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Agricultural
water management

Agricultural Water Management 65 (2004) 39–57

www.elsevier.com/locate/agwat

Spatial and temporal variations of water quality in drainage ditches within vegetable farms and citrus groves

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Received 17 February 2003; received in revised form 1 July 2003; accepted 11 July 2003

Abstract

Water quality is influenced by agricultural development and varies with surrounding land management. Seasonal and spatial patterns in the concentrations of nitrogen (NH₄-N and NO₃-N), phosphorus (P), and heavy metals were investigated at six drainage ditches distributed in commercial vegetable farms and citrus groves in St. Lucie County, Florida. The concentrations ranged from nondetectable to 9.13 mg l⁻¹ for NH₄-N, to 283 mg l⁻¹ for NO₃-N, and to 4.86 mg l⁻¹ for total P. The concentrations of Cu and Zn ranged from nondetectable to 63.7 and 121.7 μg l⁻¹, respectively. Spatial and temporal variations of water quality were noted among the different drainage ditches. Since fertilizer rates were higher on the vegetable farms than in the citrus groves, the concentrations of N, P and K were generally higher in the ditches on the vegetable farms than in the citrus groves. Seasonally, the higher concentrations of N, P, K, Cu, and Zn occurred in the wet season than in the dry season, which might result from higher nutrient input from the adjacent field. Mean N, P, Zn, and Cu concentrations in the ditch water were significantly correlated with soil test N, P, Zn, and Cu levels and annual amounts of N and P applied in the adjacent fields. However, the concentrations of Cd, Co, Cr, Ni, Pb, Mo, and As were generally low, with small seasonal variations, probably due to limited water-soluble Cd, Co, Cr, Ni, Pb, Mo, and As in the soil of adjacent fields. The results indicate that nutrients and heavy metals accumulated in the soils and fertilization practices have significant influences

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on water quality in adjacent drainage ditches, and water quality of drainage ditch can vary with season.

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Keywords: Drainage ditch; Heavy metals; Nutrients; Temporal variation; Water quality

1. Introduction

Accelerated water quality degradation of rivers and lakes is among the greatest challenges facing water quality management (Sharpley et al., 1994). This problem is generally related to the increased annual input of pollutants to surface water (Carpenter et al., 1998; Correll, 1998). The losses of P, N, and heavy metals from agriculture to watercourses have increased over the past few decades as a result of intensive farming and development of a more industry-based type of agriculture (USEPA, 1998). The amount of elements entering water bodies depends on land use, soil type, soil characteristics, and type of runoff events (Burwell et al., 1975; Barisas et al., 1978; Duxbury and Pevery, 1978; Reddy et al., 1978; Baker and Lafen, 1982; Mueller et al., 1984; Edwards and Daniel, 1993).

Vegetable and citrus production in Florida has contributed to the eutrophication of state groundwater and surface-water bodies (Stanley et al., 1995; Sigua et al., 2000). The potential degradation of water quality in the area by nutrient inputs from agricultural soils has been a public concern. Because of the shallow water table in the Flatwoods area of Florida, profitable farming has been made possible only by construction of an extensive network of drainage ditches. Recharged chemicals from agricultural fields accumulate in ditches within and adjacent to the fields and are discharged into natural water bodies via off-farm drainage systems, which connect fields and natural waterways.

The contribution of P, N, and heavy metals from drainage ditches to surface water depends on concentrations and variations of the elements in the ditch water, which, in turn, reflects transport of the elements from the agricultural fields. However, water quality in the drainage ditches in the Flatwoods area and its relation to soil nutrient and heavy metal accumulation in adjacent fields has not been thoroughly investigated. There is minimal information available on the chemical forms and their seasonal and spatial variations of N, P, and heavy metals in ditch water, which is needed for agricultural water management. The objectives of this study were to investigate site-specific differences and temporal variation of ditch water quality in representative agricultural production areas in the St. Lucie County, Florida.

2. Materials and methods

A total of six ditches from four citrus groves (C1, C2, C3, C4) and two vegetable production farms (V1, V2) in St. Lucie County, Florida were selected for this study. The ditches were from 0.5 to 1.3 m deep and ranged in length from 150 to 300 m. The ditches were shallow with water depths ranging from 0.1 to 1.0 m, depending on time of the year. Precipitation during the period of the study varied seasonally, and most of the precipitation occurred from May to October (Fig. 1).

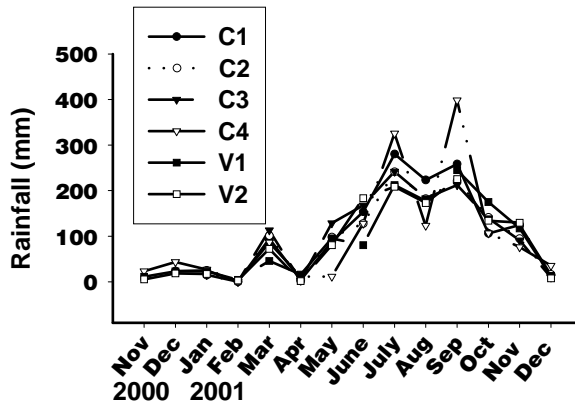


Fig. 1. Monthly rainfall at the six field locations (C1: citrus grove 1; C2: citrus grove 2; C3: citrus grove 3; C4: citrus grove 4; V1: vegetable farm 1; V2: vegetable farm 2).

During 1 December 2000–31 January 2002, triplicate water samples were collected at 2 weeks intervals from each of six sampling ditches. Acid-rinsed bottles were used to store water samples. Prior to filtration, pH and electrical conductivity (EC) of the water samples were determined using a pH/ion/conductivity meter (Accumet model 50, Fisher Scientific). Total P in the unfiltered water sample was determined using the molybdenum-blue method after digestion with acidified ammonium persulfate (EPA 365.1) (Greenberg, 1992). Sub-samples were filtered through a 0.45 μm syringe filter. The concentrations of anions and cations including $\text{NH}_4\text{-N}$, F, Cl, Br, $\text{NO}_3\text{-N}$, $\text{PO}_4\text{-P}$, and $\text{SO}_4\text{-S}$ were measured within 24 h after sample collection using an ion chromatograph (DX 500; Dionex Corporation Sunnyvale, CA). Dissolved reactive P was directly measured using the molybdenum-blue method. Concentrations of total dissolved elements (Ca, K, Mg, Na, Al, Fe, Cu, Zn, Mn, Cd, Co, Cr, Pb, Se, Mo, Ni, As) in the water samples were determined using an inductively coupled plasma atomic emission spectrometer (ICP-AES, Ultima, JY Horiba Inc., Edison, NJ).

Eight composite surface soil samples (0–15 cm) in adjacent fields for each site were also randomly collected in December 2000, prior to fertilizer application. Each composite sample was made by mixing six soil core samples taken randomly from each site. All samples were air-dried and ground to pass a 2 mm sieve. pH was measured in water at a solid: water ratio of 1:1 using a pH/ion/conductivity meter (Accumet Model 50, Fisher Scientific). Available P (Olsen-P) was extracted using $0.5 \text{ mol l}^{-1} \text{ NaHCO}_3$ and the P concentration in the extracts was determined by the molybdenum-blue method (Kuo, 1996). Soil available N ($\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$) was determined by shaking a 2.5 g air-dried soil sample in 25 ml $2 \text{ mol l}^{-1} \text{ KCl}$ for 1 h. Concentrations of $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ in the filtrate were analyzed with an autoanalyzer (AA III, Bran Luebbe, Buffalo Grove, IL). Available Cu and Zn were extracted by DTPA-TEA and measured using the ICP-AES (Reed and Martens, 1996). Water-soluble P and metals (Cu, Zn, Fe, Mn, Cd, Co, Cr, Pb, Se, Mo, Ni, and As) were determined by shaking a 4 g sample in 40 ml $0.01 \text{ mol l}^{-1} \text{ CaCl}_2$ for 2 h, centrifuging the suspension at $7500 \times g$ (rcf) for 30 min at 20°C , filtering the supernatant solution through a Whatman #42

Table 1
Characteristics of the soils and fertilizer application in the study sites^a

Property	C1	C2	C3	C4	V1	V2
Soil						
Soil type ^b	Waveland fine sand	Wabasso sand	Ankona sand	Ankona sand	Nettles sand	Wabasso sand
Permeability	Moderately rapid	Moderately slow	Moderate	Moderately slow	Moderately rapid	Moderately slow
Groundwater level (m)	0.65	0.85	0.95	0.80	0.60	0.50
Organic C (g kg ⁻¹)	2.61	8.97	7.48	9.67	4.90	7.38
Sand (2–0.05 mm, g kg ⁻¹)	959	930	961	954	946	956
Silt (0.002–0.05 mm, g kg ⁻¹)	15	32	14	17	27	16
Clay (<0.002 mm, g kg ⁻¹)	26	38	25	29	27	28
pH	5.1	7.4	5.5	4.4	7.6	7.2
Olsen P (mg kg ⁻¹) (mg kg ⁻¹)	13.6	11.1	16.3	20.6	57.7	69.6
Available NH ₄ -N (mg kg ⁻¹)	1.67	2.82	2.89	2.00	3.66	4.12
Available NO ₃ -N (mg kg ⁻¹)	3.26	2.11	4.66	3.11	32.7	11.6
DTPA extractable Cu (mg kg ⁻¹)	16.9	5.81	9.42	6.22	17.3	8.20
DTPA extractable Zn (mg kg ⁻¹)	4.66	2.35	3.93	1.67	3.04	5.07
Water-soluble P (mg kg ⁻¹)	5.47	1.32	3.15	2.68	9.77	8.64
Water-soluble Cu (mg kg ⁻¹)	0.53	0.09	0.27	0.05	0.50	0.22
Water-soluble Zn (mg kg ⁻¹)	1.66	0.54	1.59	0.27	0.97	0.46
Water-soluble Fe (mg kg ⁻¹)	0.44	0.83	0.96	1.11	0.28	0.49
Water-soluble Mn (mg kg ⁻¹)	0.37	0.13	1.02	0.55	0.46	0.76
Water-soluble Cd (μg kg ⁻¹)	3	5	4	2	1	2
Water-soluble Co (μg kg ⁻¹)	3	9	4	2	5	3
Water-soluble Cr (μg kg ⁻¹)	2	5	6	3	4	4
Water-soluble Pb (μg kg ⁻¹)	0	0	2	2	1	3
Water-soluble Se (μg kg ⁻¹)	5	7	10	9	3	5
Water-soluble Mo (μg kg ⁻¹)	6	7	3	2	4	3
Water-soluble Ni (μg kg ⁻¹)	4	6	5	5	5	3
Water-soluble As (μg kg ⁻¹)	19	16	11	13	12	15

Management	Grapefruit	Grapefruit	Grapefruit	Grapefruit	Peppers ^c	Peppers ^c
Crop	Grapefruit	Grapefruit	Grapefruit	Grapefruit	Peppers ^c	Peppers ^c
Production period	Whole year	Whole year	Whole year	Whole year	September to next April	September to next April
Irrigation	Microjet	Microjet	Microjet	Microjet	Drip	Seepage
Annual N (kg ha ⁻¹)	168	168	142	165	376	291
Annual P (kg ha ⁻¹)	38	38	16	37	78	90

^a C1: citrus grove 1; C2: citrus grove 2; C3: citrus grove 3; C4: citrus grove 4; V1: vegetable farm 1; V2: vegetable farm 2.

^b Nettles sand: sandy, siliceous, hyperthermic, ortstein Alfic Arenic Haplaquods; Wabasso sand: sandy, siliceous, hyperthermic Alfic Alaquods; Waveland fine sand: sandy, siliceous, hyperthermic, ortstein Arenic Alaquods; Ankona sand: sandy, siliceous, hyperthermic, ortstein Arenic Ultic Alaquods.

^c Beds were covered with plastic mulches during the period of crop production.

filter paper, and then measuring the concentrations of P, Cu, Zn, Fe, Mn, Cd, Co, Cr, Pb, Se, Mo, Ni, and As in the filtrate using the ICP-AES. Soil properties and field management for each site are given in Table 1. Extractable soil P and N, and annual N and P application were higher in the vegetable farms than in citrus groves. Water-soluble soil Cu and Zn reached high levels in some of the test sites (C1, C3, and V1), whereas water-soluble soil Cd, Co, Cr, Pb, Se, Mo, Ni, and As were very low for all the sites. The differences in concentrations of nutrients and heavy metals in the soils were likely due to the differences in application rates of fertilizers and other amendments. The mineralogy of the tested sandy soils is dominated by 1.4 nm minerals, montmorillonite, kaolinite and quartz for clay fraction, and quartz for silt and sand fractions.

Statistical differences in water quality parameters among the six ditches and correlations among water quality parameters were conducted using the SAS computer programs (SAS, 1988).

3. Results and discussion

3.1. Nitrogen

Ammonium-N and $\text{NO}_3\text{-N}$ concentrations varied widely among the sampling sites and times, ranging from nondetectable levels to 9.13 and 283 mg l^{-1} , respectively. The arithmetic mean of $\text{NH}_4\text{-N}$ concentrations was from 0.21 to 0.95 mg l^{-1} for all six locations and decreased in the order of V1 (0.95 mg l^{-1}) > V2 (0.68 mg l^{-1}) > C3 (0.47 mg l^{-1}) > C2 (0.32 mg l^{-1}) > C4 (0.29 mg l^{-1}) > C1 (0.21 mg l^{-1}). The mean $\text{NH}_4\text{-N}$ concentration in the ditch water on vegetable farms was higher than those in citrus groves (Table 2). The $\text{NH}_4\text{-N}$ concentrations were higher during the wet season (May–November) (Fig. 2), reflecting effects of storm-generated runoff from agricultural fields, caused by heavy rain (Fig. 1). In a study of the effect of drainage on nutrient pollution of surface waters, Grazhdani et al. (1996) observed that the majority of the N (50%) was lost in the period of intense rainfall. Arheimer and Liden (2000) found that P and inorganic N concentrations in agricultural catchments were elevated during a flow increase, and the increased P and N concentrations were linked to high precipitation and high water discharge. The $\text{NH}_4\text{-N}$ in the ditch water is not stable because of high pH of the water ($\text{pH} > 7$). The $\text{NH}_4\text{-N}$ concentration tended to decrease in the dry season due to lack of $\text{NH}_4\text{-N}$ supplement. Therefore, in the dry season (December and April), the $\text{NH}_4\text{-N}$ concentrations were much lower than in the wet season. The arithmetic mean of $\text{NO}_3\text{-N}$ concentration in water from each ditch ranged from 0.01 to 13.64 mg l^{-1} and decreased in the order of V1 (13.64 mg l^{-1}) > C3 (0.34 mg l^{-1}) > V2 (0.22 mg l^{-1}) > C1 (0.06 mg l^{-1}) > C4 (0.03 mg l^{-1}) > C2 (0.01 mg l^{-1}). The $\text{NO}_3\text{-N}$ concentrations were generally low (close to nondetectable) for most times of the year. The highest concentrations of $\text{NO}_3\text{-N}$ were detected on 11 July for C1 (0.81 mg l^{-1}) and V1 (283 mg l^{-1}), on 22 October for C3 (7.76 mg l^{-1}), on 10 September for C4 (0.95 mg l^{-1}), and on 29 June for V2 (6.45 mg l^{-1}) (Fig. 2). The mean $\text{NO}_3\text{-N}$ concentrations in V1 were much higher than the other locations (Table 2). This was probably due to a moderately rapid drainage condition and high rate of N application in the V1 (Table 1). The high $\text{NO}_3\text{-N}$ concentrations in the ditch

Table 2

Mean of pH, electrical conductivity (EC), total P (TP), dissolved reactive P (P), PO₄-P, NH₄-N, and NO₃-N concentrations in the ditch water from the six field locations^a

Property	C1	C2	C3	C4	V1	V2
pH	7.46 B ^b (6.91–8.11) ^c	7.89 A (7.39–8.30)	7.70 AB (7.18–8.21)	7.72 AB (7.30–8.33)	8.08 A (7.10–9.14)	7.50 B (6.90–8.05)
EC ($\mu\text{S cm}^{-1}$)	1.07 A (0.59–1.61)	1.22 A (1.00–1.48)	1.24 A (1.01–1.53)	1.25 A (0.71–1.72)	1.16 A (0.21–1.63)	1.23 A (0.44–1.56)
TP (mg l^{-1})	0.47 A (0.06–1.36)	0.04 B (0.00–0.16)	0.11 B (0.00–1.15)	0.20 AB (0.00–1.65)	1.06 A (0.04–4.86)	0.84 A (0.01–3.31)
DRP (mg l^{-1})	0.38 A (0.02–0.95)	0.02 B (0.00–0.12)	0.08 B (0.00–0.95)	0.18 AB (0.00–1.60)	0.95 A (0.01–4.70)	0.80 A (0.00–3.18)
PO ₄ -P (mg l^{-1})	0.21 A (0.00–0.79)	0.01 B (0.00–0.06)	0.06 B (0.00–0.90)	0.16 AB (0.00–1.60)	0.84 A (0.00–4.67)	0.71 A (0.00–2.57)
NH ₄ -N (mg l^{-1})	0.21 A (0.00–3.98)	0.32 A (0.00–8.87)	0.47 A (0.00–8.28)	0.29 A (0.00–9.13)	0.95 A (0.00–7.29)	0.68 A (0.00–5.94)
NO ₃ -N (mg l^{-1})	0.06 A (0.00–0.81)	0.01 A (0.00–0.14)	0.34 A (0.00–7.76)	0.03 A (0.00–0.95)	13.64 A (0.00–283)	0.22 A (0.00–6.45)

^a C1: citrus grove 1; C2: citrus grove 2; C3: citrus grove 3; C4: citrus grove 4; V1: vegetable farm 1; V2: vegetable farm 2.^b Mean values within a row with the same letter(s) are not different at $P = 0.05$ probability level.^c Values inside a parenthesis are range of each parameter.

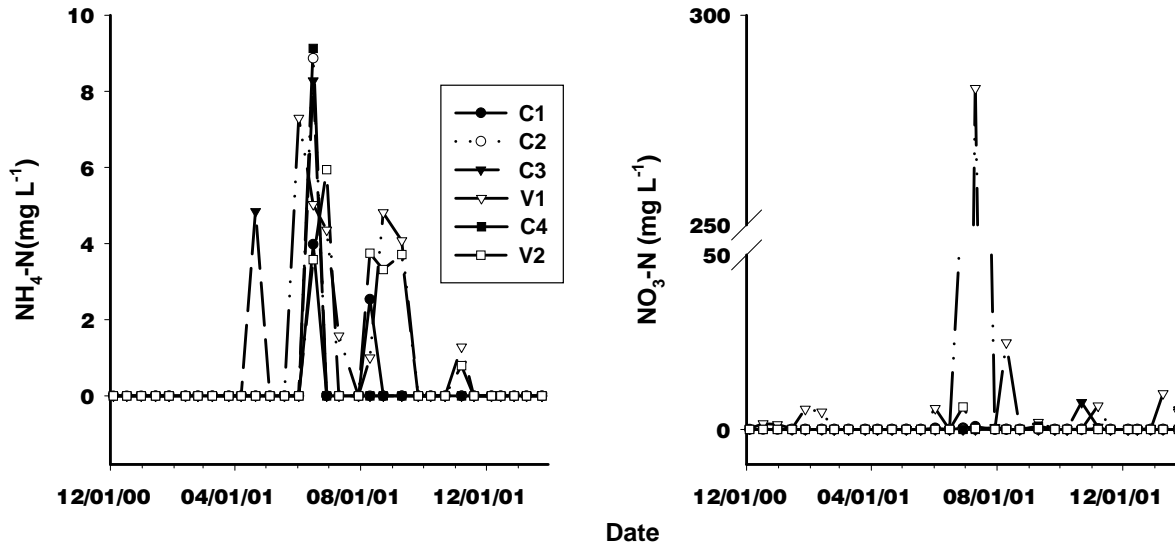


Fig. 2. Seasonal variations of $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ concentrations in the ditch water from the six field locations (C1: citrus grove 1; C2: citrus grove 2; C3: citrus grove 3; C4: citrus grove 4; V1: vegetable farm 1; V2: vegetable farm 2).

water detected on 11 July from the location V1 likely resulted from runoff caused by a heavy rain event (78.7 mm) immediately after removal of plastic covers from the adjacent fields. This result suggests that there is a high potential for rapid, incidental losses of N to occur after removal of plastic covers from soils in plastic-mulched vegetable production system.

3.2. Phosphorus

Total P, dissolved reactive P (DRP) and $\text{PO}_4\text{-P}$ concentrations varied widely among the six locations (Fig. 3), and ranged from a nondetectable level to 4.86, 4.76, and 4.70 mg l^{-1} , respectively. The arithmetic mean total P concentrations for the six locations decreased in

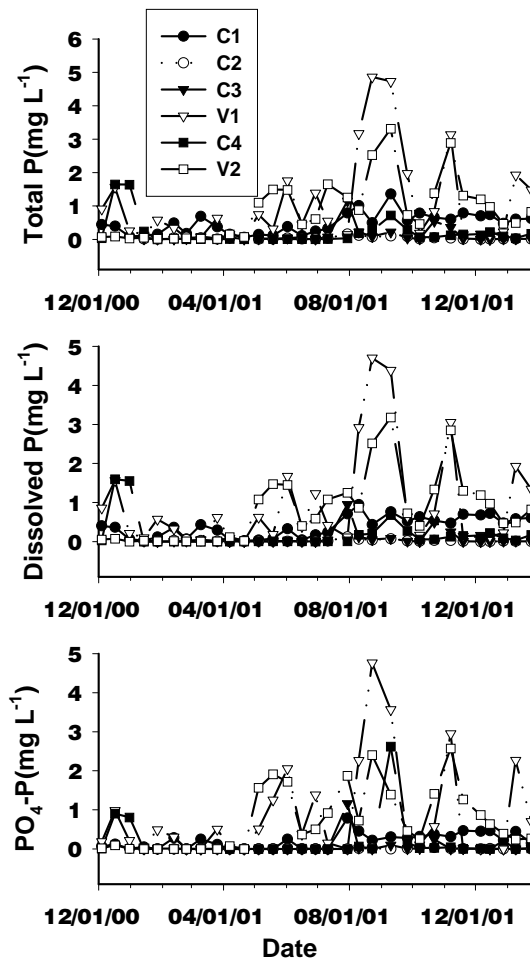


Fig. 3. Seasonal variations of P concentrations in the ditch water from the six field locations (C1: citrus grove 1; C2: citrus grove 2; C3: citrus grove 3; C4: citrus grove 4; V1: vegetable farm 1; V2: vegetable farm 2).

the order of V1 > V2 > C1 > C4 > C3 > C2, and were higher in the vegetable farm than in the citrus groves (Table 2). Percentages of the total P as PO₄-P ranged from 20 to 100% with a mean value of 73%. Similar to N, higher P concentration in the ditch water from five of the six locations (C1, C3, C4, V1, and V2) occurred during the wet season (May–November) when high amounts of runoff likely carried P into the ditches from the adjacent fields. Phosphorus concentrations in the ditch water were the lowest (<0.16 mg l⁻¹) for location C2 through most of the period because of low available soil P in the site. The decreased P concentration in the ditch water in the dry season may partially due to the fixation of P by the ditch bottom sediment.

3.3. Copper and zinc

Copper and Zn concentrations in all the ditch water samples were below 63.7 and 121.7 µg l⁻¹, respectively (Table 3). Mean Cu concentrations for each ditch ranged from 3.0 to 14.07 µg l⁻¹, and decreased in the order of V1 > C1 > C3 > V2 ≫ C2 > C4 (Table 3). Mean Zn concentrations were approximately 10 µg l⁻¹ for all the six locations. There were no significant differences in Zn concentration among the six locations. However, both Cu and Zn concentrations in the ditch water varied seasonally (Fig. 4). The higher concentrations of Cu and Zn (>20 µg l⁻¹) generally occurred in the wet season (May–November), corresponding to the rainy season with more runoff events. Occurrence of higher Cu and Zn concentrations in the ditch water was probably related with soil Cu and Zn accumulation in the adjacent fields. It has been common for the citrus and vegetable production in the areas to routinely apply micronutrient fertilizers (annual foliar application of Cu and Zn ranged from 2.2 to 5.6 kg ha⁻¹ as copper sulfate, 2.2 to 4.5 kg ha⁻¹ as zinc sulfate or 0.8 to 1.1 kg ha⁻¹ as chelated zinc), Cu- and Zn-containing pesticides/fungicides (such as copper hydroxide) that accelerated Cu and Zn accumulation in the soils. Significant runoff loss of Cu and Zn from sandy soils can occur during wet conditions with substantial rainfall, because the sandy soils were sensitive to erosion. Zhang et al. (2003) reported that both discharge and soil available Cu and Zn had a significant influence on Cu and Zn loads in surface runoff.

3.4. Other trace elements

Concentrations of Cd, Co, Cr, Pb, Se, Mo, Ni, and As were low for all the six locations and were below 0.50, 1.10, 2.05, 5.53, 27.02, 19.79, 3.05, and 18.67 µg l⁻¹, respectively (Table 3). The concentrations of Cd, Cr, Pb, Se, Ni, and As were lower than their drinking water standards (Cd 5 µg l⁻¹, Cr 100 µg l⁻¹, Pb 15 µg l⁻¹, Se 50 µg l⁻¹, Ni 100 µg l⁻¹, As 50 µg l⁻¹) (Stewart et al., 2001). Except for Mo, there were no statistical differences in the concentrations of the trace elements among the six locations. The seasonal variations of Cd, Co, Cr, Pb, Se, Mo, Ni, and Se were small and no significant temporal changes in the concentrations of the elements were observed. Low concentrations of the elements in the ditch water were related to their low accumulation in the soils on adjacent fields. In addition, the high soil pH values (pH > 7) limited release of the elements from the soils because of low solubilities of the elements in high pH values.

Iron and Mn concentrations in the ditch water varied widely, ranging from 0 to 1242 and 1738 µg l⁻¹, respectively. The Fe concentrations for all the water samples from four

Table 3
Mean concentrations ($\mu\text{g l}^{-1}$) of trace elements in the ditch water from the six field locations^a

	C1	C2	C3	C4	V1	V2
Cu	10.1 AB ^b (0.0–59.1) ^c	4.0 B (0.0–21.4)	8.5 AB (0.0–52.7)	3.0 B (0.0–22.9)	14.7 A (0.0–63.7)	7.0 AB (0.0–30.3)
Fe	336 B (0–1242)	62 AB (0–201)	137 AB (0–451)	70 AB (0–240)	34 B (0–239)	56 B (0–225)
Zn	12.2 A (0.0–56.7)	9.8 A (0.0–121.7)	12.1 A (0.0–45.1)	8.4 A (0.0–20.0)	10.8 A (0.0–28.4)	9.0A (0.0–43.3)
Mn	65 A (3–251)	15 A (1–94)	28 A (1–120)	30 A (0–180)	268 A (0–1738)	62 A (0–365)
Cd	0.02 A (0.00–0.19)	0.04 A (0.00–0.26)	0.03 A (0.00–0.24)	0.04 A (0.00–0.31)	0.05 A (0.00–0.50)	0.02 A (0.00–0.14)
Co	0.10 A (0.00–0.65)	0.08 A (0.00–0.69)	0.13 A (0.00–1.10)	0.08 A (0.00–0.46)	0.11A (0.00–1.00)	0.10 A (0.00–0.65)
Cr	0.33 A (0.00–1.37)	0.17 A (0.00–0.77)	0.32 A (0.00–1.26)	0.21 A (0.00–0.82)	0.52 A (0.00–2.05)	0.42 A (0.00–1.68)
Pb	0.37 A (0.00–2.58)	0.98 A (0.00–4.38)	1.19 A (0.00–5.53)	0.95 A (0.00–3.27)	0.80 A (0.00–4.07)	0.85 A (0.00–3.88)
Se	5.7 A (0.5–15.2)	8.5 A (2.6–23.6)	8.6 A (1.8–26.4)	8.8 A (3.7–26.2)	9.0 A (0.2–24.8)	8.5 A (0.3–27.0)
Mo	2.7 B (0.0–13.9)	10.4 A (1.0–19.8)	4.9 AB (1.2–16.0)	4.1 AB (0.0–19.3)	2.7 B (0.0–13.1)	4.2 AB (0.0–16.6)
Ni	1.0 A (0.0–2.9)	0.9 A (0.0–3.5)	1.2A (0.0–2.8)	0.7 A (0.0–1.7)	0.9 A (0.0–3.0)	0.9 A (0.0–2.9)
As	6.5 A (0.8–13.1)	6.7 A (0.6–15.1)	6.6 A (0.1–16.1)	8.0 A (0.8–16.9)	8.0 A (0.0–16.7)	9.1 A (2.4–18.7)

^a C1: citrus grove 1; C2: citrus grove 2; C3: citrus grove 3; C4: citrus grove 4; V1: vegetable farm 1; V2: vegetable farm 2.

^b Mean values within a row with the same letter(s) are not different at $P = 0.05$ probability level.

^c Values inside a parenthesis are range of each parameter.

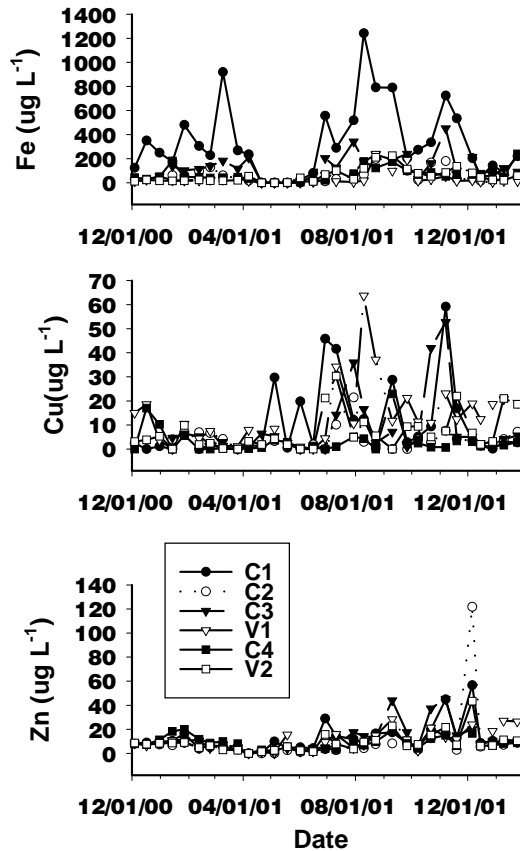


Fig. 4. Seasonal variations of Fe, Cu and Zn concentrations in the ditch water from the six field locations (C1: citrus grove 1; C2: citrus grove 2; C3: citrus grove 3; C4: citrus grove 4; V1: vegetable farm 1; V2: vegetable farm 2).

of the six locations (C2, V1, C4, V2) were below the drinking water standard ($300 \mu\text{g l}^{-1}$) (Stewart et al., 2001). Several water samples from locations C1 and C3 had Fe concentrations above the drinking water standard (Fig. 4). For all the six locations, approximately 60% of the water samples had Mn concentrations above the drinking water standard ($50 \mu\text{g l}^{-1}$) (Table 3). However, no obvious seasonal trends in Fe and Mn concentrations were observed. The Fe and Mn in the water might be originated from the bottom sediments in the ditches. The variations in concentrations of Fe and Mn in the ditch water were possibly associated with the redox potential changes and biological process in the ditch water.

3.5. pH, electrical conductivity, calcium, magnesium, potassium, and sodium

Liming is a common practices to maintain soil pH close neutral in the citrus and vegetable production systems in Florida. Irrigation water from wells in limestone aquifers is

an additional source of alkalinity. The combination of routine additions of lime and use of alkaline irrigation water has resulted in soil pH greater than 7.0 for most of the agricultural soils in Florida. Thus pH values of the ditch water was generally higher than 7.0. In this study, the pH of the ditch water ranged from 6.9 to 8.5, except for the V1 location where exceptionally high pH values (above 8.6) were observed on 7 April, 26 September, 6, 12 and 28 December 2001, and 24 January 2002 (Fig. 5). The exceptionally high pH values were likely related to alkaline irrigation water.

Electrical conductivity (EC) can be used to evaluate the total soluble salt concentration of a water sample, it refers to the presence of the major dissolved inorganic solutes, essentially Na^+ , Mg^{2+} , Ca^{2+} , K^+ , Cl^- , SO_4^{2-} , HCO_3^- and CO_3^{2-} , in water samples. The EC of the ditch water ranged from 0.21 to 1.72 mS cm^{-1} (Table 2). Sodium and Mg in the ditch water ranged from 6 to 320 mg l^{-1} and 3 to 67 mg l^{-1} , respectively (Table 4). Magnesium concentrations of the ditch water were low. EC values, Na, and Mg concentrations were similar among the six locations (Tables 2 and 4). However, the EC values, Na, and Mg concentrations were slightly higher in the dry season than the wet season (Figs. 5 and 6), indicating that evaporation possibly concentrated Na, Mg and water-dissolved salts. Calcium concentrations in the ditch water ranged from 11 to 291 mg l^{-1} (Table 4). The greatest variation of Ca concentrations occurred at location V1 (Table 4). The Ca concentration in the ditch water at location C1 was the lowest among the six ditches (Fig. 6). However, minimal season-trend variation was observed in Ca concentrations (Table 4). In contrast, K concentrations of the ditch water varied widely from 1 to 180 mg l^{-1} (Table 4). The highest K concentration was observed at the V1 location from May through October (Fig. 6). The EC values were significantly correlated with concentrations of Cl, SO_4 , K, Ca, Mg, and Na ($r = 0.31^{**}$, 0.35^{**} , 0.21^{**} , 0.61^{**} , 0.78^{**} and 0.80^{**} , respectively, $n = 174$). Sodium, Mg and Ca had the most significant effect on the EC.

3.6. Fluoride, chloride, bromide, and sulfate

Fluoride, Cl, Br, and SO_4 could be originated from irrigation water and soil amendments such as fertilizers and lime. Small season-trend variations were observed in F, Br, Cl, and SO_4 concentrations in the ditch water (Fig. 7). The F concentrations were between 0 and 1 mg l^{-1} throughout the year with few exceptions. All the ditch water samples contained F below the drinking water standard (4 mg l^{-1}) (Stewart et al., 2001). Chloride concentrations ranged widely from 20 to 2450 mg l^{-1} , but were mostly below 500 mg l^{-1} (Fig. 7). Few extremely high concentrations (above 1000 mg l^{-1}) were observed at locations C2 and C3 during the dry season as a result of evaporation. Bromide concentrations of the ditch water varied from 0 to 5.5 mg l^{-1} . The SO_4 -S concentrations of the ditch water were below 100 mg l^{-1} , with only few exceptions. Significant correlation was noted between concentrations of Cl and SO_4 ($r = 0.62^{**}$, $n = 174$), suggesting that these two elements had similar sources.

3.7. Relationships between water quality parameters and soil nutrient and heavy metal accumulation

Soil nutrient and heavy metal accumulation and fertilizer application rates had significant influences on water quality in the drainage ditches. There were significant correlations

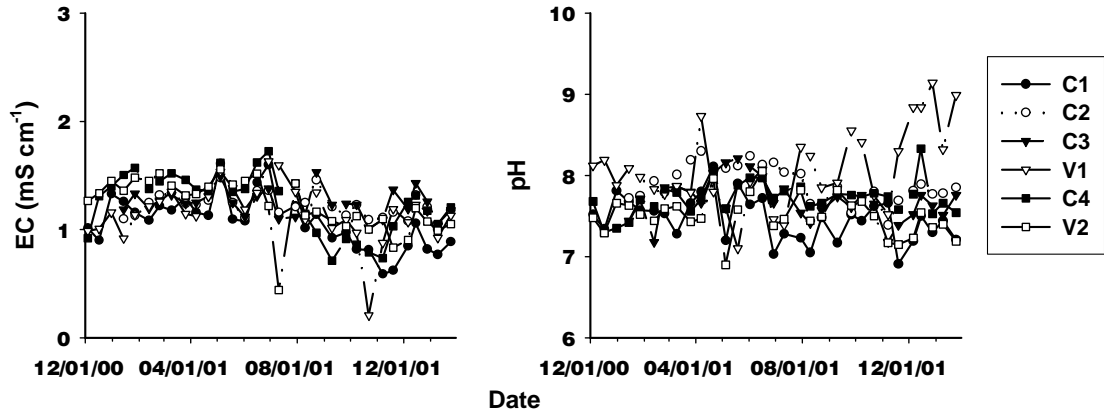


Fig. 5. Seasonal variations of pH and electrical conductivity (EC) in the ditch water from the six field locations (C1: citrus grove 1; C2: citrus grove 2; C3: citrus grove 3; C4: citrus grove 4; V1: vegetable farm 1; V2: vegetable farm 2).

Table 4
Mean concentrations (mg l^{-1}) of macro-elements in the ditch water from the six field locations^a

	C1	C2	C3	C4	V1	V2
K	13.4 A ^b (55.3–34.4) ^c	6.5 B (4.6–10.5)	6.4 B (3.7–14.1)	12.1 A (5.3–25.7)	28.2 AB (1.2–180.6)	19.2 A (5.2–62.1)
Na	109 A (29–209)	122 A (69–177)	126 A (64–167)	169 A (26–320)	118 A (6–244)	144 A (22–290)
Ca	82 B (32–141)	122 A (59–164)	135 A (62–200)	109 AB (55–177)	98 AB (11–291)	102 AB (27–200)
Mg	23 A (11–48)	26 A (16–38)	25 A (16–34)	36 A (11–64)	28 A (3–67)	32 A (7–56)
Al	0.33 A (0.11–0.69)	0.26 A (0.12–0.78)	0.28 A (0.13–0.80)	0.36 A (0.08–0.93)	0.30 A (0.04–0.61)	0.33 A (0.08–0.82)
F	0.39 B (0.19–0.70)	0.54 AB (0.22–1.97)	0.48 AB (0.24–1.98)	0.44 AB (0.28–0.71)	0.66 A (0.09–1.77)	0.47 AB (0.26–0.91)
Cl	249 A (81–587)	476 A (115–1450)	332 A (89–1767)	344 A (68–957)	274 A (20–608)	283 A (50–794)
Br	0.7 B (0.0–1.7)	1.2 AB (0.4–5.4)	1.1 AB (0.3–4.3)	1.5 AB (0.0–3.3)	1.5 AB (0.1–3.2)	1.8 A (0.0–5.1)
SO ₄ -S	27 B (0–62)	45 AB (14–178)	53 A (14–271)	28 AB (0–80)	25 B (0–92)	30 AB (0–143)

^a C1: citrus grove 1; C2: citrus grove 2; C3: citrus grove 3; C4: citrus grove 4; V1: vegetable farm 1; V2: vegetable farm 2.

^b Mean values within a row with the same letter(s) are not different at $P = 0.05$ probability level.

^c Values inside a parenthesis are range of each parameter.

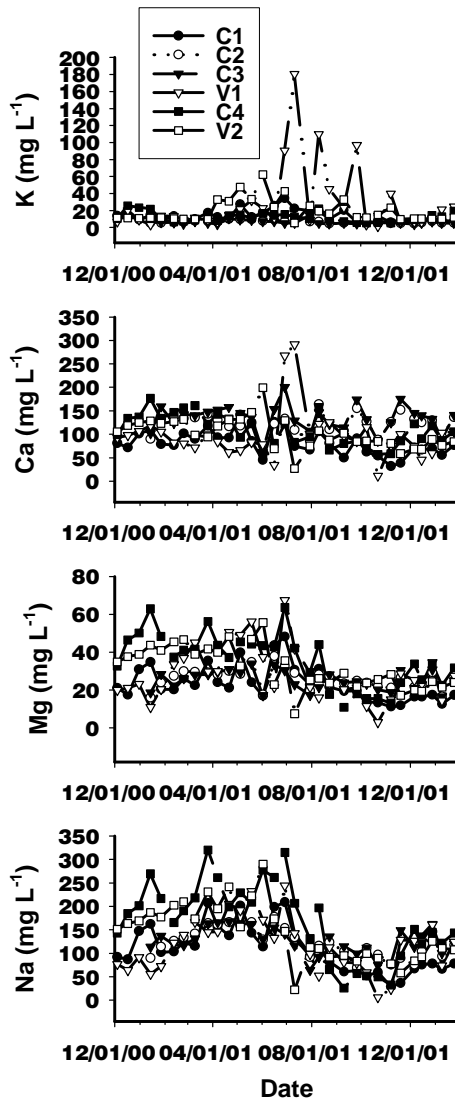


Fig. 6. Seasonal variations of Ca, Mg, K, and Na concentrations in the ditch water from the six field locations (C1: citrus grove 1; C2: citrus grove 2; C3: citrus grove 3; C4: citrus grove 4; V1: vegetable farm 1; V2: vegetable farm 2).

($P < 0.05$) between mean P (TP, DRP, and $\text{PO}_4\text{-P}$) concentrations in the ditch water and soil water-soluble P and Olsen P. The correlation coefficients (r) of the TP, DRP, and $\text{PO}_4\text{-P}$ in ditch water with soil test P were 0.98**, 0.98** and 0.97** for water-soluble P, and 0.88*, 0.91*, and 0.94** for Olsen P, respectively. Significant correlations were also found between annual P application rates and the mean TP, DRP and $\text{PO}_4\text{-P}$ concentrations

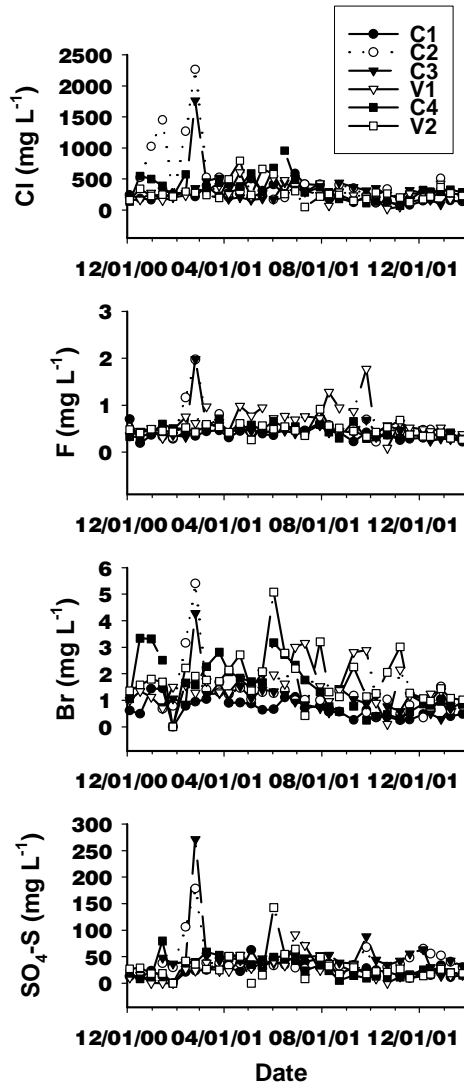


Fig. 7. Seasonal variations of F, Cl, Br, and SO₄-S concentrations in the ditch water from the six field locations (C1: citrus grove 1; C2: citrus grove 2; C3: citrus grove 3; C4: citrus grove 4; V1: vegetable farm 1; V2: vegetable farm 2).

in the ditch water with correlation coefficients of 0.88*, 0.91* and 0.92**, respectively. Mean NH₄-N concentrations in the ditch water were significantly correlated with soil available NH₄-N and annual N application rates ($r = 0.85^*$ and 0.92^{**} , respectively), whereas mean NO₃-N concentration in the ditch water was significantly correlated with soil available NO₃-N and annual N application ($r = 0.96^{**}$ and 0.83^* , respectively). Mean Cu concentration in the ditch water was significantly correlated with both soil water-soluble Cu and

DTPA-Cu ($r = 0.92^{**}$ and 0.91^* , respectively). Mean Zn concentrations in the ditch water were only significantly correlated with soil water-soluble Zn ($r = 0.98^{**}$). However, no significant correlations were found between mean concentrations of Cd, Co, Cr, Ni, Pb, Mo, Se, and As in the ditch water and water-soluble Cd, Co, Cr, Ni, Pb, Mo, Se, and As in the soils, probably due to limited water-soluble Cd, Co, Cr, Ni, Pb, Mo, and As in the soils. These results suggest that the differences in accumulation of nutrients and heavy metals in the soils were one of the reasons causing spatial variation of water quality in drainage ditches.

4. Conclusions

Water quality of drainage ditches within vegetable farms and citrus groves on Flatwoods soils in St. Lucie County, Florida varied widely among the sampling sites and times. The concentrations of $\text{NH}_4\text{-N}$, $\text{NO}_3\text{-N}$, and total P ranged from nondetectable level to 9.13, 283 and 4.86 mg l^{-1} , respectively. Concentrations of Cu and Zn ranged from nondetectable to 63.7 and 121.7 mg l^{-1} , respectively. Nitrogen, P and K concentrations were higher in the ditches on the vegetable farms than in the citrus groves. The concentrations of N, P, K, Cu, and Zn in ditch water were higher during the wet season than the dry season, indicating higher nutrient input through runoff from the adjacent fields during the wet season. Since water-soluble Co, Cr, Ni, Pb, Mo, and As in the soils were limited, Cd, Co, Cr, Ni, Pb, Mo, and As concentrations in the ditch water were generally low for all the six ditches with small seasonal variations. However, the EC, and concentrations of Na and Mg in the ditch water were slightly higher during the dry than the wet season. There were minimal seasonal variations in Ca, F, Br, Cl, and SO_4 concentrations for all the ditches, although there were considerable variations in the concentrations among the different sampling times. The concentrations of P, N and heavy metals in the ditches water were affected by soil nutrient and heavy metal accumulation in the adjacent fields.

Acknowledgements

This study was, in part, supported by a section 319 Nonpoint Source Management Program grant (DEP contract # WM746) from the US Environmental protection Agency (US EPA) through a contract with the Nonpoint Source Management/Water Quality Standard Section of the Florida Department of Environmental Protection (FDEP) and by a grant (DEP contract # G0018) from the FDEP. Florida Agricultural Experiment Station Journal Series No. R-08931.

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