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A comparison analysis of edge-of-field run-off from two sugarcane fields

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Agricultural run-off is an important source of nonpoint source pollution. Surface run-off driven by rainfall events was analyzed at two sugarcane fields (SC1 and SC2) in Louisiana, USA. The study site was within a watershed confined by the Mississippi River levee and a drainage canal (St. James Canal). In total, 14 representative rainfall run-off events were analyzed. For comparison with onsite monitoring, a modeling technique was used to estimate run-off. The results show that run-off/rainfall ratios at SC1 were significantly higher ($p < 0.0001$, $n = 14$) than at SC2, probably mainly due to a higher sand content of the soil and a higher infiltration rate at SC2 than at SC1. Model-calculated run-off showed substantial overestimation compared with the monitoring results, especially at SC2. Comparison analysis suggests that significant infiltration following precipitation is expected in sandy fields, and water discharge into the groundwater aquifer cannot be ignored. Without considering groundwater discharge in model algorism, the model calculation may significantly overestimate actual surface run-off.

Keywords: nonpoint source; groundwater table; CN method; run-off; water quality

Introduction

Nonpoint source (NPS) pollution has been recognized as a worldwide problem (Clean Water Act 1972; available at http://cnie.org/NLE/CRSreports/Briefing-Books/Laws/). Controlling NPS pollution is difficult because of its nondiscrete nature. Agriculture is a major type of NPS pollution, by which various pollutants (i.e. nutrients and pesticides) enter the aquatic ecosystem through surface run-off or groundwater discharge following precipitation or irrigation (Southwick et al. 1995; Sethi et al. 2005). Factors affecting run-off from agricultural fields can be divided into subfactors associated with precipitation and subfactors associated with the field. Precipitation subfactors include intensity, duration and area of distribution. Field subfactors include size and shape, topography, soil type and surface cover (Rogers 1972).

In the state of Louisiana (USA), ~ 69% and 58% of the river kilometers and lakes assessed, respectively, were impacted by NPS pollution (LDEQ 2002). The water-quality problems were mainly related to low dissolved oxygen (O_2) caused by organic enrichment, suspended solids, turbidity and nutrients. In addition, pesticides

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in surface water can have a deleterious effect on aquatic organisms or contaminate drinking water supplies. In St. James Parish of the upper Barataria Basin, Louisiana, a major source of pollutants impacting water quality is run-off from sugarcane (*Saccharum officinarum* L.) fields (Bengtson et al. 1998). A two-year watershed study has been conducted to address NPS pollution associated with sugarcane production and its impact on adjacent wetland and water bodies (Yu et al. 2008). The data generated can be incorporated into watershed plans, which will guide efforts to improve water quality within this region of the state.

Most sugarcane run-off is believed to enter drainage basins through a series of ditches and canals. However, a portion of the run-off may travel through the groundwater, affecting groundwater quality and contributing to surface water contamination as well (Birtles 1978). In this two-year study, major edge-of-field run-off driven by rainfall events was monitored using onsite instruments at two sugarcane fields (SC1 and SC2). For comparison with onsite monitoring, a model simulation of run-off was also conducted to calculate the run-off following the same rainfall events.

Material and methods

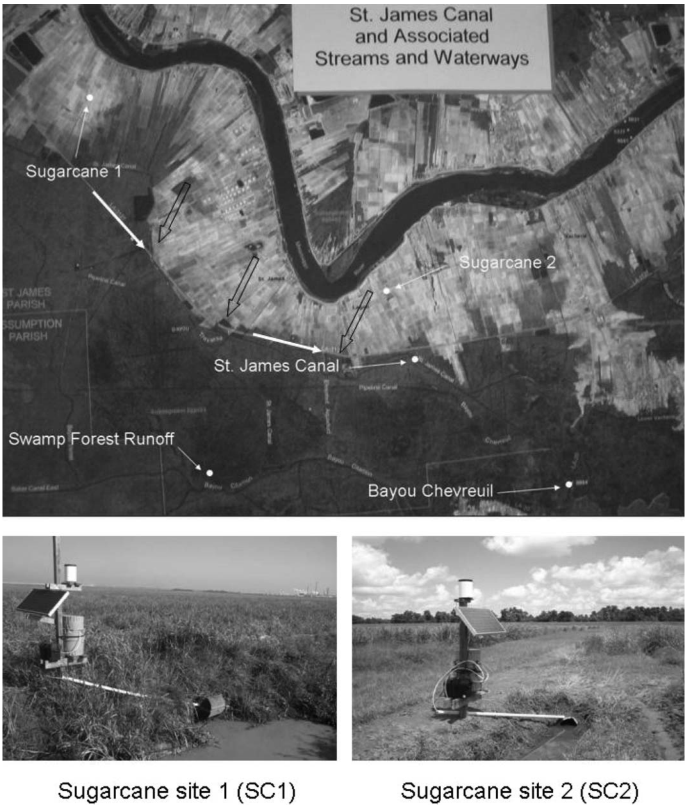
Study site

A map of the study area is shown in Figure 1, and general descriptions of the locations are summarized in Table 1. Surface run-off from sugarcane fields located on the elevated natural levee of the Mississippi River flows along the elevation gradient into adjacent wetland in the coastal drainage basin. Water is diverted through a series of drainage ditches and canals into St. James Canal (receiving run-off from an area of $\sim 6000\ \text{ha} = 6 \times 10^7\ \text{m}^2$), which discharges into Bayou Chevreuil connected to the Louisiana Gulf of Mexico Baratarian Basin estuary (US Environmental Protection Agency 1999).

The study was conducted in 2005 and 2006. Field management practices for the two sugarcane sites were similar and can be found in a previous publication (Yu et al. 2008). For SC1, the sugarcane stubble was second year in 2005 and third year in 2006. For SC2, the sugarcane stubble was third year in 2005 followed by fallow in 2006. Sugarcane residues were left on the field without burning after harvest at both sites. Soil (top 20 cm) in SC1 is classified as silt loam with sand, silt and clay contents of 18.3%, 56.7% and 25.0%, respectively. Soil (top 20 cm) in SC2 is classified as loam with sand, silt and clay contents of 47.5%, 45.0% and 7.5%, respectively (Yu et al. 2008).

On site monitoring of run-off

Two representative sugarcane fields (SC1 and SC2) were selected in this study. At each sugarcane field, an ISCO water sampler (ISCO Inc., Lincoln, NE, USA) was installed for run-off quantification at edge-of-field. The system was powered by a 12 V battery that could be charged by a solar panel. A culvert was installed in the drain and the equipment was mounted on top of the culvert. A flow meter was used in conjunction with this installation with an area velocity flow meter. At SC1, run-off from the drain discharged immediately into a major drainage ditch before reaching the St. James Canal. At SC2 and the adjacent sugarcane field, the run-off water discharged directly into the St. James Canal along the natural gradient of the Mississippi River levee (Figure 1). The two automated water samplers were



Sugarcane site 1 (SC1)

Sugarcane site 2 (SC2)

Figure 1. Map of the study area and two sugarcane run-off sampling locations. Open black arrows indicate the discharge direction of sugarcane run-off to the St. James Canal. Solid white arrows indicate flow directions in the St. James Canal.

Table 1. Sampling sites and selection criteria for each site.

Sampling site	Label	GPS coordinate	Description
Sugarcane field 1	SC1	N30.0503, W90.9129	Drainage area 60.7 × 10^3 m^2
Sugarcane field 2	SC2	N29.8855, W90.7980	Drainage area 40.5 × 10^3 m^2
St. James Canal	SJC	N29.9584, W90.7910	Immediate impact by run-off
Bayou Chevreuil	BC	N29.9117, W90.7300	Run-off impact on lower watershed
Swamp Forest Run-off	SFR	N29.9182, W90.7902	Background reference

Note: Each location was recorded by Global Positioning System (GPS) coordinates during site visit, and is labeled in the map (Figure 1). Soil in SC1 and SC2 is classified as silt loam and loam, respectively (Yu et al. 2008).

maintained by regular field visits at a frequency of two or three times per month to ensure their function over this two-year study period. The quantity of rainfall and run-off volume was obtained using a rain gauge and the flow meter integrated with each automatic water sampler. Hydrographs at the two sugarcane fields were developed to evaluate the relationship between rainfall and run-off volume, using

Flowlink 4.15 software (ISCO, copyright 1997–2002). Run-off was reported in mm and was calculated for each of the two sugarcane fields according to Equation (1):

$$\text{Run-off (mm)} = \frac{\text{Run-off volume (m}^3)}{\text{Drainage area (m}^2)} \times 1000 \tag{1}$$

Model calculation of run-off

Because onsite monitoring on a large scale with many locations is not feasible, most of times run-off in different watersheds are estimated using various modeling approaches (Arhonditsis et al. 2002; Pandey et al. 2008; Paudel et al. 2009). Characterizing the dynamic relationship between rainfall and run-off is a highly interesting modeling problem in hydrology. The curve number (CN) method (commonly called SCS CN method) was used in this study to estimate run-off from the two sugarcane fields. The primary purpose of this model estimation is to provide a reference for the onsite monitoring results at these two sugarcane fields. Validation of this modeling technique in this study area was not attempted. This method was developed by the United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS), and is widely used because of its high efficiency in determining the approximate amount of direct run-off from a rainfall event in a particular area. Run-off (mm) can be calculated according to the following empirical equation:

$$Q = \frac{(P - 0.2 \times S)^2}{(P + 0.8 \times S)} \tag{2}$$

Where, Q represents run-off in mm and P represents precipitation in mm. S is a term related to soil type and moisture condition, and can be calculated according to:

$$S = \frac{1000}{CN} - 10 \tag{3}$$

Where CN stands for curve number with a range from 30 to 100; lower numbers indicate low run-off potential, whereas larger numbers are for increasing run-off potential. According to CN values for different land covers with four hydrologic soil groups (SCS 1986; Table of Run-Off Curve Numbers, available at: http://www.emrl.byu.edu/gsda/data_tips/tip_landuse_cntable.html.), SC1 was identified as having a CN value of 81 (Group B), and SC2 had a CN of 72 (Group A) for 2005 and 77 for the fallow year of 2006.

Water stages at the St. James Canal and at the Mississippi River

We hypothesize that part of the precipitation may discharge into groundwater at the study area, so the groundwater level may be an important factor affecting surface run-off quantity. Because the groundwater table was not monitored in this study, water stages at the St. James Canal and the Mississippi River would be a good indicator. Real-time water stages at St. James Canal near Donaldsonville, LA (the closest location to the study site) were available from the United States Geological

Survey website with ID 073804751. The Mississippi River stages at Donaldsonville, LA were found at United States Army Corp of Engineers website with ID 01220.

Calculation and statistical analysis

Statistical analysis was conducted using SAS (V8 for Windows, SAS Institute Inc., Cary, NC, USA). Analysis of variance (AVOVA) using PROC GLM was conducted to determine the difference of means of various measurements. The significance level was chosen at 0.05 for all statistical analysis.

Results and discussion

Field run-off following rainfall event

During the two-year study, 14 representative rainfall-run-off events (six in 2005 and eight in 2006) were recorded at different seasons of the year, which accounted for approximately one-third of the annual precipitation. Average annual precipitation was 1114 ± 93 mm with no significant difference ($p = 0.99$) between the two sugarcane sites and between the two years. Rainfalls in small quantity generated little or no surface run-off, especially when soil conditions were dry. Among the 14 major rainfall events, there was no significant difference in precipitation quantity between the two sugarcane fields ($p = 0.76$), but run-off from SC1 was much larger ($p = 0.0003$) than from SC2 (Table 2).

Table 2. Comparison of field run-off between onsite monitoring and model calculation at major rainfall events.

	Rainfall (mm)		Run-off (mm) – onsite monitored		Run-off/ Rainfall – onsite monitored		Run-off (mm) – model calculated	
Date	SC1	SC2	SC1	SC2	SC1	SC2	SC1	SC2
17 March 2005	23.6	38.1	16.3	12.1	0.7	0.3	21.0	33.8
1 May 2005	21.8	41.4	15.5	7.6	0.7	0.2	19.2	37.1
31 May 2005	100.3	93.5	65.1	17.6	0.6	0.2	97.5	89.0
17 July 2005	13.5	14.5	8.2	1.6	0.6	0.1	11.0	10.7
31 August 2005	73.2	68.6	33.6	7.9	0.5	0.1	70.5	64.1
25 September 2005	113.5	176.3	18.8	20.6	0.2	0.1	110.7	171.7
Subtotal	345.9	432.4	157.5	67.4			343.1	427.8
24 Janusry 2006	30.2	39.6	19.7	6.7	0.7	0.2	27.6	35.3
26 February 2006	30.5	21.8	17.0	0.1	0.6	0.0	27.9	17.7
27 April 2006	64.3	54.1	13.5	0.0	0.2	0.0	61.6	49.7
7 July 2006	23.1	32.5	15.8	0.6	0.7	0.0	20.5	28.3
10 August 2006	73.2	75.0	19.5	6.0	0.3	0.1	70.5	70.5
13 September 2006	51.1	30.0	28.1	2.1	0.5	0.1	48.4	25.8
17 October 2006	17.3	17.0	6.3	5.7	0.4	0.3	14.8	13.1
8 November 2006	34.3	29.5	23.9	8.0	0.7	0.3	31.6	25.3
Subtotal	324.0	299.5	143.7	29.1			321.2	294.9

Note: On 31 August and 25 September 2005, site visits and data download were conducted immediately following Hurricanes Katrina and Rita, respectively. There was no precipitation between these two hurricanes.

The run-off/rainfall ratio (so-called effective run-off) at SC1 was 0.46 and 0.44 for 2005 and 2006, respectively, with no significant difference ($p = 0.65$). The run-off/rainfall ratio at SC2 was 0.16 and 0.10 for 2005 and 2006, respectively (Table 2). Without transpiration from sugarcane plants in the fallow year, the run-off/rainfall ratio at SC2 was surprisingly lower in 2006 than in 2005, however, statistically there was no significant difference ($p = 0.38$). For the same amount of rainfall, SC1 generated much more run-off than SC2 ($p < 0.0001$, $n = 14$). The major cause of such a difference was likely associated with a higher sand content in the soils at SC2 than at SC1 (Table 1). It is suggested that at SC2, a large portion of rainfall was probably infiltrated into the groundwater aquifer, instead of leaving the field as surface run-off.

Comparison of field run-off between onsite monitoring and model calculation

Model estimation of the run-off using the CN method gave much higher values than seen using the onsite instrumental monitoring. At SC1, monitored run-off was 48 and 47% of the model calculated run-off in 2005 and 2006, respectively. This percentage was found much lower at SC2, only 17% and 11% in 2005 and 2006, respectively (Table 2). Although application of the CN method does not seem valid for this study area, it provides a valuable reference for comparing the run-off quantities, driven by the same rainfall events, from the two sugarcane sites.

The results indicate some limitation of the CN method which considers only different land covers and hydrologic groups of soil. Without considering the infiltration of precipitation into groundwater, the model calculation can substantially overestimate the field run-off quantity, as shown in this study.

Potential impact of the groundwater table on field run-off

The study site represents a small watershed confined by two water systems, the St. James Canal and the Mississippi River. Water stages at the St. James Canal were impacted immediately by precipitation in this area (Figure 2). Water stages at the St. James Canal generally fluctuated between 1.5 and 2.0 m, occasionally reaching 2.5 m, depending on the amount of precipitation. It is likely that the St. James Canal

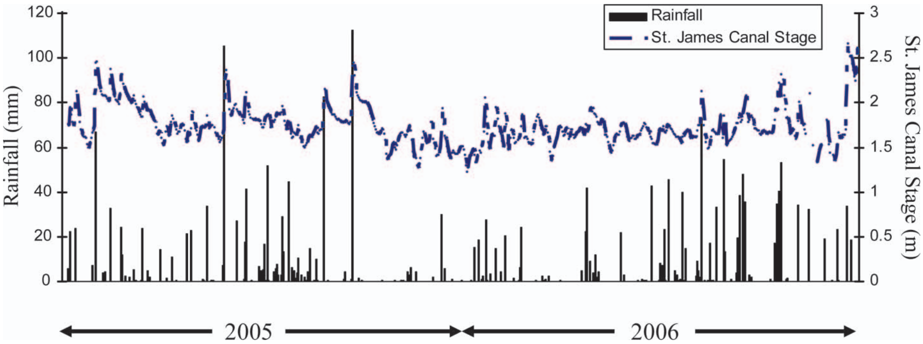


Figure 2. Variations in water stage in the St. James Canal and their response to rainfall events.

had little effect on changes in the groundwater table in this watershed, because of: (1) small variations in the water stages in the two year study period, and (2) elevation of the water stage actually due to the run-off driven by rainfall. This cause-and-effect relationship between run-off and the St. James Canal stages suggests a minor impact of the St. James Canal stage on run-off quantity from the studied sugarcane fields.

However, the model simulation analysis strongly suggests that a portion of the precipitation might discharge into the groundwater aquifer in order to interpret the water budget in this watershed. The Mississippi River stage showed a clear seasonal pattern, because it was determined by the water budget in the entire Mississippi River watershed with little contribution from the study area. The higher stages were generally found in the winter and spring and the lower stages in the summer and autumn (Figure 3). Because groundwater table measurements were not conducted in this study, it was not clear how much this river stage affected the groundwater table in the study area. However, it is reasonable to assume that the groundwater table would be higher when the Mississippi River stage was higher, and vice versa. In 2005, the ratio of monitored run-off to rainfall and the Mississippi River stage showed a strong positive correlation with R^2 values of 0.524 and 0.875 for SC1 and SC2, respectively (Figure 3). However, this correlation was not seen in 2006 ($R^2 = 0.001$ for SC1, and $R^2 = 0.022$ for SC2). The Mississippi River stage could be a potential factor responsible for the lower run-off/rainfall ratio found at SC2 in 2006 than in 2005 (Table 2). Annual Mississippi River stage was 30% lower in 2006 than in 2005, and most of the lower river stages occurred in the first half of 2006. Consequently, it is likely that less rainfall water discharged as surface run-off because of the lower groundwater table, especially at the sandy SC2 location immediately adjacent to the Mississippi River levee.

The potential impact of the Mississippi River stages on the groundwater table at the study sites could be seen during regular site visits. Occasionally, even if there had been no recent precipitation, standing water could be observed in the drain at SC2, and the water table in the ditch at SC1 was unusually high, indicating groundwater seepage to the surface (Birtles 1978). Instrumental monitoring reported several back flows (water flow toward the Mississippi River, instead of toward the St. James Canal) in the drain at SC2 (Figure 1). However, such back flows would not initiate

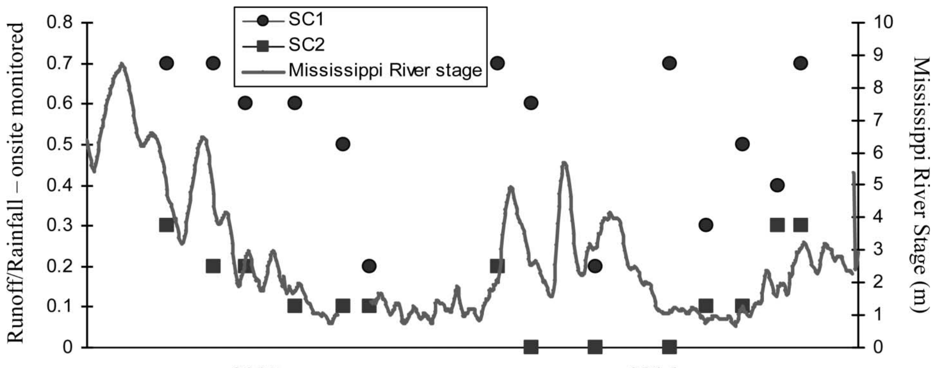


Figure 3. The ratios of run-off to rainfall from the two sugarcane fields and their relationship with the Mississippi River stage.

the auto-sampler to take a water sample from the drain at SC2. Back flows were not found at SC1 because the drain (where the monitoring instrument was installed) was ~1.5 m above the ditch bottom (Figure 1).

The sampling events summarized in Table 2 were all rainfall driven. Because of similar field management practices at both sugarcane fields, the run-off water samples showed no significant difference in the concentrations of various nutrients (nitrate + nitrite, total ammonium, TKN, dissolved phosphorus and total phosphorus with *p*-values ranging between 0.1 and 0.84) and two pesticides (atrazine and metribuzin with *p*-values of 0.30 and 0.22, respectively). More information on the nutrients and pesticides from this study can be found in a previous publication (Yu et al. 2008). However, the lower groundwater table may substantially reduce the run-off volume, especially at SC2 with a higher infiltration rate due to the higher sand content in the soil (Table 1). On the other hand, the higher groundwater table might cause an unexpected rise in the water table in the ditch (at SC1) and the drain (at SC2), and might even cause back flow (at SC2) (Dunne et al. 1975; Blowes and Gillham 1988). Because the auto-sampler was designed to initiate water sampling activity when run-off flow (positive flow) exceeded a threshold level, there was little opportunity for the sample run-off water to mix with the groundwater on the surface. If they did mix, the nutrients and pesticides would be diluted and their concentrations would be lower than normal, assuming that the groundwater had lower contents of these pollutants.

Conclusion

Analysis of the run-off results from the two sugarcane fields suggests that there are some limitations to application of the widely used CN method for run-off calculation from a watershed, as also found by other studies (Lewis et al. 2000; Mishra and Singh 2004). For sandy soil, significant infiltration following precipitation is expected, and water discharge into the groundwater aquifer cannot be ignored. In this case, the model calculation may substantially overestimate the actual quantity of surface run-off. If a study site is adjacent to a major water system that can directly affect the groundwater table, surface run-off quantity may vary with the water stage. Consequently, a large amount of rainfall may discharge into the groundwater aquifer to affect groundwater quality. Under these conditions, groundwater table measurement is suggested and the information should be included in the modeling attempt.

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