigation, composition of effluent, land use, soil type, local climate, and irrigation frequency all could have

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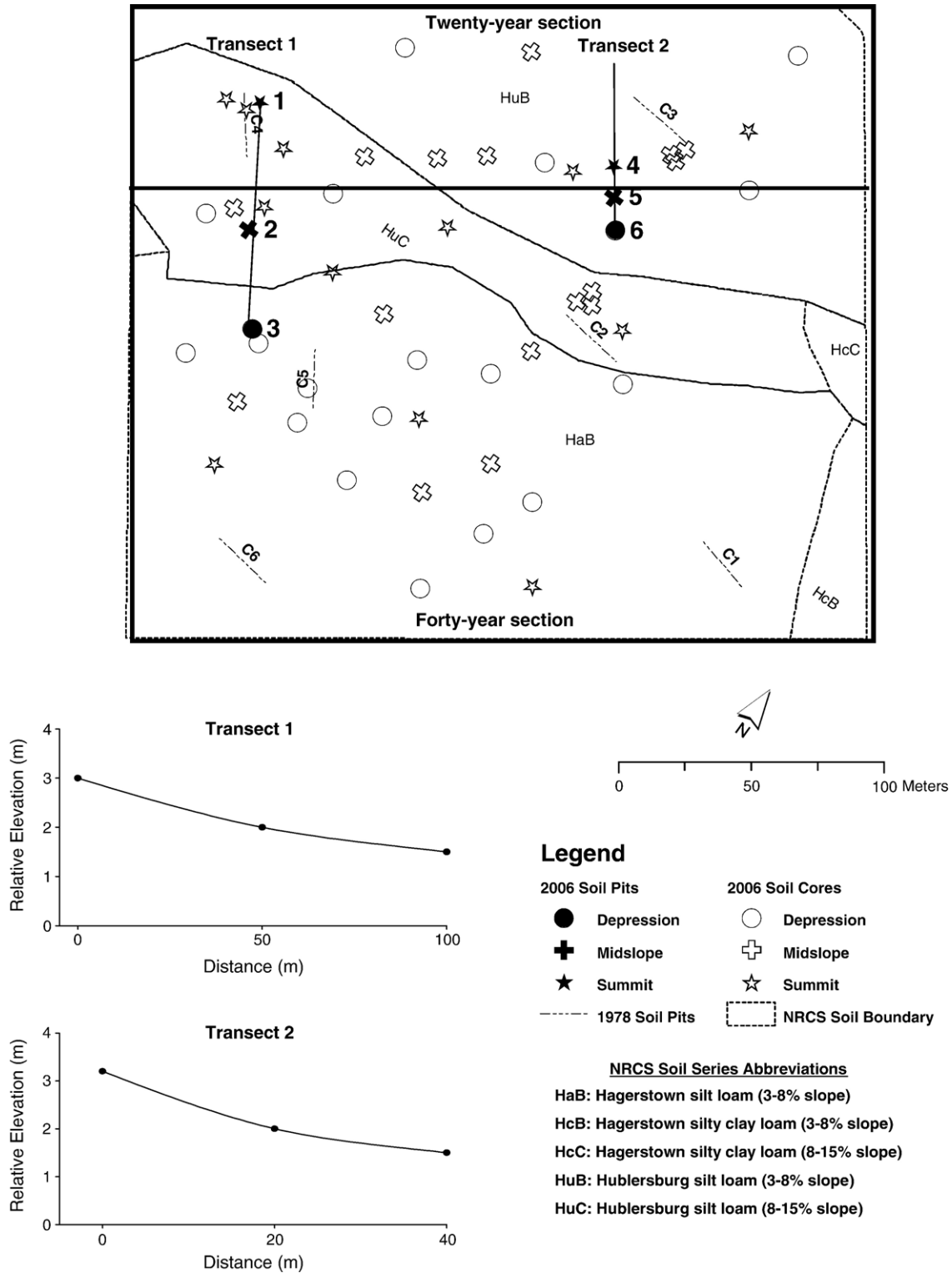


Fig. 1. Sampling scheme used in this study to determine the soil properties of the area. All sample locations were based on landscape positions (summit, midslope, and depression). The 2006 soil trenches were located in close proximity to the original soil trenches described by Simpson and Cunningham (1978). There were also 47 soil cores taken and described. The twenty-year site has now been irrigated for 23 years, whereas the forty-year site has been irrigated for over 40 years. The soils information is from the 2nd-order soil survey map. Pictured in the lower left-hand portion is the relative elevation change for the two soil trench transects.

potential impacts on how well the soil can handle excess water load. Many of these issues can be troublesome to soil quality on an individual basis, but with wastewater irrigation's increased content of salts and suspended solids, there is a

potential to produce compounding negative effects on soil quality. Throughout history, irrigation in arid and semi-arid regions has been associated with an increasing concentration of salts in the soil (Bagarello et al., 2006). High sodium contents in

irrigated soils can occur even with freshwater for irrigation. Excess sodium in soil can cause a variety of problems in agriculture, most notably the destruction of soil structure, dispersion of clays, and harm to plants. Soil structure degradation leads to reduced infiltration and hydraulic conductivity of the soil (Tarchitzky et al., 1999; Bagarello et al., 2006). The reduction in soil hydraulic conductivity not only affects how water moves through a soil profile, but can also affect water movement across the landscape (Coppola et al., 2004).

Many studies have investigated various soil physical and chemical properties in wastewater irrigation areas. Wang et al. (2003) studied the effects of wastewater irrigation by characterizing physical, chemical, and biological properties from soil samples taken from irrigated and non-irrigated California croplands. They determined bulk density, total porosity, clay content, saturated hydraulic conductivity (Ksat), and others in hope to determine the attributes that would best describe soil quality. They found that total porosity and magnesium content were the only two attributes significantly different between the irrigated and non-irrigated croplands. Pollice et al. (2004) investigated the effects of tertiary filtered wastewater drip irrigation on soils and found no change in soil chemical properties after two years of irrigation. Other research has investigated the roles that wastewater irrigation plays on soil water repellency. Wallach et al. (2005) describe soils that have developed water repellency after being irrigated for over twenty years with treated sewage effluent. The repellency was variable throughout the landscape and with soil depth. Resulting flow patterns showed “repellency” tongues that had developed mainly within the top 5 cm of the soil profile. This phenomenon could also cause runoff and affect agricultural production.

The Pennsylvania State University (PSU) has used a spray irrigation system for tertiary wastewater treatment for over 40 years. The system was designed as a research system in 1962 and was expanded in 1984 to become a full-scale operation. At that time the university stopped discharging water into the Spring Creek, a class one trout stream in the area (Tamminga, 1995). Instead, the municipal wastewater is irrigated throughout the year on both cropped and forested lands, each having a number of different soils.

The university currently uses the wastewater irrigation system to help with groundwater recharge, utilizing the soil as a living filter to provide tertiary treatment. The management practices are continuously evolving. The concept of ecosystem management,

Table 1
Average chemical characteristics of the municipal wastewater used for irrigation from Nov. 2005 until August 2006 ($n=21$) (Parizek et al., 2006)

Parameter	Concentration
Total alkalinity (mg/L as CaCO ₃)	179
Biological oxygen demand (mg/L)	8
Specific conductance (μmhos/cm)	1109
Total hardness (mg/L as CaCO ₃)	245
pH	7
Total suspended solids (mg/L)	5
Nitrate (mg/L as N)	12

Table 2

Physical and chemical properties of each horizon of the 2006 soil trenches (the trench names correspond to Fig. 1)

Location (Landscape position)	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Bulk density (mg/m ³)	Ksat (cm/h)	pH	OM (%)
<i>Trench 1 Section 1 (Summit)</i>								
Ap	0–20	33.8	52.7	13.5	1.66	1.60	7.26	2.34
B/Ap	20–28	24.8	48.4	26.8	1.67	*	7.56	1.48
Bt1	28–60	19.8	42.7	37.4	1.58	0.01	7.42	1.57
Bt2	60–112	18.7	31.4	49.9	1.77	0.01	5.29	1.47
Bt3	112–152+	22.9	15.1	61.9	*	*	5.05	1.66
<i>Trench 1 Section 2 (Summit)</i>								
Ap	0–34	35.6	50.2	14.2	1.66	1.60	7.1	2.20
Bt1	34–52	27.4	43.4	29.2	1.70	0.20	7.45	1.12
Bt2	52–80	29.2	18.1	52.7	1.49	1.00	6.04	1.37
Bt3	80–137	34.6	16.5	48.9	1.60	0.58	5.07	1.38
Bt4	137–145+	29.7	11.0	59.4	*	*	4.95	1.49
<i>Trench 2 Section 1 (Midslope)</i>								
Ap	0–20	33.1	45.6	21.3	1.54	1.40	7.23	2.48
Bt1	20–48	18.1	52.7	29.2	1.53	0.13	5.64	1.16
Bt2	48–117	26.3	36.3	37.4	1.67	0.40	4.79	1.48
Bt3	117–143+	25.6	32.7	41.7	*	*	4.99	1.41
<i>Trench 2 Section 2 (Midslope)</i>								
Ap	0–21	34.0	46.5	19.5	1.56	3.72	7.27	2.03
Bt1	21–58	20.3	26.2	53.5	1.60	0.35	6.37	1.99
Bt2	58–90	25.9	41.3	32.8	1.70	0.01	5.61	1.31
Bt3	90–104	29.3	41.7	29.0	1.66	0.11	5.14	1.07
Bt4	104–136+	11.4	15.4	73.2	*	*	5.02	2.03
<i>Trench 3 (Depression)</i>								
Ap1	0–20	23.1	63.9	13.0	1.39	7.88	7.4	3.72
Ap2	20–63	29.8	59.2	11.0	1.29	5.78	7	2.96
ApB	63–83	25.2	61.1	13.7	1.55	0.03	6.86	1.22
Bt1b	83–106	10.2	53.3	36.5	*	*	6.77	1.12
Bt2b	106–138+	8.3	48.8	43.0	*	*	6.75	1.22
<i>Trench 4 (Summit)</i>								
Ap	0–20	34.2	45.3	20.5	1.53	0.88	7.11	1.93
Bt1	20–66	24.0	31.5	44.5	1.63	0.18	6.48	1.69
Bt2	66–113	17.5	37.6	44.9	1.59	0.54	6.13	1.69
Bt3	113–140+	37.0	27.2	35.8	*	*	5.29	1.17
<i>Trench 5 (Midslope)</i>								
Ap	0–34	38.2	53.1	8.7	1.52	4.40	6.64	2.20
BE	34–67	12.4	58.3	29.3	1.46	3.56	6.7	1.16
Bt1	67–105	10.9	48.7	40.4	1.34	2.12	6.34	1.44
Bt2	105–144+	20.9	30.4	48.7	*	*	5.47	1.57
<i>Trench 6 (Depression)</i>								
Ap	0–36	25.5	59.7	14.8	1.27	12.60	6.86	2.45
BE	36–44	24.7	53.1	22.2	1.50	0.03	6.98	1.09
Bt1	44–66	22.4	47.1	30.5	1.62	0.52	7.05	*
Bt2	66–105	24.6	28.6	46.8	1.51	0.23	6.86	1.40
Bt3	105–146+	24.3	29.6	46.1	*	*	5.03	1.67

* Indicates no data.

adopted in the 1990's, provides a better distribution of the irrigation with respect to agricultural vs. environmental concerns. However, even with intense management practices, problems arise from spraying over 7500 m³ of wastewater a day on approximately 209 ha of the land (Tamminga, 1995).

Table 3
Comparison of the 1978 soil morphological properties described by Simpson and Cunningham (1978) and the 2006 soil morphological properties determined from the soil trenches

Horizon	Depth (cm)	Moist color	Texture	(Structure)			Manganese%	Redox
				Grade	Size	Type		
<i>1978 Control Area</i>								
C3								
Ap1	0–25	10 YR 4/3	Silt loam	Weak	Fine/medium	Granular	0	None
Ap2	25–35	10 YR 4/3	Silt loam	Weak	Fine/medium	Sbk/granular	0	None
BA	35–65	10 YR 5/6	Light silty clay loam	Weak	Fine/medium	Sbk	<1	None
Bt1	65–110	10 YR 5/6	Light silty clay loam	Weak/mod	Fine/medium	Platy/sbk	5–10	Many
Bt2	110–180	10 YR 5/6	Heavy silty clay loam	Weak	Fine/medium	Sbk	5	None
C4								
Ap1	0–20	10 YR 4/3	Silt loam	Weak	Fine/medium	Granular	0	None
Ap2	20–30	10 YR 4/3	Silt loam	Weak	Fine/medium	Sbk/granular	0	None
BA	30–40	7.5 YR 5/6	silty clay loam	Weak/mod	Fine/medium	Sbk	3	None
Bt1	40–50	10 YR 5/8	Clay	Weak	Fine/medium	Sbk	7	None
Bt2	50–65	10 YR 5/6	Clay	Weak/mod	Fine/medium	Platy/sbk	12	None
Bt3	65–140+	5 YR 5/6	Clay	Weak	Fine/medium	Platy/sbk	0	None
<i>1978 Irrigated Area</i>								
C1								
Ap	0–36	10 YR 4/3	Silt loam	Weak/moderate	Fine/medium	Granular	0	None
Bt1	36–84	10 YR 5/6	Heavy silt loam	Weak	Fine/medium	Platy/sbk	<2	Common
Btx	84–132	7.5 YR 5/4	Heavy silt loam	Weak	Fine/medium	Prismatic/platy	5	Common
2Bt1	132–144+	5YR 5/6	Clay	Weak	Fine/medium	Sbk	<3	None
C2								
Ap	0–30	10 YR 3/2	Silt loam	Mod/weak	Fine/medium	Granular	0	None
Bt1	30–65	7.5 YR 5/6	Clay	Moderate	Fine/medium	Sbk	4	Few
Bt2	65–100	10 YR 5/6	Clay	Weak/mod	Med/coarse	Platy/sbk	40–50	Few
Bt3	100–180+	10 YR 5/6	Silty clay to clay	Weak	Med	Sbk	0	None
C5								
Ap1	0–14	10 YR 4/3	Silt loam	Weak	Fine/medium	Granular	0	None
Ap2	14–24	10 YR 4/3	Silt loam	Weak	Med/coarse	Sbk/granular	0	None
E	24–44	10 YR 4/3	Heavy silt loam	Weak	Medium	Sbk	0	None
BE	44–60	7.5 YR 5/6	Heavy silty clay loam	Weak/mod	Fine/medium	Sbk	<2	None
Bt1	60–96	5 YR 5/6	Clay	Mod/strong	Fine/medium	Sbk	20–30	None
Bt2	96–130+	5 YR 5/6	Clay	Weak/mod	Fine/medium	Sbk	<1	None
C6								
Ap1	0–20	10 YR 4/3	Silt loam	Weak	Fine/medium	Granular/Platy	0	None
Ap2	20–32	10 YR 4/3	Silt loam	Weak	Fine/medium	Granular	0	None
BA	32–60	10 YR 6/4	Heavy silt loam	Weak	Fine/medium	Sbk	0	None
Bt1	60–84	10 YR 5/6	heavy silty clay	Weak/mod	Fine/medium	Sbk	1	None
Bt2	84–156+	5 YR 5/6	Clay	Moderate	Fine/medium	Platy/sbk	8	Common

Horizon	Depth (cm)	Moist color	Texture	(Structure)	Size	Type	Manganese%	Redox Fe Conc.	Redox Fe Dep. %
				Grade					
<i>Control area (22 years of irrigation)</i>									
Trench 1 Section 1 (Typic Hapludalf, clayey, mixed, mesic) (Redox features were found in a small pocket)									
Ap	0–20	2.5 YR 4/3	Silt loam	Strong	Medium/fine	Granular	0	0	0
B/Ap	20–28	10 YR 5/6	Loam	Moderate	Medium	Sbk	0	0	0
Bt1	28–60	10 YR 5/6	Silty clay loam	Moderate	Medium	Sbk	0	0	0
Bt2	60–112	7.5 YR 5/8	Clay	Moderate	Medium	Sbk	10	25	0
Bt3	112–152+	5 YR 5/8	Clay	Weak	Coarse	Sbk	1	<2	0
Trench 1 Section 2 (Typic Hapludalf, clayey, mixed, mesic)									
Ap	0–34	2.5 YR 4/4	Silt loam	Strong	Medium/fine	Granular	0	0	0
Bt1	34–52	7.5 YR 5/6	Clay loam	Moderate	Medium	Sbk	0	0	0
Bt2	52–80	5 YR 5/8	Clay	Moderate	Medium	Sbk	2	0	0
Bt3	80–137	5 YR 5/6	Clay	Moderate	Medium	Sbk	2	0	0
Bt4	137–145+	5 YR 5/8	Clay	Weak	Medium	Sbk	0	0	0
Trench 4 (Typic Hapludalf, clayey, mixed, mesic)									
Ap	0–20	10 YR 4/4	Loam	Strong	Medium/fine	Sbk	0	0	0
Bt1	20–66	5 YR 5/8	Clay	Moderate	Medium	Sbk	<2	0	0
Bt2	66–113	7.5 YR 5/6	Clay	Moderate	Coarse/medium	Sbk	15	0	0
Bt3	113–140+	7.5 YR 5/6	Clay loam	Weak	Coarse	Sbk	15	0	0
<i>Irrigated Area (40+ Years of Irrigation)</i>									
Trench 2 Section 1 (Typic Hapludalf, fine loamy, mixed, mesic)									
Ap	0–20	10 YR 4/4	loam	Strong	Medium/fine	Granular	0	0	0
Bt1	20–48	10 YR 5/8	Silty clay loam	Moderate	Medium	Sbk	15	15	0
Bt2	48–117	7.5 YR 5/8	Clay loam	Moderate	Coarse	Sbk	15	0	0
Bt3	117–143+	10 YR 5/8	Clay	Weak	very coarse	Sbk	2	0	0
Trench 2 Section 2 (Typic Hapludalf, clayey, mixed, mesic)									
Ap	0–21	10 YR 5/6	Loam	Strong	Medium/fine	Granular	0	0	0
Bt1	21–58	7.5 YR 6/8	Clay	Moderate	Coarse/medium	Sbk	30	0	0
Bt2	58–90	7.5 YR 6/8	Clay loam	Moderate	Medium	Sbk	2	0	0
Bt3	90–104	10 YR 5/8	Clay loam	Moderate	Medium	Sbk	30	0	0
Bt4	104–136+	5 YR 5/8	Clay	Weak	Coarse	Sbk	2	0	0
Trench 3 (Aquic Hapludalf, cumulic, mixed, mesic)									
Ap1	0–20	2.5 Y 4/4	Silt loam	Strong	Medium/fine	Granular	0	0	0
Ap2	20–63	2.5 Y 5/4	Silt loam	Moderate	Medium	Sbk	0	0	0
ApB	63–83	2.5 Y 5/3	Silt loam	Weak	Medium/fine	Sbk	0	0	0
Bt1b	83–106	10 YR 5/4	Silty clay loam	Moderate	Medium/fine	Sbk	0	0	0
Bt2b	106–138+	10 YR 5/4	Silty clay	Moderate	Medium/fine	Sbk	0	20	30
Trench 5 (Typic Hapludalf, clayey, mixed, mesic)									
Ap	0–34	10 YR 4/3	Silt loam	Strong/moderate	Fine/medium	Granular/Sbk	0	0	0
BE	34–67	10 YR 5/4	Silty clay loam	Moderate	Medium/coarse	Sbk	0	0	0
Bt1	67–105	7.5 YR 5/6	Silty clay	Moderate	Coarse	Sbk	15	<2	0
Bt2	105–144+	5 YR 5/6	Clay	Moderate	Coarse	Sbk	25	15	0
Trench 6 (Typic Hapludalf, clayey, mixed, mesic)									
Ap	0–36	10 YR 3/3	Silt loam	Strong	Medium/fine	Granular	0	0	0
BE	36–44	10 YR 4/6	Silt loam	Moderate	Coarse/medium	Sbk	0	0	0
Bt1	44–66	7.5 YR 5/6	Clay loam	Moderate	Coarse/medium	Sbk	<2	0	0
Bt2	66–105	7.5 YR 5/6	Clay	Moderate	Medium/fine	Sbk	25	0	0
Bt3	105–146+	10 YR 5/8	Clay	Moderate/weak	Medium/coarse & Medium/thin	Sbk/platy	25	<2	0

*Sbk: subangular blocky structure.

The pit locations follow the map in Fig. 1.

The Pennsylvania State University is now concerned with an apparent decrease in the infiltration and hydraulic conductivity in the irrigation area. The reduced Ksat increases the amount of runoff and decreases groundwater recharge. This study was commissioned to determine if there is an actual decrease in Ksat and to determine what soil properties are causing the reduction. In addition to the Ksat measurements, a range of morphological, physical, and chemical properties of the soils were studied to determine soil changes after decades of wastewater irrigation. We used historic data from 1970's studies as a reference to determine the degree of the soil's functionality change after the period of operation. The authors recognize potential disparities while comparing results from previous research with the results found from this study. Although the land use has not changed since the initiation of the wastewater irrigation, the farming practices in general may have resulted in some changes in several soil properties. We were not able to differentiate the changes caused by such farming practices; however, most farming practices primarily impact the soil's surface horizon. In this study, we measured soil properties throughout the surface and subsurface horizons to help overcome this difficulty.

2. Materials and methods

2.1. Study site

The study area has been continuously cropped with a corn (*Zea mays* L.) and wheat (*Triticum aestivum* L.) rotation since irrigation was initiated. Within the study area there are two different periods of irrigation, the forty-year section (40+ years of irrigation) and the twenty-year section (23 years of irrigation) (Fig. 1). Currently, no-till farming practices are in place. The Pennsylvania Department of Environmental Protection allows the study area to receive 5 cm of irrigation per week, for the entire year. Chemical characteristics of the municipal wastewater irrigation currently used are provided in Table 1.

There are two phases of the Hagerstown soil series that were mapped in the study area at the scale of 1:24,000, Hagerstown Silt Loam and Hagerstown Silty Clay Loam (Fig. 1) (Braker, 1981). The Hublersburg soil series was also mapped in the study area (Fig. 1), but did not appear to be present due to the absence of rock fragments during our field investigations. The Hagerstown soil series (*Typic Hapludalf*) is a limestone-derived residual soil that is deep and well-drained with a moderate permeability. Physical, chemical, and morphological characteristics of the soils used for this study are provided in Tables 2 and 3, including a comparison to the soil morphological properties described by Simpson and Cunningham (1978). The texture of the surface soils ranges from loam to silt loam and the surface structure is granular. The subsurface soils have silty clay loam, clay loam, silty clay, and clay textures, with a structure mostly of subangular blocky. Iron and manganese stains are also commonly seen within the soil profiles.

2.2. Sampling scheme

To determine soil physical, morphological, and chemical properties of the irrigation area, samples were taken from soil

trenches and soil cores (Fig. 1). The locations of the sample points were chosen based on landscape positions and previous research performed in the area (Fig. 1). Three major landscape positions were considered for sampling: summit, midslope, and depression (Fig. 1). A total of 47 intact soil cores (120 cm in length and 5 cm in diameter) were taken from the study area using a hydraulic Gidding's probe mounted on a tractor. The soil cores represented samples from each of the 11 depressional areas observed in the landscape and various midslope and summit positions. These cores were sealed in plastic tubes until they were morphologically described and subsampled for analysis. Six soil trenches were also excavated, described, and sampled to determine a full suite of soil morphological, physical, and chemical properties. We located the soil trenches in the proximity of four soil trenches previously excavated by Simpson and Cunningham (1978). The locations of Simpson and Cunningham's (1978) trenches were obtained from a hand drawn map, which was then georeferenced. Although the exact location of Simpson and Cunningham's (1978) soil trenches could not be found, both the current study and 1978 study had evaluated soils from each of the three landscape positions. Note that the overall difference in elevation between these positions is on average not more than 1.5 m (Fig. 1). The prior physical and chemical analyses (Hook, 1971; Sopper and Richenderfer, 1978) were performed on 20 representative samples from the same site. Two of the soil trenches were in the original control of the 1978 study (twenty-year section), which has been irrigated for 23 years now. The remaining four soil trenches were located in the original irrigated area of the 1978 study (forty-year section), which has received wastewater effluent for over 40 years now (Fig. 1). All sample locations and landscape depressional areas were determined using a Trimble Global Positioning System Unit, followed by a post-processing using a base station to increase the measurement accuracy.

2.3. Soil morphological analysis

The soil trenches and intact soil cores were described according to the USDA–NRCS field guide book (Schoeneberger et al., 2002). Each trench had a single description if the trench was relatively homogeneous; however, two descriptions were given for trenches #1 and 2 because of the exposed heterogeneous soil profiles. Information collected for each description included the following: horizonation, hand-determined texture, rupture resistance, color, roots, pores, structure grade, structure size, structure type, and redoximorphic features. The redoximorphic features were separated into two main categories, manganese oxide coatings, and iron depletions and concentrations. The percentage of manganese oxide was based on visual estimates of the ped face coatings within the described pedon or soil core. The percentage of iron depletions and concentrations were also visually estimated within the soil profile. Each soil profile has been classified according to the U.S. Soil Taxonomy (Soil Survey Staff, 2006) (Table 3).

2.4. Soil physical analysis

Intact ring samples (6 cm in height and 5.4 cm in diameter) were separately taken from the soil trenches for laboratory Ksat

and bulk density measurements (in triplicate). The methodology used to determine Ksat followed that prescribed by Klute and Dirksen (1986), with the addition of a flow separating permeameter to reduce the effects of boundary flow (Walker, 2006). The Ksat was calculated based the flow measured from the inner part of the core. While performing the Ksat measurements we noticed boundary flow between the soil and the brass ring used to hold the sample; therefore, we measured the flow occurring from the inner portion of the core (4-cm diameter) using a modified device (Walker, 2006). Although the original methods (Sopper and Richenderfer, 1978) did not employ this technique, they used larger cores, which would also reduce the effects of boundary flow due to the smaller boundary area to volume ratio. Sopper and Richenderfer (1978) did not report any evidence of boundary flow. After the Ksat measurements were completed, the cores were placed in a 105 °C oven and dried until a constant weight to determine the soil bulk density. Similar methods were employed in the 1978 study by Sopper and Richenderfer (1978); however, they used larger cores (7.5-cm in diameter and 7.5-cm in height).

In situ saturated and unsaturated hydraulic conductivity tests were performed adjacent to each of the soil trenches using the standard tension infiltrometer (Ankeny et al., 1991; Lin et al., 1997). Three tension infiltrometers were set up with pressure transducers to measure both the height of water in the reservoir and the tension at the interface between the soil surface and infiltrometer disc, as described in Walker et al. (2006). Site preparation followed the protocol of Lin et al. (1997). Sequential tensions of 12, 6, 3, 2, 1, and 0 cm were applied to determine near saturated flow characteristics. Calculations were made using a pair of supply tensions to calculate saturated and unsaturated hydraulic conductivity using the Wooding's equation (Lin et al., 1997).

Soil texture was analyzed in the laboratory using a rapid method (Kettler et al., 2001). This method has been compared with the standard pipette method, and standard samples with known textures were also analyzed along with the unknown samples in this study. Our results showed that the range of difference between the rapid method of (Kettler et al., 2001) and the pipette method was from 0.35% to 4.75% (mean of 1.93%) for silt, 0.06% to 4.02% (mean of 0.64%) for clay, and 0.25% to 2.68% (mean of 1.20%) for sand. Soil texture was not compared with the 1978 study because the previous study did not provide laboratory texture results.

2.5. Soil chemical analysis

Soil pH was measured using a 1:1 ratio by mass of distilled water and soil. The samples were stirred every 5 min until the saturation period reached 0.5 h. The pH was then determined by a temperature-compensated pH electrode (VWR International, West Chester, PA). The same method was used for the 1971 data obtained by Hook (1971). Organic matter content was determined by the loss on ignition method (Schulte et al., 1991). A five gram soil sample was dried at 105 °C until it reached a constant weight. The soil was then placed in a 360 °C oven for 2 h, which was followed by cooling to 150 °C and weighing using a

draft-free scale. The weight change due to loss on ignition was then converted to organic matter content using a regression equation established for Pennsylvania soils between the standard Walkley–Black method (Walkley and Black, 1934) and the loss on ignition (LOI) method (data not published, Stecko, 2006):

$$\text{Organic matter(\%)} = -0.23 + (0.80 \times \text{LOI\%}) \quad (1)$$

The 1971 soil organic matter data obtained by Hook (1971), however, was determined by a variation (different indicator solution) of the Walkley–Black method described by Peech et al. (1947).

3. Results and discussion

3.1. Soil morphological properties

Four out of the six soil trenches and 11 out of 47 soil cores displayed iron (Fe) redox concentrations (trenches 1, 2, 3, 5). Trench 3 displayed iron depletions with a chroma of 1, while three other trenches (trenches 1, 2, 6) had depleted areas with a chroma of 3. Trench #3 (depression), #5 (midslope), and #6 (depression) had Fe redoximorphic features present throughout the whole trench. However, the redoximorphic features found at trench #1 (summit) and #2 (midslope) existed only in small pockets. Trench #4 (summit) did not display any Fe redoximorphic features. Four of the soil cores had Fe depletions with a chroma of less than two, whereas 6 soil cores had Fe depletions with a chroma of 3. We found that the size of the redoximorphic features were coarse (5 to <20 mm) at all trenches except for trench #6, which had a fine size (<2 mm). The depleted areas occurred primarily around macropores or ped faces, whereas the concentrations occurred within the soil matrix. The majority of the redox features were found in the 2nd and 3rd Bt horizons. The horizons that displayed redoximorphic features had a texture of either clay, silty clay, or silty clay loam (Table 3). These horizons frequently exhibited coarse sub-angular blocky structure, or were overlying a horizon with coarse subangular blocky structure (Table 3). Lin et al. (1999) found a negative relationship between structure size and the ability to transmit water vertically, which may explain the presence of redoximorphic features within those areas with coarse size structure.

The intact soil cores that displayed redoximorphic features in Bt horizons (Fe depletions and concentrations) were also distributed among the three landscape positions. The depression areas, where redox features occurred (5 cores), received run-on from adjacent summit and midslope areas, and exhibited a buildup of A-horizon material. In contrast, most of the midslope points (5 cores) and the summit area (1 core) where redoximorphic features were located did not experience a buildup of A-horizon material, neither did they show signs of ponding such as transported debris on the surface.

Another morphological indicator of water within the soil profile is the presence of manganese coatings. As with the movement of iron, manganese oxides are highly dependent on the Eh and pH of the local soil environment (Gambrell, 1996).

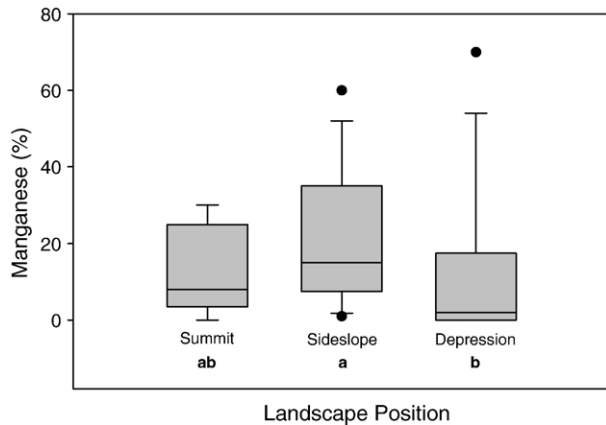


Fig. 2. Maximum manganese coating percentage in the soil profile (i.e., maximum percentage found in the B-horizon) grouped by the landscape positions ($n=47$). The error bars represent the 10th and 90th percentile data. The box represents the median and 25th through the 75th percentile data. The dots represent data below the 10th percentile and above the 90th percentile. Same letters represent no significant difference ($p < 0.05$).

The oxidation and reduction of manganese oxides commonly occur at a less saturated, higher Eh value than iron does (Buol et al., 1997). Five out of six soil trenches (83%) and 40 out of the 47 soil coring (85%) sites in this study displayed manganese oxide coatings in Bt horizon soils in locations different from iron depletions or concentrations. Maximum profile manganese coating percentage was significantly different ($p=0.035$) among the three landscape positions (Fig. 2). The midslope position had the highest median percentage of manganese coatings (15%), while the depressions had the lowest median percentage (2%), and the summits fall in between (8%). McDaniel et al. (1992) found similar distributions of Mn while comparing different landscape positions. The manganese coating distribution along the landscape in this study suggests that there are different degrees of saturation and a lateral movement of water from the summit areas to the depressional areas, even though the relief difference between these landscape

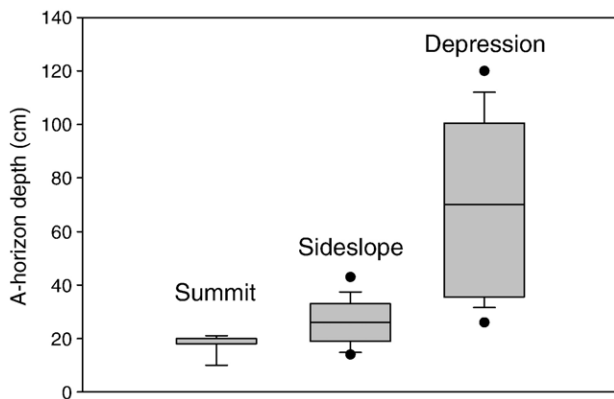


Fig. 3. A-horizon depths based on landscape positions ($n=47$). The error bars represent the 10th and 90th percentile data. The box represents the median and 25th through the 75th percentile data. The dots represent data below the 10th percentile and above the 90th percentile. Different letters represent significant difference ($p < 0.05$).

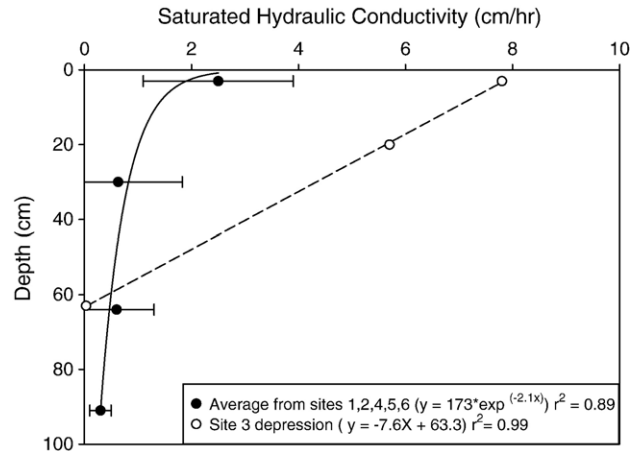


Fig. 4. Mean saturated hydraulic conductivity (constant head laboratory method) for all six trenches as a function of soil depth (middle of the core). Error bars represent one standard deviation from the mean ($n=15$ for each horizon, except for the site 3 depression plot, in which $n=3$ for each horizon).

positions was relatively low (< 2 m) (Fig. 1) (McDaniel et al., 1992).

As with the Fe concentrations and depletions, the Bt2 and Bt3 horizons were the most common soil layers in which manganese oxide coatings were found, with 71% of all the sites studied having amounts ranging from 1 to 50% (by area). Although manganese oxide coatings were less frequent in the lower portion of the B-horizon, they displayed some of the highest amounts of manganese oxide coatings on the basis of horizon area, with some exceeding 50%. The sizes of the manganese oxide coatings were predominately medium to coarse (i.e., 2 to < 20 mm).

Landscape position had a statistically significant effect on the A-horizon thickness distribution, with depression and summit areas having median thickness of 65 and 19 cm, respectively (Fig. 3). Govers et al. (1996) found similar patterns of soil redistribution as result of soil tillage, instead of overland flow. Four of the cores collected from the depressional areas had an A-horizon thickness of over 100 cm. There were also eight buried A-horizons (a dark horizon located below transported A-horizon material) found in the study area, all of them located in depressions. The 1978 study (Simpson and Cunningham, 1978) also reported multiple A-horizons in several trenches, with the deepest accumulation being 80 cm.

While investigating the soil texture of the trench samples (Table 3), we found that most of the surface horizons had a silt loam or loam texture, which is normal for the Hagerstown soil series. Some deviation from this norm might have been related to soil transport that occurred in some areas. The sites that had the higher percentages of silt and lower percentages of clay in the first subsurface horizon were also the sites that displayed redoximorphic features lower in the subsurface horizons, indicating the possible collection of sediment from runoff. Throughout the sample area, there existed a negative relationship between clay content and soil color regardless of soil horizons, as the soil hue became more yellow, the clay content decreased. In many subsurface horizons found in Pennsylvania,

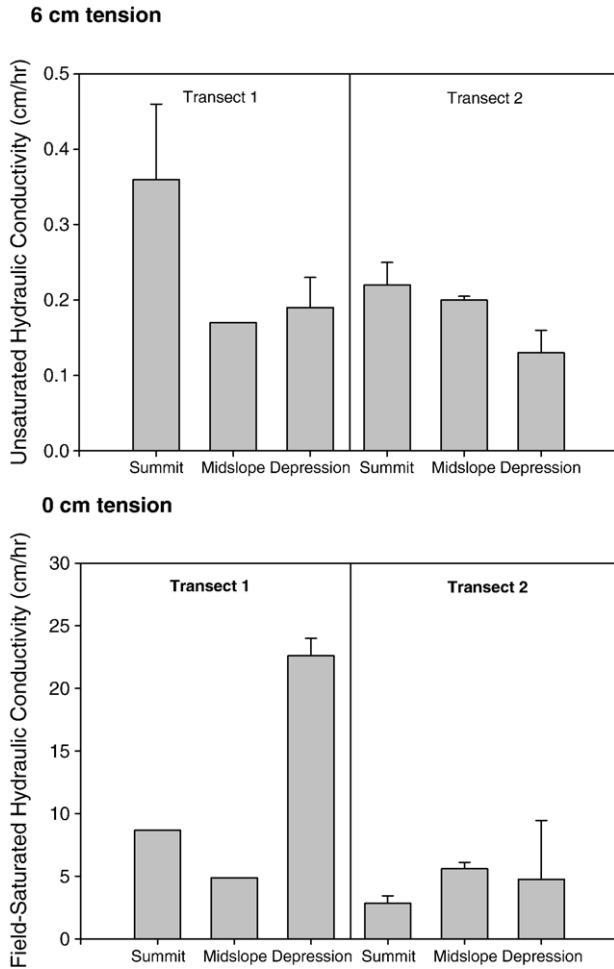


Fig. 5. Results from the tension infiltrometer measurements conducted at each trench area. The error bars represent one standard deviation from the mean for the three replicates (except at transect 1: midslope (6 cm tension) and summit and midslope (0 cm tension), which had 1 measurement due to equipment failure). Initial volumetric water contents for transect 1 were 22.7%, 22.3%, and 31.2% for the summit, midslope, and depression, respectively. Initial volumetric water contents for transect 2 were 30.6%, 30.3%, and 33.8% for the summit, midslope, and depression, respectively.

colors normally range from 2.5 YR (red hues) to 10 YR (yellowish brown) hues (Ciolkosz and Dobos, 1990). The soils in our study area had hues ranging from 2.5 YR to 2.5 Y. The red hues are normally due to a high concentration of hematite (Fe_2O_3), whereas yellowish brown colors indicate the presence of goethite (FeOOH) (Schwertmann and Taylor, 1989).

3.2. Soil physical properties

The average surface soil Ksat (3.8 cm/h) was found to be lower than the average value measured for the same area in 1978 (11.6 cm/h). Sopper and Richenderfer (1978) reported average laboratory Ksat values for the twenty-year section and the forty-year section in the study area (Fig. 1) to be 14.23 and 9.06 cm/h, respectively. In the current study, the mean laboratory determined Ksat values are 1.2 cm/h and 6.5 cm/h for the twenty-year section and the forty-year section, respectively. The large drop in Ksat for the twenty-year section

may have been due to the sampling location being in the summit area. While there were no statistically significant relationships between landscape position and Ksat values, the depression area did have the highest mean surface Ksat (10.2 cm/h) and the summit position had the lowest (1.2 cm/h). This difference is thought to have been caused by higher bulk density and the mixing of B-horizon material in the summit positions and lower bulk density in the depressions with transported thickened A-horizon.

Although there is no historical data on the subsurface Ksat, our study showed that there is an exponential decrease in Ksat from the surface to each subsequent subsoil horizon down to about 1m depth (Bt3 horizon) for all of the sites except the large depression (Fig. 4). The depression at site 3 had the highest surface Ksat along with a linear reduction to the subsurface horizons. The exponential decrease in Ksat for the lower Bt horizons corresponds to the increased frequency of both iron and manganese features in different portions of the same sample horizons.

The Kunsat at 6-cm water tension is used here to illustrate the difference among the landscape positions. The Kunsat at 6-cm water tension was highest at the summit positions for both transects, suggesting that the summit areas are dominated by smaller pores, whereas the midslope and depressional areas have more macropores (Fig. 5). Trench #3 (depression) had the highest field Ksat measured with the tension infiltrometer (average 22.6 cm/h), while trench #4 (summit) had the lowest (average 2.8 cm/h). We have observed that trench #3 had coarse macropores and trench #1 had medium-sized macropores, while the other sites had only fine or very fine pores in the surface horizons.

Previous studies have also demonstrated correlations between tillage practices and infiltration rates. Early studies indicate that conservation tillage practices are beneficial because of the potential network of long-continuous macropores that it

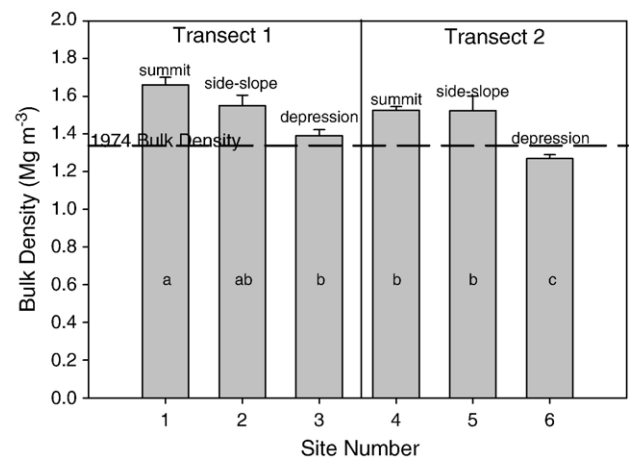


Fig. 6. Results from the bulk density analysis for each soil trench. The surface measurements were performed in triplicate and the error bars represent one standard deviation from the mean. Same letters represent no significant difference ($p < 0.05$). The surface soil bulk density in 1974 was 1.27 mg/m^3 and 1.41 mg/m^3 for the control and irrigated areas, respectively (Sopper and Richenderfer, 1978). There was no previous data for subsurface bulk density.

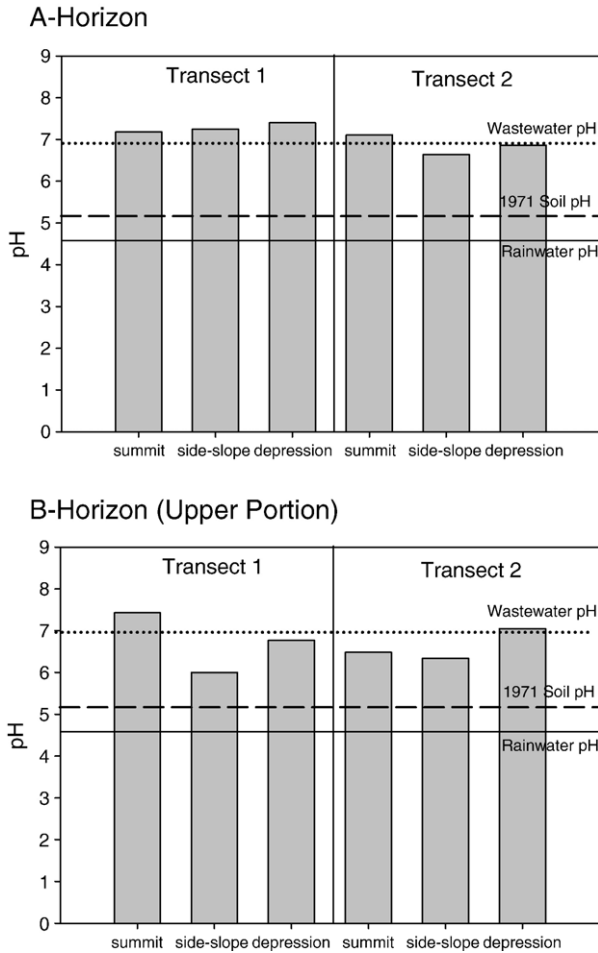


Fig. 7. Results from pH analysis (1:1 soil to water by mass) for each trench based on horizon. The control was based on data provided by Hook (1971). Wastewater pH was based on a 10 week average (Nov, 2005–January, 2006) (Parizek et al., 2006). Rainfall pH was provided by the National Atmospheric Deposition Program (NADP, 2006).

can sustain (Hangen et al., 2002). Other studies have found that minimum tillage systems have the highest infiltration rates, and no-till systems have the lowest infiltration rates (Akinoyemi and Adedeji, 2004). Our study area has been in a no-till practice for at least fifteen years and has what appears to be compacted surface layer, which may be reducing the infiltration capacity. The data from the tension infiltrometer measurements supports the idea that most of the infiltration in the study area occurs through macropores, which are often well associated with conservation and no-till practices.

The overall high bulk density of the surface soil layers (Fig. 6), which signifies compaction and reduced porosity, has been a common finding in wastewater irrigated areas (Wang et al., 2003; Coppola et al., 2004). High bulk density may also occur in regular farming systems that utilize heavy machinery for planting, fertilizing, and harvesting (Lipiec and Hatano, 2003; Trautner and Arvidsson, 2003). High bulk density is not surprising, especially in view of the fact that the soils have often been moist while farming practices are occurring. An increase in bulk density had been observed in the initial research performed

in the same study area (Sopper and Richenderfer, 1978). Across the whole landscape, there was a significant difference in surface soil bulk density between the summits and depressions: The summit position had the highest average bulk density value of 1.6 mg/m^3 , whereas the depression and sideslope positions had mean values of 1.33 mg/m^3 and 1.54 mg/m^3 , respectively (Fig. 6).

3.3. Soil chemical properties

Soil pH has increased throughout the profile as compared to that measured in 1971 by Hook (Fig. 7). The soils have increased in pH even though there has been no application of lime; however, the wastewater sprayed on the area does have a high amount of alkalinity ($150\text{--}170 \text{ mg/l}$ as CaCO_3) (Table 1). The soil pH profile is moving closer to being at equilibrium with the pH of the wastewater (Parizek et al., 2006). The increase in pH is common for soils receiving wastewater irrigation (Filip et al., 1999; Presley et al., 2004; Hu et al., 2006) and can help reduce farming costs because the soils do not require lime. In some situations, the soil's pH profile was indicative of its Ksat values. For instance, trench #2 and #4 had sharp decreases in their pH values directly below the surface, corresponding to low Ksat values found both in the laboratory and the field (Table 2). The low pH of the soils below the horizons with lower Ksat values may indicate that water is being held up in those horizons.

Soil organic matter (SOM) displayed a trend similar to the soil pH (Fig. 8). Comparing to SOM measured in 1971 by Hook, the soils have experienced a slight increase in SOM in the surface horizons but a sharp increase in subsurface horizons. Similar increases in organic matter content have also been noted by Qian and Mecham (2005) on golf course fairways that had been irrigated for 5 years with recycled wastewater. We note that although SOM and carbon are generally considered beneficial, some problems may arise from elevated levels, such as soil hydrophobicity and thus reduced hydraulic conductivity under certain conditions (Magesan

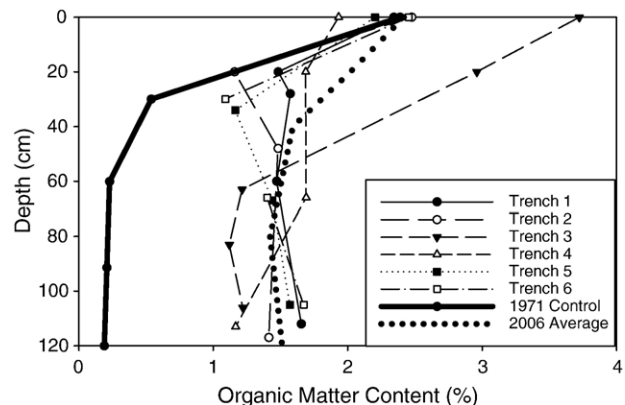


Fig. 8. Results of organic matter analysis (using loss on ignition). The 1971 control was from Hook (1971). The 0 cm depth represents a composite sample from the 1st A-horizon.

et al., 2000; Wallach et al., 2005). Further investigations of the transport of organic and inorganic materials down the deeper soil profiles in association with soil hydrologic dynamics would be desirable.

4. Summary and conclusions

The soils at the wastewater irrigation system have experienced several unfavorable effects after 40 years of operation, such as soil transport, low Ksat, high bulk density, and local saturation. Reduced Ksat and increased bulk density are typical in wastewater irrigation systems located in drier climates (Wang et al., 2003; Wallach et al., 2005), although the origin of these problems is different. Excessive water was the main cause of soil degradation in our study area as a result of constant waterdrop impact, soil transport, and machinery compaction, whereas the accumulations of salts normally induce problems for wastewater irrigation in drier climates. However, each of the three landscape positions within the study area (summit, midslope, and depression) has reacted differently to the 2540 mm/yr of additional wastewater, despite their close proximity to each other and relatively small elevation changes.

Morphologically speaking, the summit areas had the shallowest A-horizon, few redoximorphic features (iron depletions and concentrations), and few manganese oxide coatings. The shallow depth of A-horizon material indicates that these areas have been subject to soil movement. Their subsoils appeared to be less weathered than that of the other landscape positions. These features suggest that the summit soils do not receive as much percolating water as what the lower landscape positions do. The summit areas also exhibited the highest bulk density and generally lowest Ksat when compared to the other landscape positions.

The midslope landscape position showed signs of being the hydraulic link between the summits and depressions. These regions had the highest percentage of manganese oxide coatings as compared to the summit and depression positions. The manganese coatings are an indicator of water movement and suggest lateral flow of water from the summit areas to the depressional areas (McDaniel et al., 1992). In addition, midslopes had a higher occurrence of redoximorphic depletions and concentrations as compared to the summit areas, indicating that these areas were subject to periodic reducing conditions, whereas the summit positions were not. The midslope areas also had a deeper A-horizon than the summit position, but did not exhibit a significant accumulation as that experienced in the depressional areas. The soils in the midslope positions had Ksat and bulk density values similar to that of the summit positions.

The depressional areas serve as a sink of material transport from the surrounding areas. They had the deepest A-horizon and a high occurrence of redoximorphic features. Manganese coatings were not as prevalent in these areas due to the more frequent saturated environment. Although the depressions have the wettest morphologic features, their physical properties indicate that the thick surface layers have low bulk densities and high Ksat values. These results suggest that although the depressional regions are saturated more frequently, and sometimes ponded (*in situ*

observations), this may be caused by run-on rather than low soil permeability. How long such depressional soils can sustain added water loading will require further study, especially with regard to its subsoil hydrologic functions vs. the timing and amount of wastewater/rainwater inputs.

Throughout the surface and the upper B-horizons, the pH of the soils across the landscape has increased by one to two pH units over a time period of more than three decades. This increase has occurred without the addition of lime, and despite the influence of acid precipitation that occurred in the study area. The wastewater has a high content of calcium carbonate, as indicated by its alkalinity and hardness. These alkaline anions in the wastewater consume H^+ in the soil, resulting in an increased soil pH (Binkley and Richter, 1987). Organic matter, in the subsurface horizons, has also shown an increase throughout the soil profiles by over 1%. It is reasonable to propose that the increase is due to a decreased mineralization rate caused by increased wetness, although research has yet to confirm this.

Overall, although the soils in the study area have experienced morphological, physical, and chemical properties change after the prolonged period of wastewater irrigation, the soils have so far retained most of their capabilities to act as a living filter. By taking a landscape perspective, insights have been gained to differentiate distinct areas within the whole field and help explain the mechanisms and dynamics of soil properties change across the landscape. This approach allows us to designate specific areas within the field to remediate, in contrast to the costly remediation of the entire field. Although periodic ponding occurs in the depressional areas, remediation measures should also consider the summit areas as the sources of some observed problems such as low Ksat and high bulk density.

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