ELSEVIER Computers and Electronics in Agriculture 12 (1995) 131–145

Computers
and electronics
in agriculture

An instrumented, field-scale research facility for drainage and water quality studies

R. Tait, C.A. Madramootoo *, P. Enright

Agricultural Engineering Department, Faculty of Agricultural and Environmental Sciences, McGill University, Macdonald Campus, 21111 Lakeshore Road, Sainte Anne-de-Bellevue, QC H9X 3V9, Canada

Accepted 21 October 1994

Abstract

A large-scale, fully instrumented field research facility covering 4.2 ha was established in southern Québec, Canada to assess the impacts of controlled drainage/subirrigation, cropping systems, and fertilizer practices on water quality. Eight treatments are replicated three times in a randomized complete block design. A subsurface drain lateral is located in the centre of each plot; a plastic barrier surrounds each plot to isolate flows from adjacent plots. Subplots with surface inlets are located in one block for measuring surface runoff. Flows, from subsurface drains and surface runoff plots, are continually measured, and water quality samples are acquired year-around in two heated instrument buildings. A data acquisition (DAQ) and control system monitors sensors, collects data, and automatically actuates the sampling system. Performance of the facility during the first year of operation has been very close to theoretical predictions. Results from studies undertaken at the facility will be used to test computer simulation models and develop best management practices for reducing pollution in both drainage effluent and surface runoff.

Keywords: Drainage; Subirrigation; Water quality; Computer systems

---

1. Introduction

Grain, cereal, and forage crops are grown extensively in the Lower Great Lakes/ St. Lawrence River regions, of the northeastern U.S. and Canada. There are also extensive dairy, livestock, and poultry operations in the area. The predominant soil types on which these activities take place are clays, clay loams, and shallow

---

* Corresponding author.

SSDI 0168-1699(94)00043-3

sandy soils over a clay subsoil. Many of these soils are characterized by poor internal drainage. Subsurface drainage, to remove excess soil water, has been installed on over 2,000,000 ha of cropland in the provinces of Ontario and Québec. Artificial drainage, using buried plastic pipe, is essential for crop production given that the growing season is relatively short, and annual precipitation exceeds potential evapotranspiration by about 400 mm. Typical benefits of subsurface drainage include: improved aeration of the root zone, improved field machine trafficability, better nutrient uptake, and higher crop yields.

Monoculture grain corn is predominant in these regions, with high inputs of nitrogen fertilizer and pesticides required. A further nitrogen input to the soil is the land application of manures. There are concerns that nitrates and pesticides are easily leached to subsurface drains, and that harmful levels may be encountered in ground water wells and in streams, lakes, etc. Research in eastern Canada has found NO_3^--N concentrations as high as 40 mg l^{-1} in drainage water (Milburn and MacLeod, 1991; Madramootoo et al., 1992). This has led to an emphasis on developing integrated cropping and water management systems which reduce nitrate contamination.

The use of controlled drainage, as compared to conventional drainage, has been shown to reduce NO_3^--N losses 46.5% in field runoff (Evans et al., 1989) and to reduce its accumulation as much as 52% below the root zone in soil (Madramootoo et al., 1993). Controlled drainage and water table management reduce nitrate losses through three principal mechanisms: (i) nitrates are retained in the soil matrix for future plant uptake; (ii) higher soil moisture may slow the nitrification process; (iii) denitrification may be enhanced, due to higher dissolved organic carbon (Steenvoorden, 1989), and occur before nitrates leach to the ground water.

Research is currently underway in various locations in North America, to better understand the hydrologic, chemical, physical and biological processes which will lead to reduced NO_3^--N and chemical transport to the subsurface drains. A better understanding of these processes will enable the development of pollution abatement and management strategies. Studies are currently being conducted in Iowa (Kanwar et al., 1990), Prince Edward Island (Milburn and MacLeod, 1991), Michigan (Belcher and Merva, 1991), Ohio (Fausey et al., 1991), North Carolina (Skaggs et al., 1991), Louisiana (Willis et al., 1991), and Ontario (Soultani et al., 1993) to address these questions.

Since soil, crop, and climatic conditions are different in southwestern Québec than these locations, an on-going research project was initiated in Québec to examine the integrated effects of different cropping systems, water table management, and fertilizer rates on water and nitrate movement to subsurface drains. This paper describes the research facility and instrumentation installed at the site.

2. Site description and experimental lay-out

The 4.2 ha experimental site is located in Soulanges County, Québec, approximately 25 km southeast of the Macdonald Campus of McGill University. Surface slope of the field is about 0.5% and the soil type a Soulanges very fine sandy loam.

Table 1
Crop, fertilizer and drainage treatments at the experimental site

Treatment number	N Fertilization (kg ha^{-1})	Cropping system		Water table depth from soil surface (m)
		Crop	Intercrop	
1	none	grain corn	–	1.0 [a]
2	180	grain corn	–	1.0 [a]
3	270	grain corn	–	1.0 [a]
4	270	grain corn	ryegrass	1.0 [a]
5	270	grain corn	–	0.5
6	270	grain corn	ryegrass	0.5
7	270	grain corn	–	0.75
8	270	grain corn	ryegrass	0.75

[a] Conventional drainage.

This soil series is typically about 0.5 m in depth, underlain by a clay loam layer, itself underlain by clay parent material. Saturated hydraulic conductivity, as determined by the auger hole method, ranges from 0.1 to 1.1 m day^{-1}. Average bulk densities were determined to be 1.63, 1.60, and 1.49 Mg/m^3 for depths of 0–0.2, 0.2–0.4, and 0.4–0.6 m, respectively.

Eight treatments are being investigated (Table 1, Fig. 1). Each treatment is replicated thrice in a randomized complete block design, and assigned to a plot 75 m long and 15 m wide, with a 76-mm subsurface drain lateral, centrally located along the length. Maximum drain depth is 1.0 m, with the pipes laid on a 0.3%

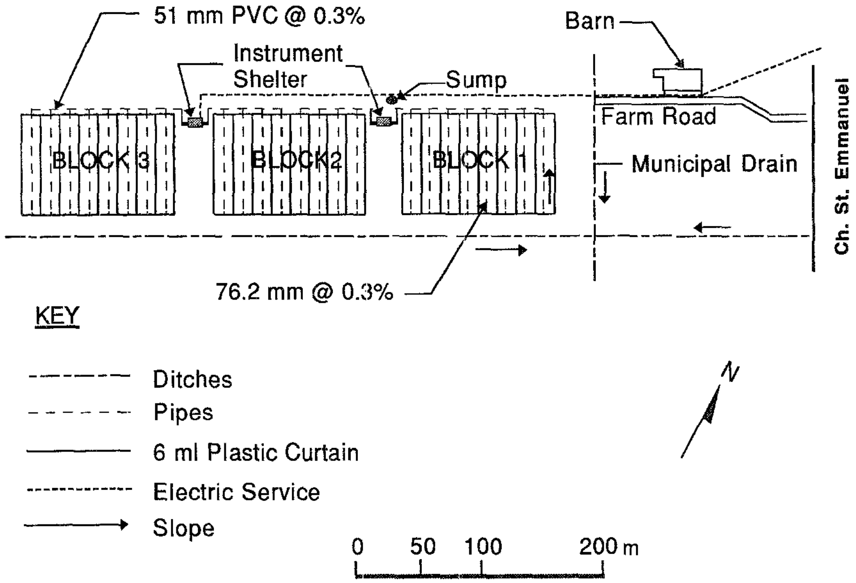


Fig. 1. Research facility lay-out.

slope, and a drain spacing of 15 m. At the discharge end of each lateral, a 5 m length of non-perforated pipe was attached to allow for a transition into individual 51- mm PVC mains. The PVC pipes were laid in a common trench and routed to one of the two sampling buildings. Surface runoff is measured from 5 × 10 m subplots in the middle block. Surface runoff inlets were installed at the discharge end of the eight subplots. These inlets are made of 76-mm perforated drainage tubing, extending 0.2 m above the soil surface. Below the ground surface, the inlets are connected to individual 51-mm PVC main lines, which are also routed to the sampling buildings.

Two buildings (5 × 5 m) were constructed at the site. The first is located between Blocks 1 and 2, and the second between Blocks 2 and 3 (Fig. 1). Twelve subsurface drain laterals and four surface runoff laterals enter each of the buildings. Electricity is available in each building which allows for heating and ventilation, thus permitting year-around operation of flow measuring equipment and water sampling devices. Fig. 2 is a schematic representation of the drain discharge of one of the controlled drainage/subirrigation plots. All drain flow and surface runoff, following measurement, are discharged through a floor drain to a large sump, constructed of 1 m diameter double- wall polyethylene pipe, from which it is subsequently pumped into a collector pipe, and then drains by gravity into an open ditch.

During the growing season, water is pumped from a deep well to water control tanks in each building, in order to obtain the controlled water tables of 0.5 and 0.75 m. The basic components of the control system include: a ball valve to change from free drainage to controlled drainage/subirrigation, water table control chamber, float

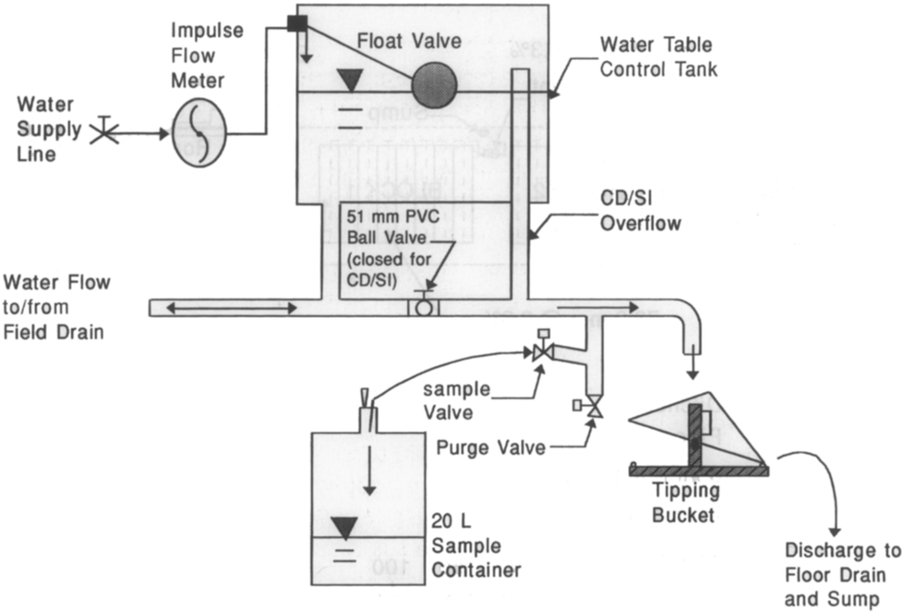


Fig. 2. Drain discharge, schematic.

valve to control fresh water supply, and overflow to permit drainage during controlled drainage/subirrigation. The operating principle of the system is to: (i) allow free drainage during spring planting and fall harvesting, and (ii) control the water table in the plot at a constant, predetermined level during the growing season. In order to isolate flows between plots, a plastic barrier was installed around the periphery of each plot. This barrier consists of double thickness 6-mil polyethylene installed to a depth of 1.5 m below the soil surface. The barrier was installed with a trenchless drain plough, incorporating a modified box at the rear for uncoiling the plastic.

3. Data acquisition (DAQ)/control system and instrumentation

3.1. Selection of DAQ/control system

While reviewing the options for a DAQ and control system, the following criteria were considered:

(1) provide a fully instrumented research facility which would meet the study objectives, be expandable and flexible, be within the capital budget, and require a minimal operating and maintenance budget;
(2) electrical service was available on site;
(3) the components would not be exposed to ambient weather conditions;
(4) the control system must meet the need for water table control and water quality sample acquisition (flow-weighed composite sampling);
(5) the acquisition and control system would provide adequate "on screen" information for personnel servicing the site to verify system performance and, if necessary, troubleshoot the system, and;
(6) provide for remote access, via telephone.

Based on the above criteria, bench-top equipment used in factories and laboratories is well suited to the needs of this research facility. These systems, which consist of a chassis and plug-in IC cards, are designed to be flexible and are controlled by a computer using proprietary software and an interface card. The supplier chosen was Sciemetric Instruments Inc. of Ottawa, Ont., Canada.

Each building has a DAQ and control system, with a dedicated computer. At the time of installation, the least expensive computer on the market was a 386SX/33 with 2 Mb DRAM, SVGA, math co-processor, 1.44 Mb floppy disk drive, 85 Mb fixed disk drive, and a VGA monochrome monitor. These computers, while far exceeding the minimum requirements for the software, were the simplest units available. The operating system installed on the fixed disk is Microsoft DOS 5.0, and the acquisition and control software is BENCHMATE.

The PCs and DAQ are protected from variances in the 120 VAC power supply by APC Back-UPS 900 uninterruptable power supply. These are designed for single phase, 120 VAC service operating at 60 Hz ± 5%, and are protected against over current and short circuit. Back-up power is supplied through sealed lead-acid batteries with a 6–10 h recharge time. Further benefits of the uninterruptable power supplies are surge suppression (240 joules, 6500 A peak, with immediate response time) and noise filters (both EMI and RFI in the range 100 kHz to 10 MHz).

3.2. Instrumentation

Components of the instrumentation system are shown in Fig. 3. Flow measurement is accomplished using tipping buckets which were designed in-house and custom fabricated. The bucket capacity was determined from the maximum theoretical drain flow, resulting in a bucket capacity of about 1 l tip^{-1} and maximum design tip rate of 30 tips min^{-1}. A low bucket profile allowed placing the drain outlets close to the top edge of the bucket dividing wall; this reduced the amount of splash occurring during higher flow rates. A magnetic reed switch (normally open) is mounted on the bucket so that every second tip (about 2 l) produces a switch closure for the DAQ. The tipping bucket was calibrated to determine the relationship between the tip rate (tips min^{-1}) measured by the DAQ system and the flow rate (l s^{-1}). The calibration constant for each bucket was programmed into the DAQ software.

During subirrigation, water is supplied to the water table control tanks from a pumped well supply. A water meter (Kent Model C-700, 1 pulse l^{-1}) equipped with a digital output, is connected to the supply line of each tank, to measure water consumption for subirrigation.

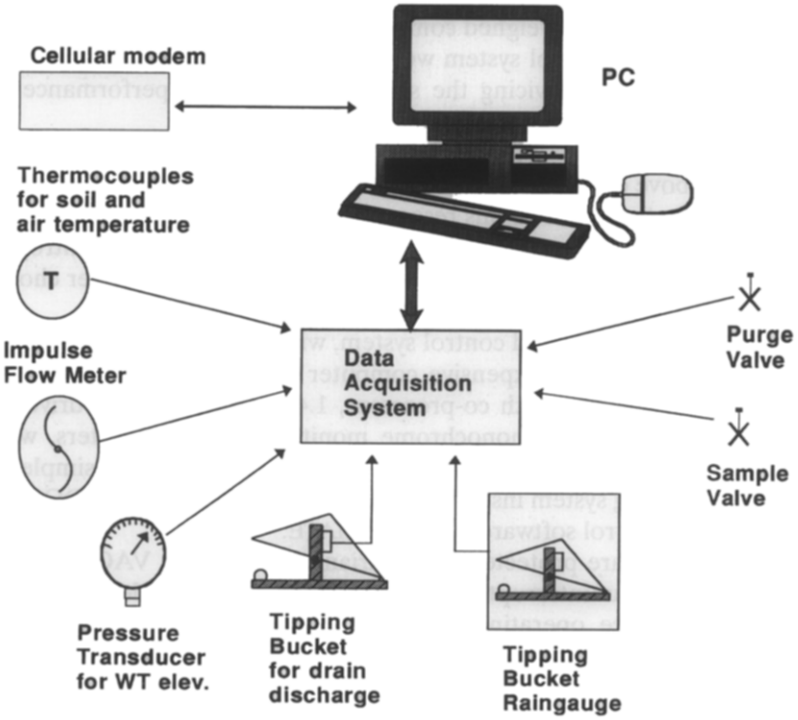


Fig. 3. Components of the DAQ/control system.

The water quality sampling system, installed at each drain outlet, comprises 12.5-mm, electrically operated purge and sample valves and a 20-l food-grade plastic carboy equipped with an airlock. The collection of flow-weighed, composite samples is controlled by the DAQ and control system. Following drain flow, or surface runoff events, water quality samples are taken from the carboys, for analysis in the laboratory.

The DAQ system installed in the first building is equipped with an A/D converter, to monitor thermocouples and pressure transducers. A T-type thermocouple is located in a Stevenson screen, near the first building, to measure ambient air temperature. In each plot in the second block, two T-type thermocouples are installed to measure soil temperature at depths of 0.2 and 0.5 m. Pressure transducers are located in each plot of Block 2, to monitor water table depth. A heated tipping bucket rainguage is installed on the roof of one building. This not only permits rainfall measurements, but also the water equivalent of snow and freezing rain. On the second building an unheated tipping bucket rainguage was installed.

3.3. Description of DAQ/control system software

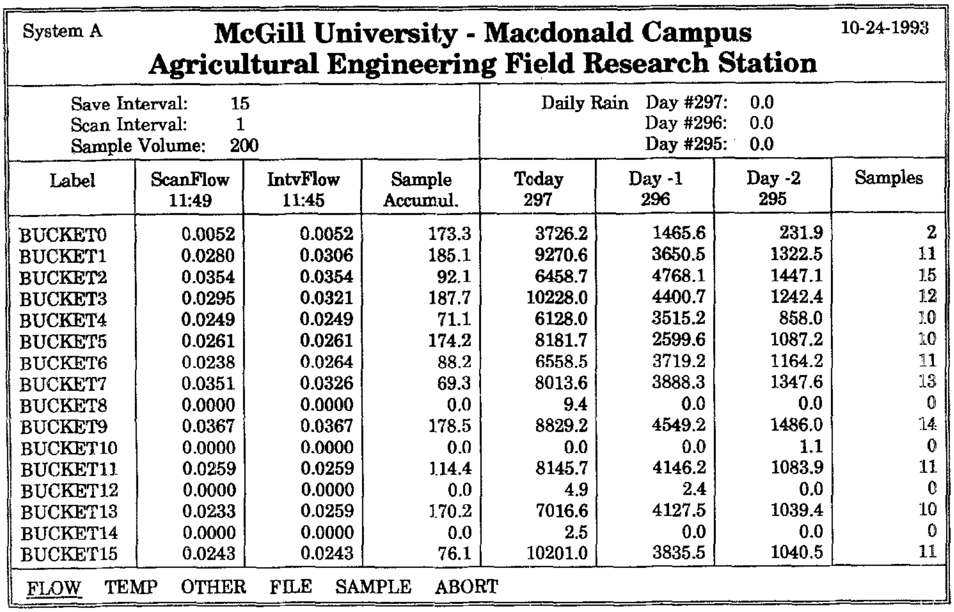
Sciemetrics Instruments Inc. provide a complete, general software package, called BENCHMATE, which configures and controls all of their components in a DAQ. The software was preconfigured to support the necessary modules and sensors. BENCHMATE is a menu- driven application that can be customized to provide support for DAQ and/or control systems. The basic software package comprises menus, utilities, and three system modules.

The pop-up menus are customized according to user specifications, and provide access to all other modules in the software. These include utilities which provide access to the database, user-definable alarms, and customization of the display. The three modules included in the basic package are:

(1) sensor module which accesses the sensor table so that the user may change the function attributes of the sensors;
(2) control module which accesses the control table so that the user may change the function attributes of the controllers; and
(3) graphics module, used to configure graphs for real-time or post-test display.

Sciemetrics Instruments Inc. provided customized programming for the software, which was included in the purchase price.

When the DAQ and control system are operating, the user has access to several information “screens”. The screen shown in Fig. 4, presents drain discharge information. The box at the top of the screen indicates the current date and which DAQ system (“A” or “B”, depending upon the building) is being observed. Daily rainfalls, measured to the nearest 0.1 mm, for the current day and for the two previous days are displayed in the upper right corner of the screen. The *Save* and *Scan Intervals* (in minutes) and *Sample Volume* (sampling frequency in liters) are displayed in the upper left. The scan interval is the frequency at which the DAQ system reads all channels, and is usually set to one minute. The save interval is the frequency at which the data are saved on the hard disk. Currently,



System A **McGill University - Macdonald Campus** 10-24-1993
Agricultural Engineering Field Research Station

Save Interval: 15
Scan Interval: 1
Sample Volume: 200

Daily Rain Day #297: 0.0
Day #296: 0.0
Day #295: 0.0

Label	ScanFlow 11:49	IntvFlow 11:45	Sample Accumul.	Today 297	Day -1 296	Day -2 295	Samples
BUCKET0	0.0052	0.0052	173.3	3726.2	1465.6	231.9	2
BUCKET1	0.0280	0.0306	185.1	9270.6	3650.5	1322.5	11
BUCKET2	0.0354	0.0354	92.1	6458.7	4768.1	1447.1	15
BUCKET3	0.0295	0.0321	187.7	10228.0	4400.7	1242.4	12
BUCKET4	0.0249	0.0249	71.1	6128.0	3515.2	858.0	10
BUCKET5	0.0261	0.0261	174.2	8181.7	2599.6	1087.2	10
BUCKET6	0.0238	0.0264	88.2	6558.5	3719.2	1164.2	11
BUCKET7	0.0351	0.0326	69.3	8013.6	3888.3	1347.6	13
BUCKET8	0.0000	0.0000	0.0	9.4	0.0	0.0	0
BUCKET9	0.0367	0.0367	178.5	8829.2	4549.2	1486.0	14
BUCKET10	0.0000	0.0000	0.0	0.0	0.0	1.1	0
BUCKET11	0.0259	0.0259	114.4	8145.7	4146.2	1083.9	11
BUCKET12	0.0000	0.0000	0.0	4.9	2.4	0.0	0
BUCKET13	0.0233	0.0259	170.2	7016.6	4127.5	1039.4	10
BUCKET14	0.0000	0.0000	0.0	2.5	0.0	0.0	0
BUCKET15	0.0243	0.0243	76.1	10201.0	3835.5	1040.5	11

Fig. 4. BENCHMATE screen display.

a 15-min save interval is used, which gives 96 values per day. The sample volume parameter determines how frequently the water sampling system is activated. The DAQ system totalizes flow after the scan interval, and, once the sample volume has been exceeded, it activates the water samplers, and resets the counter to zero. This is done for each channel, and each scan interval. For each of the drains (*Label*), the following data are displayed:

ScanFlow	Flow rate (l s^{-1}) over the last *Scan Interval.*
IntvFlow	Flow rate (l s^{-1}) over the last *Save Interval.*
Sample Accumul.	Accumulated flow volume. When this value equals or exceeds *Sample Volume*, a 500-ml sample is acquired. This counter is then reset to zero.
Today	Accumulated flow volume since 0001 h of the current day.
Day-1	Accumulated flow volume for the previous day.
Day-2	Accumulated flow volume for the day prior to *Day-1*.
Samples	A counter for the number of samples acquired since the 20-l sampling bottles were last emptied. This is reset to zero following sample collection.

Other functions and displays, that can be accessed during operation, are shown at the bottom of the screen. *TEMP* accesses the thermocouple display screen; *OTHER* accesses the display screen for the pressure transducers and Kent flowmeters; *FILE* copies data to a diskette without interrupting DAQ; *SAMPLE* resets *Samples* to zero; and *ABORT* ceases all operations. By aborting the DAQ mode, the software exits to the main menu where system configuration, file management, and set-up of the DAQ and control modes takes place.

4. Calibration of tipping buckets and water quality sampling valves

4.1. Tipping buckets

Thirty-five tipping buckets were fabricated for the project; 32 were installed and three are spares. Eight of 35 tipping buckets were calibrated in a laboratory. Each was set on a level surface, and connected to a datalogger. Water from a centrifugal pump was discharged through a horizontal 51 mm diameter pipe, into the tipping bucket, and then collected in a container resting on a balance. A portable datalogger was used to monitor the tip rate (tips min^{-1}). Based on the weight of the water and the time for the container to fill, the bucket discharge was calculated. This procedure was repeated for various pumping rates. Analysis of the data included plotting the tip rate vs. flow (Fig. 5) and performing a linear regression through a zero intercept. In all eight cases, the correlation coefficient (R) was greater than 0.99. The general form of the discharge equation was:

$$Q = R_c X \tag{1}$$

where Q is the flow rate (l min^{-1}), X is the tip rate (tips min^{-1}), and R_c is a calibration constant.

To extrapolate the results from the eight buckets tested to the remaining 27, a relationship between the calibration constant (R_c) and the zero-tip volume (V_0, ml) was determined (Fig. 6). The zero-tip volume is defined as the volume of water that each side of the bucket holds as the flow rate approaches 0 l s^{-1}. The following

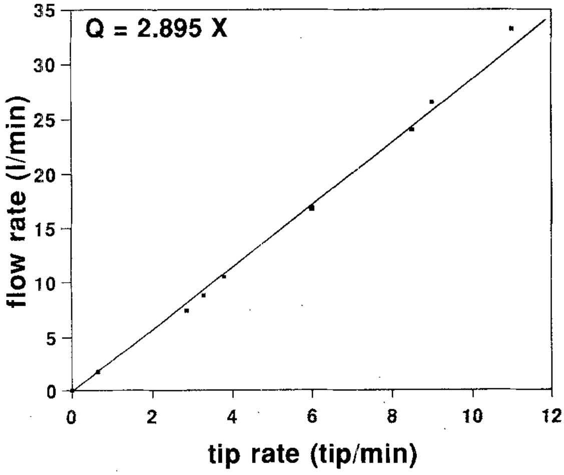


Fig. 5. Tipping bucket calibration curve.

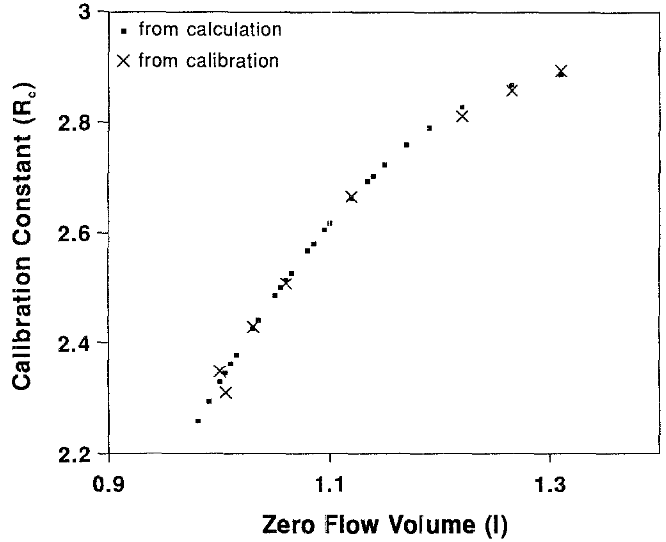


Fig. 6. Calibration constant vs. zero-tip volumes.

second-order polynomial equation was obtained:

$$R_c = -6.271 + 13.785V_0 - 5.186V_0^2 \tag{2}$$

Once the three constants were determined for the polynomial, the V_0 values for the remaining 28 buckets were measured, and the corresponding R_c values determined. The value of R_c for each bucket was entered into the sensor module in BENCHMATE.

4.2. Water quality sampling system

To assure that the composite sample collected in the 20-l bottle is representative, the volume of water obtained from each valve activation must be independent of the flow rate. This required the water sampling valves to be calibrated in the laboratory. Since the sampling system operates by gravity, calibration of the purge and sample valves was required to determine the relationship between the length of time the valves are kept open, and the volume of water collected. A prototype of the system installed in the field was constructed in the laboratory. Water was pumped through the valve system at various rates of discharge. The discharge from the prototype actuated a tipping bucket, which was connected to a datalogger for flow measurement.

The relationship between the activation time of the valve, the flow rate, and the sample volume collected was determined (Fig. 7). From these graphs, we were able to determine the activation time required on a sample valve in order to collect a 500-ml water sample, for various flow rates, and these were entered into the sensor module in BENCHMATE (Table 2).

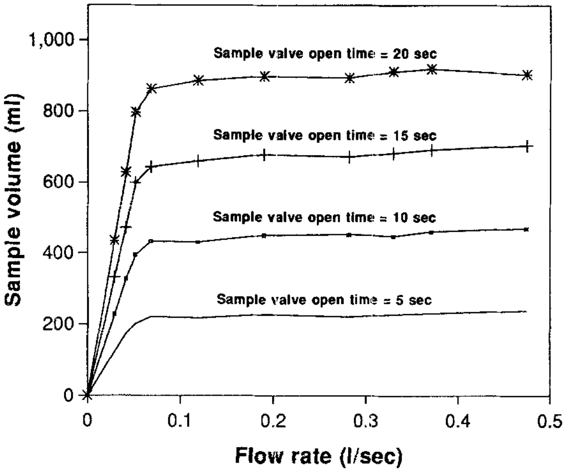


Fig. 7. Sample volume vs. discharge, 20-s activation.

Table 2
Sample valve control table

Drain discharge rate ($l\ s^{-1}$)	Valve opening time required to pass 500 ml of water (s)
0.5	10
0.4	10
0.3	10.5
0.25	10.75
0.1	11.5
0.068	12.5
0.045	15
0.037	20
0.01	30

In order to ensure that the sample valves would perform consistently for both controlled- and free-drainage modes, an additional prototype outlet structure was tested in the lab. As Fig. 8 illustrates, the volume of water collected was independent of the drainage mode.

4.3. Equipment costs

The costs of the individual components for the DAQ/control system are summarized in Tables 3 and 4. The cost of the system in the building between Blocks 2 and 3 was about CAN $22,300, while the cost of the system in the other building, which includes the meteorologic and soil sensors, was about CAN $30,000. Total cost of the instrumentation and control systems was CAN $52,300, including software and miscellaneous items.

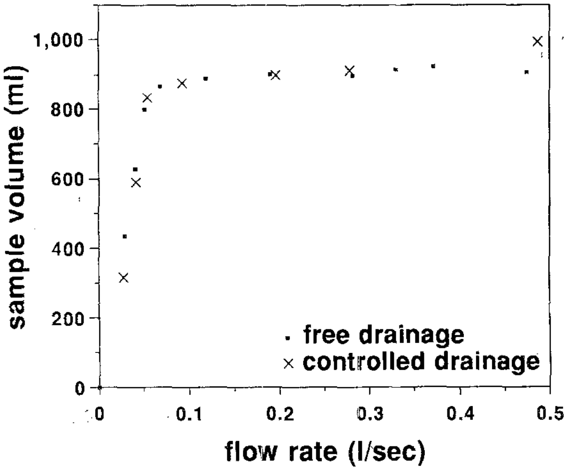


Fig. 8. Volume vs. discharge, free and controlled drainage.

Table 3
Control and instrumentation system costs

Quantity	Description	Unit	Unit cost (CAN$ 1992)
Sensors			
32	2-l stainless steel tipping bucket flow meter c/w magnetic switch	each	393.00
12	Kent Model C-700 impulse flow meter, 1 pulse l^{-1}, with digital output	each	140.00
1	GENEQ T-1500 electrically heated tipping bucket raingauge	each	1740.00
1	GENEQ T-1000 tipping bucket raingauge	each	1035.00
6	T-16 thermocouple wire (24 gauge)	1000 ft	293.00
8	OMEGA PX-181-015G5G pressure transducer	each	175.00
Water quality sampling system			
64	ASCO Red-Hat Model 8030G16, 120 VAC, 12.7-mm valve	each	80.25
32	20-l food grade plastic carboy c/w cap and airlock	each	19.10
32	Tubing, wiring, and fittings	each	70.00
Water table control system			
12	Control chamber c/w float valve	each	230.00
32	51-mm PVC ball valve	each	26.00
32	Tubing, wiring, and fittings	each	50.00
3	Grundfos BOSS 300 stainless steel submersible sump pump c/w mercury float switch	each	435.00
Computer system			
2	AST BRAVO 386SX/33 computer c/w 2 Mb DRAM, SVGA, math co-processor, 1.44 Mb floppy and 85 Mb fixed disk drives, VGA monochrome monitor, and Microsoft DOS 5.0	each	1635.00
2	APC Back-UPS 900	each	525.00

Table 4
Data Acquisition (DAQ) system costs

Quantity	Description	Unit	Unit cost (CAN $ 1992)
Data Acquisition System (Sciemetrics Instruments Inc.)			
1	Advanced Data System includes: (1) Model 290 system chassis (1) Model 290-40 power supply (1) Model 802 interface card (1) Model 236 high speed 12 bit A/D converter (1) Model 252, 32 channel analog expansion module (1) Model 242, 32 channel digital I/O module (2) Model 223, 16 channel solid state relay I/O module c/w relays (2) Model 240, 8 channel counter timer module	package	9800.00
1	Base Data System includes: (1) Model 290 system chassis (1) Model 290-40 power supply (1) Model 802 interface card (1) Model 242, 32 channel digital I/O module (2) Model 223, 16 channel solid state relay I/O module c/w relays (2) Model 240, 8 channel counter timer module	package	6378.00
1	BENCHMATE software package (BASE module)	package	2500.00
1	BENCHWARE runtime system	package	800.00

4.4. Performance

Installation of the tipping buckets and DAQ system were completed in March 1993. Initial tests showed that the DAQ system gave erroneous readings for drain flow. This was traced to a switch-DAQ incompatibility and corrected by installing a custom designed filter board, supplied by Sciemetrics Instruments Inc. Additionally, several bugs in the DAQ system were corrected during a May 1993 site visit by Sciemetrics Instruments Inc. technicians.

Since mid-September 1993, the instrumentation has been fully operational. The DAQ, control systems, and sensors performed as designed. Fig. 9 illustrates the discharge from buckets 0, 1, 2, 3 for Julian days 275 to 334 (Oct. 1 to Dec. 1). The water sampling system has also performed close to expectations. Sample volume has been consistent between sampling times, but appears to be lower than the volume achieved during calibration. Fig. 10 shows the subsurface drain discharge hydrograph for one plot, as a result of a rainfall event on November 19, 1993.

5. Summary and conclusions

Nitrate pollution of surface runoff and ground water is of major environmental concern to the agricultural community. A field research facility was constructed by the Agricultural Engineering Department of McGill University to monitor 24

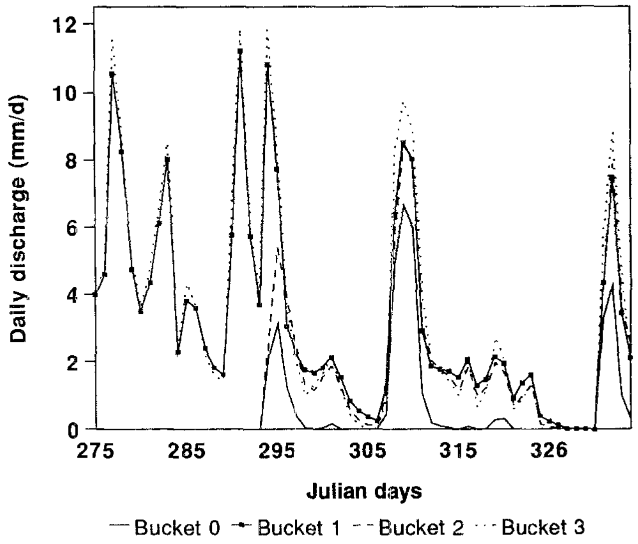


Fig. 9. Daily drainage, fall 1993, buckets 0, 1, 2, 3.

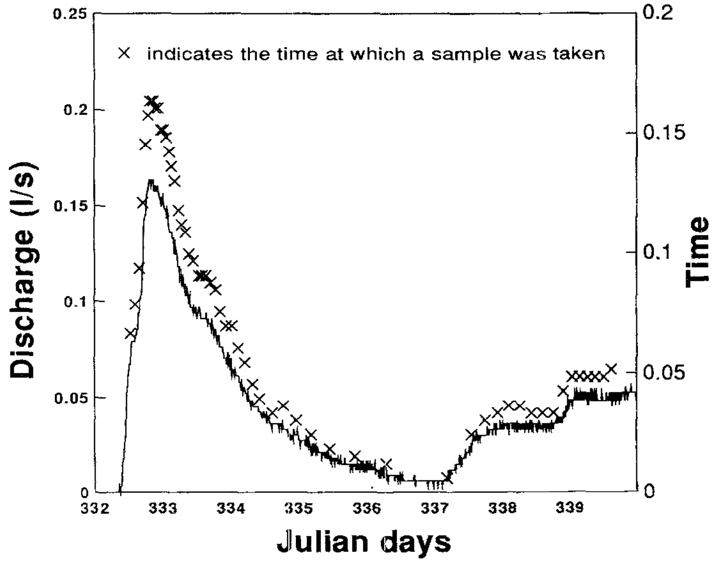


Fig. 10. Sample drain discharge curve for November 29, 1993.

field plots with varying water table depths, nitrogen fertilization rates, and either grain corn monocropping or grain corn-ryegrass intercropping. The facility uses a state-of-the-art electronic DAQ system to make measurements on a year-around basis. The instrumentation and DAQ system, at the facility, are designed to be flexible, efficient, and relatively low-cost by local standards. These features were achieved through the use of passive sensors and sampling equipment controlled by an industrial-type DAQ/control system.

Large-scale research facilities, like the one described in this paper, will lead to a better understanding of chemical movement in soil and water, and the development of best management practices to reduce nitrate leaching. Further benefits from these facilities will include more accurate testing and validation of computer simulation models.

Acknowledgements

The authors wish to thank the Natural Sciences and Engineering Research Council of Canada for providing a Strategic Grant, which enabled the establishment of this research facility, and the on-going research. The cooperation of the farm owner, Mr. Guy Vincent is deeply appreciated. Mr. Jerome Molenat is thanked for assisting with the calibration of the tipping buckets and water sampling system. Several summer students of the Department of Agricultural Engineering, McGill University helped with the construction of the research facility, and installation of equipment. They are all sincerely thanked. The assistance of Dr. Georges Dodds and Mr. M.B. Shukla with the preparation of the manuscript and drawings is most appreciated.

References

Belcher, H.W. and Merva, G.E. (1991) Water table management at Michigan State University. ASAE Paper 91-2025.

Evans, R.O., Gilliam, J.W. and Skaggs, R.W. (1989) Managing water table management systems for water quality. ASAE Paper 89-2129.

Fausey, N.R., Ward, A.D. and Brown, L.C. (1991) Water table management and water quality research in Ohio. ASAE Paper 91-2024.

Kanwar, P.K., Bakerz, D.G., Singh, P., Noh, K.M. and Honeyman, M. (1990) A field system to monitor tillage and crop rotation effects on groundwater quality. ASAE Paper 90-2526.

Madramootoo, C.A., Wiyo, K.A.W. and Enright, P. (1992) Nutrient losses through tile drains from two potato fields. Appl. Eng. Agric., 8(5): 639–646.

Madramootoo, C.A., Dodds, G.T. and Papadopoulos, A. (1993) Agronomic and environmental benefits of water-table management. J. Irrig. Drain. Eng., 119(6): 1052–1064.

Milburn, P. and MacLeod, J. (1991) Considerations for tile drainage-water quality studies in temperate regions. Appl. Eng. Agric., 7(2): 209–215.

Skaggs, R.W., Evans, R.O., Gilliam, J.W. and Parsons, J.E. (1991) Water management in North Carolina. ASAE Paper 91-2023.

Soultani, M., Tan, C.S., Gaynor, J.D., Neveu, R. and Drury, C.F. (1993) Measuring and sampling surface runoff and subsurface drain outflow volume. Appl. Eng. Agric., 9(5): 447–450.

Steenvoorden, J.H.A.M. (1989) Agricultural practices to reduce nitrogen losses via leaching and surface runoff. In: J.C. Germon (Editor), Management Systems to Reduce Impact of Nitrates. Elsevier, Amsterdam, pp. 11–118.

Willis, G.H., Fouss, J.L., Rogers, J.S., Carter, C.E. and Southwick, L.M. (1991) System design for water table management. In: R.G. Nash and A.R. Leslie (Editors), Groundwater Residue Sampling Design, ACS Symposium Series 465. American Chemical Society, New York, N.Y., pp. 326–343.