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An Automated System for monitoring the Quality and Quantity of Subsurface Drain Flow

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An automated flow data collection system was installed in a subsurface drainage system to determine discharge volumes and drainage flow rates. An experimental site was established by installing a subsurface drainage system on 36 plots, each of 0·4 ha, to measure subsurface drain flows and collect drain water samples for water quality analysis. Subsurface drains from individual plots were intercepted at the end of plots and routed to individual sumps to collect drain water. Flowmeters connected to individual sump pumps measured the volume of water pumped from these sumps. Electronic outputs of the flowmeters were recorded with data loggers, and readings of the analog registers were recorded manually. The data loggers recorded the time when each sump pump started and stopped pumping water. Data collected by data loggers were used to calculate drain discharge volumes and drain flow rates. This monitoring system was evaluated by comparing the drain volume rates between flowmeter readings and the data collected by data loggers for some rain events.

Subsurface drain flow measured by the data logger system was not significantly different from the manual readings taken by the flowmeters. The data logger system was an effective method for measuring changes in subsurface drain flow rates over short time periods and drain flow response to individual rainfall events. This automated system was also used to monitor the movement of nitrate–nitrogen (NO_3–N) to subsurface drain water.

1. Introduction

Contamination of groundwater by nitrate and pesticides has been documented by several state and federal agencies in the United States.[1] Groundwater pollution is of increasing concern because about 50% of the drinking water comes from groundwater. With the increasing concern on water quality, it is important to determine the effects of current agricultural production systems on the quality of water drained from agricultural watersheds. Many of the agricultural watersheds in the Midwest are artificially drained to remove excess water from the soil profile for proper crop growth. It is also important to understand the mechanisms of water and chemical movement through the soil profile in these artificially drained areas. The water drained from artificially drained areas is now considered a source of pollution as it contains agricultural chemicals (which may have adverse effects on human and animal health).

Subsurface drainage water quality monitoring is useful for assessing the loss of agricultural chemicals to shallow groundwater because it gives more representative chemical leaching information from a larger area than point sampling methods. Subsurface drains integrate the effects of both preferential and matrix flow within the groundwater system. Everts and Kanwar[2] have presented a method to calculate preferential and matrix flows from the tile flow data. Several studies have been conducted to monitor subsurface drainage water quality in the Midwest and the USA.[3–10]

2. System design

2.1. *Rationale*

Typically, four types of subsurface drain flow measurement systems have been used for water quality studies: (1) weirs or flumes with stage recorders, (2) sump pumps with flowmeters, (3) tipping buckets, and (4) ultrasonic flow measurement instruments. Weirs and flumes collect continuous subsurface drain flow data[11,12] for water quality purposes but takes long time to read flow charts and make calculations for flow discharges. Both tipping buckets and sump pumps collect data at discrete flow intervals but provide the convenience of collecting continous data using the data loggers. A certain volume of water is required to tip the bucket or activate a pump. The precision of these systems is determined by the size of the bucket or sump. The ultrasonic flow measurement system has been used for drain flow measurements but requires precise maintenance. One advantage of a sump pump system, however, is that water does not have to flow by gravity from the plots to an outlet as for weirs, flumes or tipping buckets. The sump pump system requires little maintenance, has worked well most of the time and is not a very expensive system to install. Because of its simple design and economic consideration, a state-of-the-art system was designed and installed to measure subsurface drain flow with sump pumps, flowmeters and data loggers. The sump pump system with an orifice outlet allowed continuous and composite water samples to be collected for water quality analysis. Therefore, the overall objective of this paper is to describe the design and installation procedures for this subsurface drain monitoring system and present some data on water quality and quantity collected by this system.

2.2. *Drain sump and pump design*

The meter sumps were 0·4 m diameter PVC air duct tubing with sealed bases. Inside each meter sump was a flow metering assembly which included a 110 V powered sump pump, check valve, flowmeter and quick release coupler (*Fig. 1*). A 38 mm diameter PVC pipe connected the sump pump to a spring-type check valve and the check valve to a positive displacement water meter. Water pumped from the meter sump flowed through a flowmeter and then to a collection sump, which was a 0·6 m diameter corrugated black plastic culvert. An overflow pipe with a check valve allowed water to flow to the collection sump if the sump pump malfunctioned. Water-tight seals were used on all lower connections to the meter sumps to ensure a good seal against groundwater seeping into the sumps. Water in collection sumps was discharged by gravity to the outlet tile line (*Fig. 1*).

Approximately 40 l of water was pumped from a given sump during a pump cycle. The use of a sump pump system relies on a switching arrangement of the pump. The switch on and off timings determine the water levels in the sump and determine the amount of volume pumped from the sump in each cycle. This pumping cycle can be explained by the following equation:

$$a = \frac{1}{b} + \frac{1}{1-b} \quad \text{where } a = \frac{T_c Q_{out}}{V}, \quad \text{and} \quad b = \frac{Q_{in}}{Q_{out}}$$

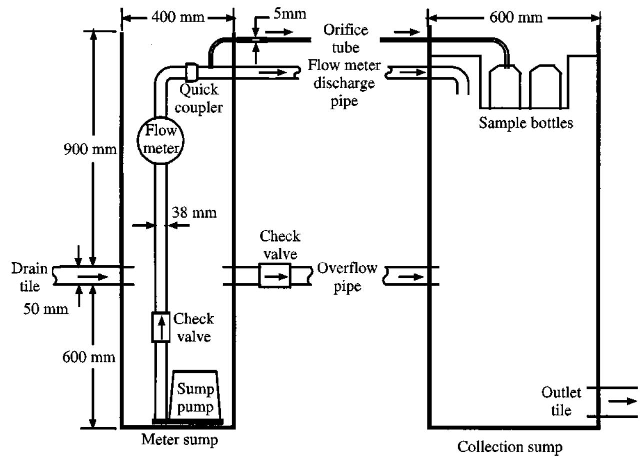

Fig. 1. Schematic diagram of meter sump and collection sump

where T_c is the pump cycle time, Q_{out} is the pumping rate, Q_{in} is the drain flow rate and V is the total pumped drain water volume between switch on and off timings. Therefore, the value for T_c varies depending on the drain flow rate. This technique provides average flow data over cycle times that vary depending upon subsurface flow rates.

2.3. *Data logging system*

Neptune T-10 flowmeters were used which have nutating disc measuring chambers which measure volume by the positive displacement principle. Analogue registers and Tricon/E transmitters were mounted on the meters. The analogue register recorded flow to 0·001 m^3. The electronic transmitters output both current and pulses. The current output varied from 4 at no flow to 20 mA at maximum flow. The pulse output monitored volume by sending a pulse every time approximately 25 ml of water flowed through the meter.

Three Campbell Scientific CR10 data loggers were used to monitor output from the transmitters. Since each CR10 has only two channels for recording pulses, the transmitter output voltage was recorded instead by the data loggers to determine when each sump pump was operating. By recording the time when sump pumps start and stop pumping, the duration of the pump cycle and the volume of water discharged can be determined. Each data logger could monitor 12 transmitters only. As a result of meter sump locations, a multiplexer was added to one data logger to monitor the 14 transmitters in that area. The two other data loggers recorded data from 11 transmitters each. A tipping bucket rain gauge was also connected to one of the data loggers for measuring rainfall depth and intensity at the site. The electronic transmitters required a 24 V DC supply voltage and output approximately 19 V DC. Since the maximum voltage a CR10 data logger can measure is only 2·5 V DC, the output voltage was reduced to approximately 0·4 V by placing a 100 Ω resistor between the signal and ground wires on each transmitter.

2.4. *Calibration of sump pump*

The flow metering assembly was removed from each sump during the winter months and was brought to the heated area in the workshop. All flowmeters were calibrated each spring before installation again for the next season. Internal flowmeter components were replaced if the measured volume of the calibrated meter varied by more than 5% in comparison to the new meter.

For sump pump calibration, the pumping rate for each sump pump was assumed to be constant. Pumping rates were calculated using manually collected flowmeter data from the analogue register and automatically measured time data from the data logger. The drain flow volume was divided by the total time the sump pump ran during the interval between manual flowmeter readings. Pumping rates were calculated for each interval when manual flowmeter readings were recorded, usually three times per week. Table 1 shows the pumping rate calculations for one experimental plot.

Table 1
Pumping rate calibration for the plot 10 sump pump for selected rain storms in 1993

Date	*Flow volume*, l*	*Time†, h*	*Pumping rate, l/s*
11 June	11 439	3·0	1·06
18 June	4984	1·3	1·05
23 June	7203	1·9	1·05
25 June	5191	1·4	1·04
28 June	5173	1·4	1·04
30 June	4527	1·2	1·10
02 July	7358	2·0	1·01
06 July	7804	2·1	1·03
07 July	1150	0·3	1·04
14 July	22 090	6·1	1·01
16 July	15 293	4·3	0·99
21 July	12 850	3·4	1·04
23 July	7616	2·0	1·04
26 July	6616	1·8	1·03
28 July	3551	1·0	1·02
30 July	2647	0·7	1·04

* From manual flowmeter readings. † Measured by data logger.

2.5. *Water sampling*

Continuous water samples for nitrate and pesticide analysis were collected using an orifice tube located on the discharge pipe (*Fig. 1*). Approximately 0·2% of the water pumped from the sump pump flowed through a 5 mm diameter polyethylene tube to a water sampling bottle located in the collection sump. Flow to the sampling bottles was regulated by No. 35, stainless-steel orifice plates which are used commercially as flow regulators in spraying systems. Once sampling bottles were filled, they were replaced with empty bottles manually and filled bottles were sent to the laboratory for chemical analysis.

3. System evaluation

3.1. *Experimental site*

The field site was established on 36 plots, each of 0·4 ha, having four tillage and two crop rotation systems, at Iowa State University's Northeast Research Center near Nashua, IA. Subsurface drainage system at this site consisted of 100 mm diameter corrugated plastic subsurface drains installed approximately 1·2 m deep at 28·5 m spacings in all 36 plots (*Fig. 2*). Subsurface drains were installed in the centres of plots and on the borders between plots. Subsurface drains installed in the centre of the plots were intercepted for drain flow measurements and water quality sampling. The drains along the plot borders were not disturbed and acted as a boundary on the northern and southern sides of the plots. The plots were isolated on the eastern and western sides with berms. The centre drain lines were routed to individual meter sumps at one of ten collection sites. The collection sites were located such that tile water flows by gravity from the plot drains to the meter sumps. Each collection site had two to six meter sumps (*Fig. 2*). For example, *Fig. 2* shows that collection site 1 has two meter sumps, site 2 has three, whereas site 3 has six meter sumps. Each intercepted subsurface drain was connected to a 50 mm diameter PVC drain pipe by a rubber coupling with stainless-steel clamps. A 76 mm, schedule-40 PVC coupling was inserted into the drain to prevent it from collapsing when the clamps were tightened.

3.2. *Flowmeters and drain flow measurements*

Subsurface drain flow volume was measured directly by manually reading the analogue registers and indirectly by measuring the time during which each sump pump ran. The analogue register on each flowmeter was recorded three times per week. Data loggers measured the

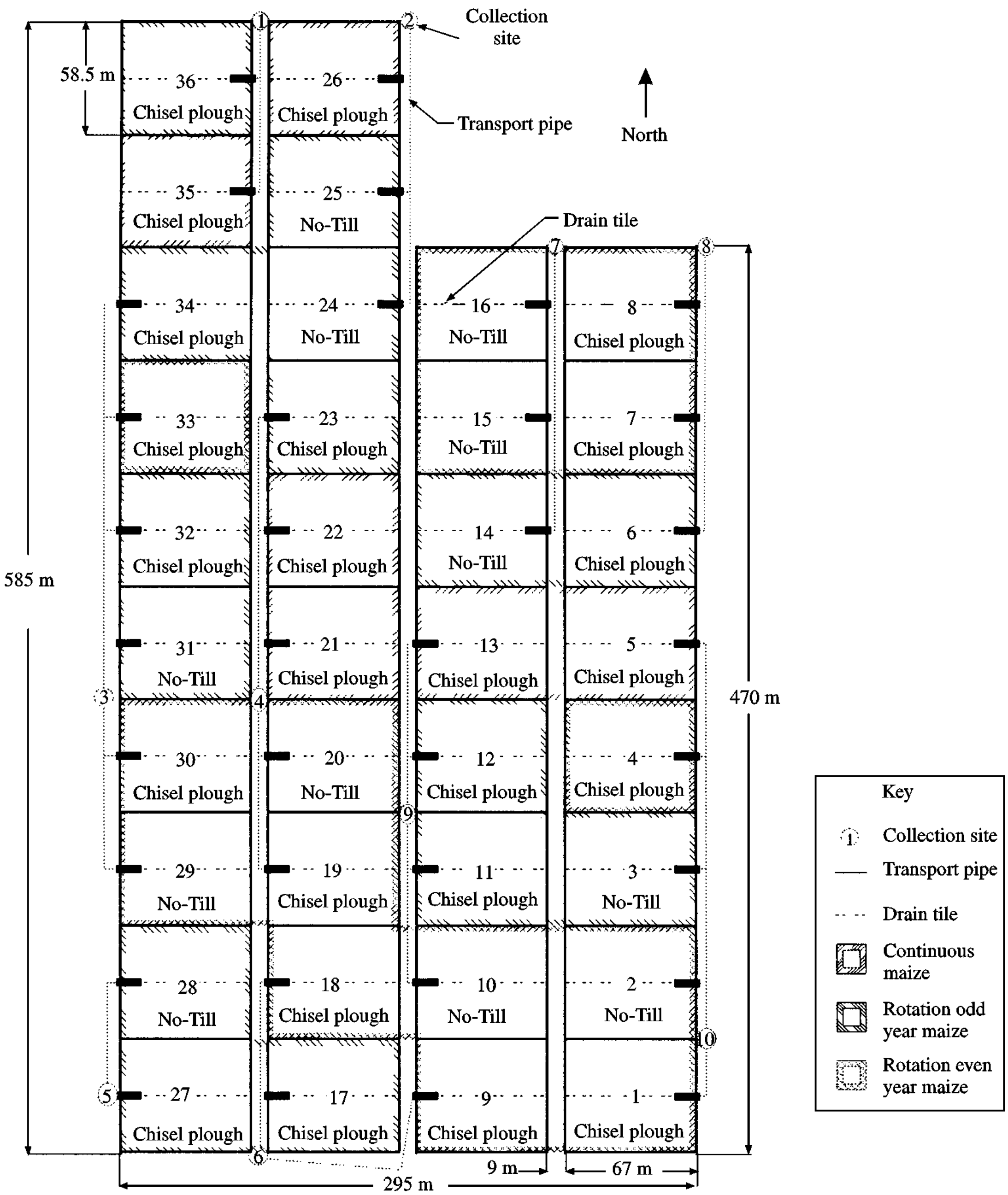

Fig. 2. Plot layout at the Nashua water quality site

output voltage from each transmitter at one second scan intervals. The output voltage for both the present time interval and previous interval were stored in the CR10 and compared to determine if the sump pump was on or off. The sump pump was running if the output voltage increased between scan intervals. Similarly, the pump had stopped running when the output voltage decreased between scan intervals. Output voltage from the transmitters increased approximately 2·5 times when the sump pump was running. The volume of water discharged during a pump cycle was calculated by multiplying the duration of the pump cycle by the pumping rate for the sump pump.

The volume of water discharged during pump cycles was not always constant. Pump cycles were approximately 30 s long at low drain flow rates but increased to 45 s or more at higher flow rates. Periodically, drain flow rates approach the pumping rate. The volume of water discharged by a sump pump during a pump cycle was usually about 40 l but increased to over 100 l at high drain flow rates. The volume of water discharged during a pump cycle equalled the volume of water that flowed from the drain since the previous pump cycle.

Subsurface drain flow data from the data loggers were downloaded via a modem to a personal computer. The raw data file from the data loggers contained one data line for each time a sump started pumping and one line for when it stopped pumping. Campbell Scientific software was used to separate data for each plot from the raw data file for a particular time period (e.g. one month). A Basic computer program was then used to calculate the duration of each pump cycle, volume discharged during a pump cycle, and the average drain discharge rate for the time between two consecutive pump cycles. The drain flow rate was calculated by dividing the volume of water pumped during the pump cycle by the time since the previous pump cycle. The output file was imported into a spreadsheet for the preparation of graphs and evaluating data.

4. Results

Overall, the sump pump and flowmeter system has worked well for measuring subsurface drain flows and collecting continuous water samples for water quality analysis. One exception has been the spring-type check valves. Several of the check valves in the discharge pipes did not seal because sand or other small objects lodged in the valves. Maintenance on sump pumps has been minimal after the metal base plates were replaced with plastic.

Subsurface drain flow data from June and July, 1993 were used to calculate pumping rates for each sump pump. The system was evaluated during August 1993 by comparing drain flows measured automatically by data loggers with the flow data from manually analogue readouts of the flowmeters. Data from one plot, plot 10, is included as a working example in this paper. This plot was under no-till, corn–soybean rotation with soybeans planted in 1993 (*Fig. 2*).

4.1. *Subsurface drain flow measurements*

August 1993 was a good month for evaluating the automatic monitoring system because a period of very low drain flow was followed by two, high flow drainage events (*Fig.* 3) immediately after heavy rains. In fact, the largest rain of the season of 56 mm occurred on 23 August (day 235).

The data loggers measured drain flow rate more precisely than the manual readings of flowmeters taken three times per week. *Figure 3* shows the manual readings did not detect the peak flow rates or the rapid changes in subsurface drain flow rates that occurred during August. Data loggers output the date and time for approximately every 40 l of tile discharge or 0·02 mm of drainage from a plot. Subsurface drain flow between manual readings varied from 40 to 24 800 l for plot 10.

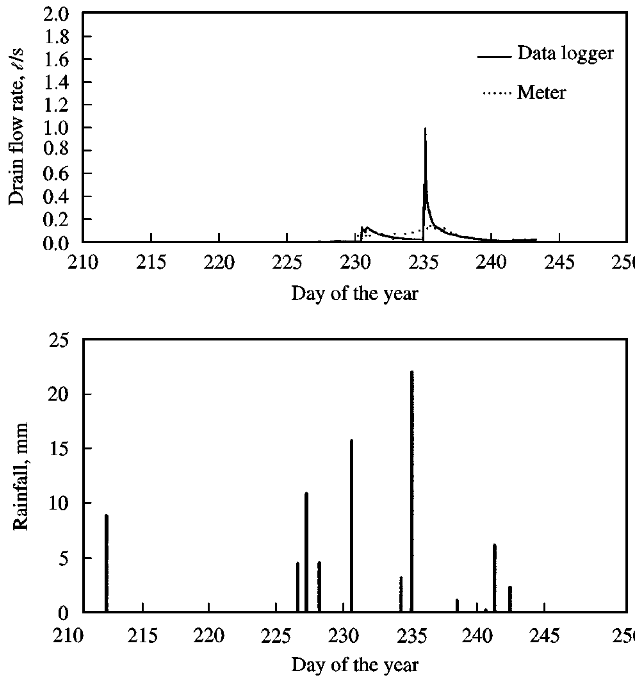

Fig. 3. Subsurface drain flow rate and rainfall for plot 10 for August, 1993

Although drain flow rates calculated with data logger information were more dynamic than the rates calculated from manual readings, the discharge volumes were not significantly different. In Table 2, the results are presented for the cumulative drainage as an equivalent depth for plot 10 during August. The difference between the two measurement methods was less than 0·73 mm, or 1·8%, for all time intervals and the total difference in drainage volume at the end of the month was 0·07 mm. The differences between the two methods appear to be random and do not increase with time. Measurement differences also do not appear to vary directly with drain flow rate. These results confirm that the automatic data collection system properly read the flow meter.

Figure 4(a) gives the daily measured values of subsurface drain flow as a function of two tillage systems (no-till and chisel plough), and *Fig. 5(a)* gives similar values for other two tillage systems (ridge till and mouldboard plough) under continuous maize production for 1990. This figure is included in this paper to illustrate the usefulness of this automated monitoring system to produce semi-continuous hydrographs of the subsurface

Table 2
Cumulative subsurface drain flow measured by a flowmeter and a data logger for plot 10 for selected rain storms in 1993

	Drainage as equivalent depth, mm		
Date	*Flowmeter*	*Data logger*	*Difference %*
02 August	1·9	1·9	− 0·1
04 August	2·8	2·8	0·2
06 August	3·3	3·3	0·2
09 August	3·6	3·6	0·3
11 August	3·7	3·7	0·9
13 August	3·7	3·7	0·6
16 August	4·3	4·4	1·0
18 August	5·8	5·9	1·1
20 August	13·8	13·9	0·6
23 August	26·6	26·2	− 1·3
25 August	37·7	37·9	0·4
27 August	42·2	42·3	0·2
30 August	45·9	46·0	0·1

drain flows as a function of the agricultural activity in the watershed such as the effects of tillage and crop rotations.

4.2. *Subsurface drainage water quality measurements*

Figures 4(b) and 5(b) give the average NO_3–N concentrations in the subsurface drain water as a function of various tillage systems for continuous-maize production for 1990. These figures also show that the effects of various tillage systems can be observed on the NO_3–N concentrations in subsurface drain water (shallow groundwater). For example, chisel plough and mouldboard plough systems resulted in significantly higher NO_3–N concentrations in drain water compared to no-till and ridge till systems, respectively (*Figs 4(b) and 5(b)*). These effects on water quality are monitored very well by this automated monitoring system.

5. Discussion

Data collected automatically by the system are useful for monitoring flow parameters such as peak drain flow rate, drainage volume, time to peak flow rate, and water quality indicators for individual rainfall events (*Figs 3–5*). Response to individual rainfall events could not be detected very well when flowmeters were read only three times per week in the earlier study.

Automatic samplers can be connected to the system for collecting discrete water samples in addition to the continuous samples collected through the orifice tube. Additional monitoring equipment can also be connected to the data loggers to measure information such as soil temperature or soil moisture.

One drawback of the system is the buried wires. Corrosion and breaks have occurred in several wires since installation. When planning a new system, serious consideration should be given to minimizing the distance between monitoring equipment and data loggers. Troubleshooting and maintenance are much easier if monitoring equipment is located near the data loggers.

6. Conclusions

The results of this study indicate that subsurface drain flow data collected with the data logger system were within 2% of the data collected manually using the analogue readout on the flowmeters. The data logger system provides an opportunity to collect essentially continuous data on subsurface drain flows. It is capable of measuring large drain flow rate increases in short time periods that could not be detected with manual flowmeter readings. Response to individual rainfall events can also be detected by the system. This system allows

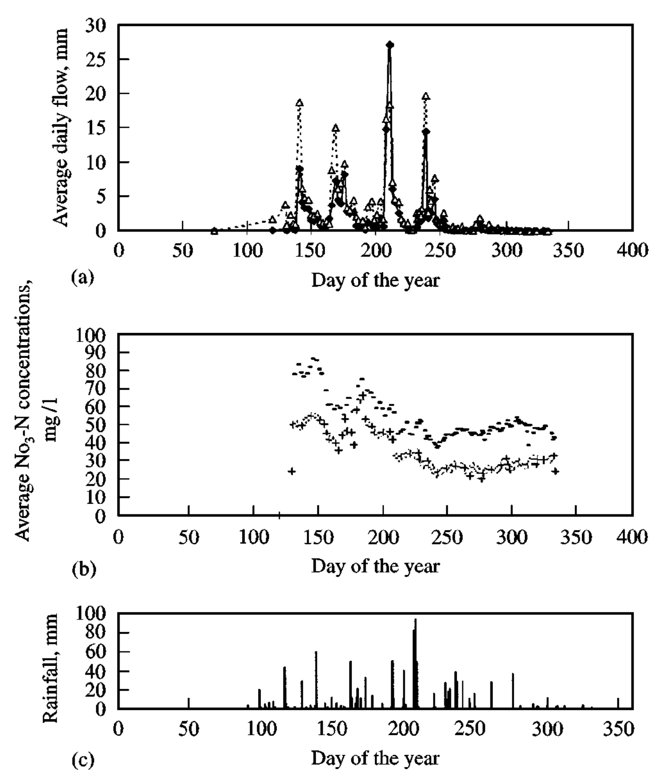

Fig. 4. (a) Daily measured values of subsurface drain flow as a function of two tillage systems (no till and chisel plough) for 1990: ——◆——, chisel plough; ----△----, no till; (b) Average NO_3-N concentrations in subsurface drain water: —, chisel plough; +, no till; (c) daily rainfall

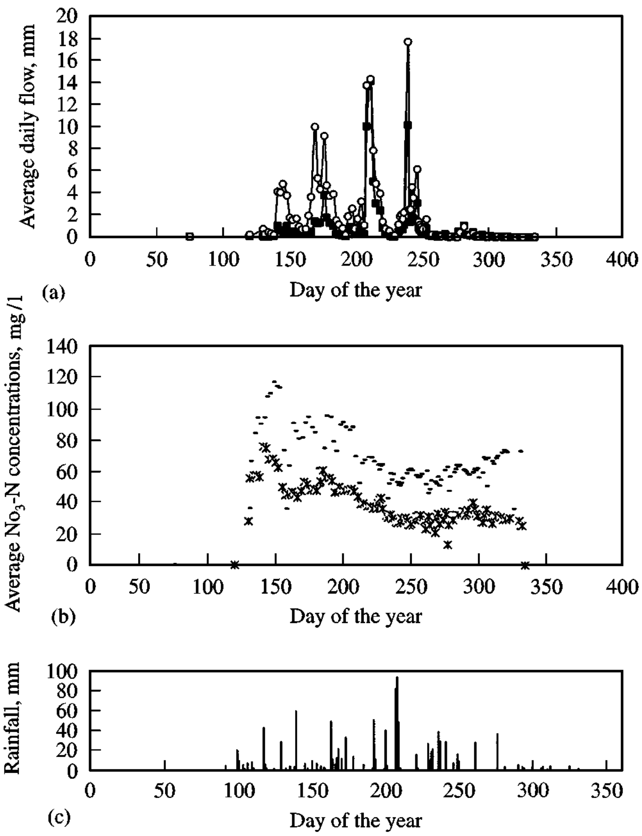

Fig. 5. (a) Daily measured values of subsurface drain flow as a function of two tillage systems (ridge till plough and mouldboard plough) for 1990: —■—, mouldboard plough; —O—, ridge till plough; (b) Average NO_3–N concentrations in subsurface drain water: —, mouldboard plough; +, ridge till plough; (c) daily rainfall

data evaluation on an hourly or daily basis. Also, we can monitor data from the office rather than driving to the field site. The orifice tube connected to the outlet pipe provides composite samples on water quality automatically without missing any sample of water.

Even though measuring pumping time is an accurate method for collecting data from flowmeters on sump pumps, broken wires and corroded connections have caused some problems. Data loggers should be located as close as reasonably possible to monitoring equipment. Furthermore, data should be downloaded automatically at set intervals to minimize chances of losing data.

The sump pump and flowmeter system has operated very well except for minor problems with check valves. Annual maintenance should include cleaning check valves and calibrating flowmeters.

Even though the electronic transmitters functioned properly, less expensive methods should be considered for measuring when sump pumps are running. Relays or pressure switches could be used in place of electronic transmitters to detect when sump pumps start and stop pumping.

Acknowledgements

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