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Surface Irrigation of Dairy Farm Effluent, Part II: System Design and Operation

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Dairy farms with as many as 200 cows still handle their wastewaters and solid manures separately. Because of the large volume produced and their low nutrient load, these dairy farm effluents (DE) are costly and time consuming to land spread using conventional equipment, such as the tanker. The purpose of this study was to test the equipment and cost to determine the cost of the equipment adapted for the simplified surface irrigation of DE and to establish best management practices to reduce risks of groundwater contamination. The project was conducted on two dairy farms in South Western of Montreal, Canada, where typical DE were applied to irrigated plots of 0·5 and 0·3 ha, respectively, and the groundwater quality was compared to a control plot of the same size. Groundwater quality was monitored for nutrients (total nitrogen, total phosphorus, total potassium and pH) and bacterial counts (total coliforms, faecal coliforms, and faecal streptococci). A manure pump and conventional water irrigation pipes were satisfactory in irrigating with the DE without clogging as long as the DE was collected in a tank separate from that of the solid manure. During all applications, subsurface seepage losses occurred, but these would not be lost to the watercourse when applied in quantities respecting irrigation guidelines and on soils where the groundwater table was at or below the depth of the subsurface drains. Nevertheless, these seepage losses represented less than 1% of the total volume of DE applied, and the seepage nutrient and bacterial load was generally less than half of that of the irrigated DE. The surface irrigation system reduced the cost of land spreading DE from CAN \$3·25 m^{-3} (conventional tanker) to CAN \$1·10 m^{-3} (surface irrigation). The heavy total potassium load of the DE requires the rotation of the irrigation plot, on an annual basis.

1. Introduction

Dairy farm effluents (DE) consist of several types of wastewaters, such as wash water from cleaning the milking equipment and urine, as well as seepage from manure piles stored in open exterior structures exposed to precipitations (Willer *et al.*, 1999). For those dairy operations with liquid waste systems, DE are used to make slurries out of manures. Nevertheless, dairy farms, with as many as 200 cows, still manage DE separately from solid manures (Ribaudo *et al.*, 2003). Owing to of their large volume and low nutrient load, DE are costly and time consuming to land spread, using conventional manure spreading systems such as a tanker pulled by a tractor or truck.

Owing to its instantaneous application of wastewaters which exceeds the infiltration capacity of the soil, conventional manure spreading systems are limited to rates of 50–100 m^3 ha^{-1}. When used to apply DE, which are typically low in nutrients, such systems only partially fertilise crops (Ali *et al.*, 2006). In comparison, surface irrigation to land spread DE can be quick and efficient, and is able to apply well over 500 m^3 ha^{-1} (Ali *et al.*, 2004). Still as compared to the conventional tanker, surface irrigation can be practiced at all time without crop damage, eliminates soil compaction and provides water for crop growth.

Practiced as early as 1872 in Augusta, USA, the surface irrigation of municipal wastewaters is not a new technology (Reed *et al.*, 1995). Conventional application methods use sprinklers or furrows, which adds to the cost of land spreading. Furthermore, most municipal wastewater projects were carried out without consideration of the risk of groundwater contamination as a result of seepage losses (Fleming *et al.*, 1990). For the irrigation of DE, best management practices are, therefore, required to adapt surface irrigation in such a way as not to require special application equipment and also to limit groundwater contamination.

For the surface irrigation of DE, the main objective of this study was to select simple equipment and develop management practices that limit seepages. Therefore, this project tested surface irrigation equipment for the efficient land application of DE at the rates of $500\,m^3\,ha^{-1}$; observed the amount and contaminant load of subsurface seepage resulting from the surface irrigation of DE to recommend ways to minimise these losses, and; conduct an economic assessment of the cost of surface irrigation *versus* that of a conventional tanker pulled by a farm tractor.

2. System design

Ali *et al.* (2004) have designed a simple DE surface irrigation system requiring a minimum of equipment. The system consists of pumping DE into a gated irrigation pipe laid on the ground perpendicular to the slope of a field, discharging the DE at the ground surface and letting them runoff over the ground surface. As the DE have a low nutrient load, small spreading surfaces are required, such as $1{\cdot}5\,ha\,(100\,cow)^{-1}$ (Ali *et al.*, 2006).

The design of such a simple DE surface irrigation system requires the computation of the plot size, the length of gated pipe required and the DE pumping rate:

(1) The plot size ensures that the nutrients provided by the DE is suitable for crop requirements; generally, this calculation is based on the most limiting nutrient, from an environmental point of view, namely phosphorus (P), especially for soils rich in P (Converse *et al.*, 2000; Simard *et al.*, 1995). For soils and crop uptake, P applications are generally expressed in terms of P_2O_5 where $2{\cdot}29$ kg of P_2O_5 are equivalent to $1{\cdot}0$ kg of P.
(2) The length of gated or perforated pipe required to irrigate the plot is governed by the length of slope below the pipe position in the field.
(3) The DE pumping rate must not exceed the soil infiltration rate, to avoid surface tail waters.

The size of the irrigation plot can be simply calculated as:

$$A = \frac{V_w}{(C_P/W_P)} \tag{1}$$

where: A is the surface area of plot to be irrigated in ha; C_p is the crop P_2O_5 requirement in $kg\,ha^{-1}$; W_p is the P_2O_5 content of the DE in $kg\,m^{-3}$; and V_w is the volume of DE to irrigate in m^3.

For example, if a forage crop requires $62\,kgha^{-1}$ of P_2O_5, and the DE contains on an average $55\,mg\,l^{-1}$ or $0{\cdot}055\,kg\,m^{-3}$ of P_2O_5, then $1127\,m^3\,ha^{-1}$ of DE need to be applied to meet the crop P requirements. If the farm storage facility holds $750\,m^3$ of DE, then the plot or receiving area measures $0{\cdot}67$ ha.

The length of irrigation pipe must equal the length of the application area A and the length of slope below the gated pipe position in the field is determined by:

$$L_p = \frac{A}{L_s} \tag{2}$$

Table 1
Recommended and measured irrigation applications rates (Schwab *et al.*, 1986)

Soil texture	*Subsurface*	*Recommended I, mm h^{-1}*		*Measured S, mm h^{-1}*	*Recommended application depth, mm m^{-1}*	*M.C., at f.c.,%*
		With vegetation	*Without vegetation*			
Fine sand	Deep	25	43	840*	67–83	12
Fine sand	Compact bed	18	30			
Silt	Deep	13	25	50†	166–208	34
Silt	Compact bed	8	15			
Clay		3	5	34–60‡	108–125	43

Note: *I*, irrigation application rate; S, soil infiltration rate; M.C. at f.c., soil moisture content at field capacity.
*Stabilised value for the gravelly sandy soils on farm MH-6, average of 3 samples.
†Stabilised value for farm MH-3, average of 3 samples.
‡Stabilised value for the clay soils of farm MH-6, average of 3 samples.

where: L_p is the length of gated pipe required in m; and L_s is the length of the consistent slope below the gated pipe position in the field in m. The value of L_p should also be optimised against the pumping pressure for the even distribution of DE over its full length because the gated pipe acts as a manifold.

The DE pumping rate Q in $m^3 h^{-1}$ must then be regulated not to exceed the infiltration rate of the soil S over the plot surface. This ensures the infiltration of all DE by the time the distance L_s is reached. The required pumping rate can be calculated from the following equation:

$$Q = A \times S \times f_s \times 10 \quad (3)$$

where: S is the soil infiltration rate in $mm\,h^{-1}$; f_s is a safety factor accounting for the fact that irregularities in the ground surface will lead to its incomplete coverage by the DE; A is the surface area in ha; and Q is the pumping rate of DE in $m^3 h^{-1}$.

One objective of the present project is to recommend values for $(S \times f_s)$ and compare these to the irrigation water application rate I suggested by Schwab *et al.* (1986), as summarised in Table 1. The design should ensure that L_p is long enough for all DE to be infiltrated by the end of the plot. This value is simply calculated from Eqns (1) and (2) and so is a reasonable estimation of $(S \times f_s)$ value, irrespective of the ground slope.

3. Methodology

3.1. *Equipment selection and plot testing*

To conduct DE surface applications, the equipment selected consisted of a liquid manure vacuum pump with a capacity of 60–600 $m^3 h^{-1}$, powered by the power take-off (PTO) of a standard 50–70 kW farm tractor. The pump delivered the DE to flexible non perforated plastic tubing measuring 100–200 m in length and 150 mm in internal diameter. This flexible tubing was connected to a gated irrigation pipe, 45 m in length and 150 mm in inside diameter, installed perpendicular to the slope of the field with enough down-slope distance to irrigate a 0·5–1·0 ha size plot. The ground slope below the gated pipe offered no counter slope, since this would stop the spreading of DE.

To gauge the pump flow rate, a flow meter was installed in a section of aluminium tubing, 300 mm long, located between two sections of flexible pipe, about 15 m from the pump. The flow meter reading was checked by monitoring the drop in DE level in the storage pit.

Ground seepage was monitored using sampling wells intercepting the subsurface drainage system under each plot (*Fig. 1a* and *b*; *Fig. 2*), and therefore resulting in

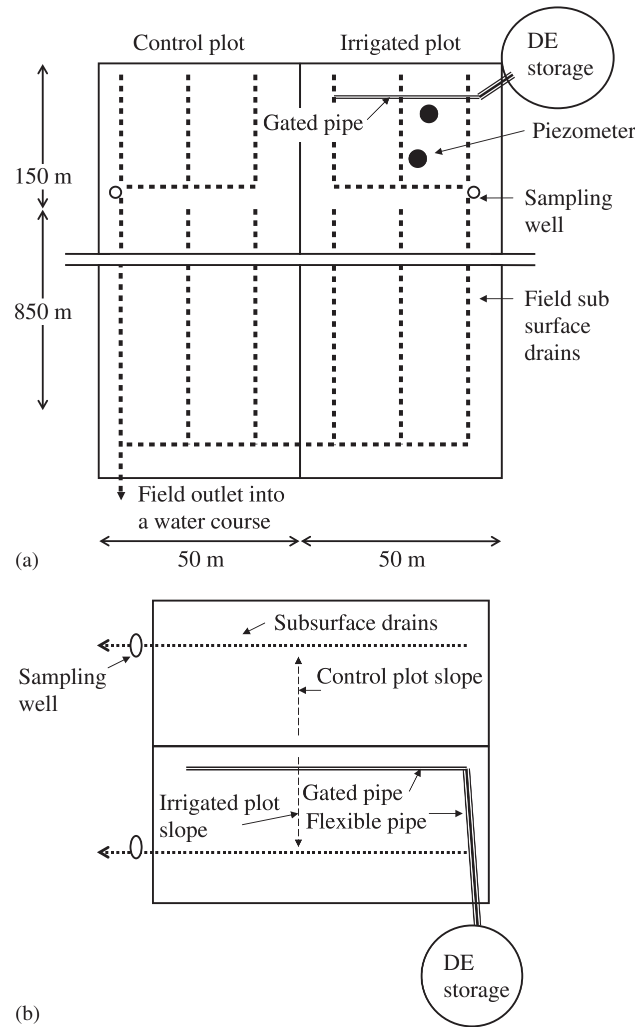

Fig. 1. (a) Experimental plots of farm MH-3, where DE is dairy effluent. (b) Experimental plots of farm MH-6, where DE is dairy effluent

same level inlet and outlet drains. The bottom of each well was 600 mm deeper than the subsurface drains to allow for sampling. Nevertheless, because of the low water table at the onset of the testing sessions each year, this 100 *l* of well space never accumulated enough water to dilute the contamination load of seepage.

In 2002, to measure the infiltration rate of the soils, three soil cores, 100 mm high by 100 mm in diameter, were randomly collected from each plot and each was subjected in the laboratory to a constant head of 10 mm to reproduce field infiltration conditions (Klute, 1965). The results were used to calculate the surface area required for irrigation [Eqn (3)]. Also performed in 2004 but not reported in this paper are the plot grid design and the soil and crop sampling for nutrient applications and yield, respectively (Ali *et al.*, 2004).

3.2. *Dairy effluent characteristics*

For three consecutive years, the DE characteristics were monitored on two farms with a slightly different handling methods (Table 2). The farms were located in the Saint Anicet region, some 75 km South west of Montreal, Canada. Farm MH-3 collected DE consisting of milk house wash waters and manure seepages, while farm MH-6 collected only manure seepages. Farms MH-3 and MH-6 managed a herd of 42 and 24 dairy cows, respectively, with a similar number of replacement animals.

The DE characteristics were monitored by sampling the storage pits in May of each year at the bottom, centre and surface, using a long collection pole holding a 1 *l* bottle with a removable cap at its lower end. Before sampling, the DE depth in the storage was measured to obtain its mid-value. Then, the collection pole was lowered to the floor of the pit and the cap was removed to collect a bottom DE sample. Once the collection bottle was emptied and washed, the procedure was repeated at mid-depth and at 300 mm from the DE surface in storage. The characteristics of the DE with depth for both farms MH-3 and MH-6 are reported in Ali *et al.* (2006), and this paper reports the characteristics averaged with depth, for all 3 years.

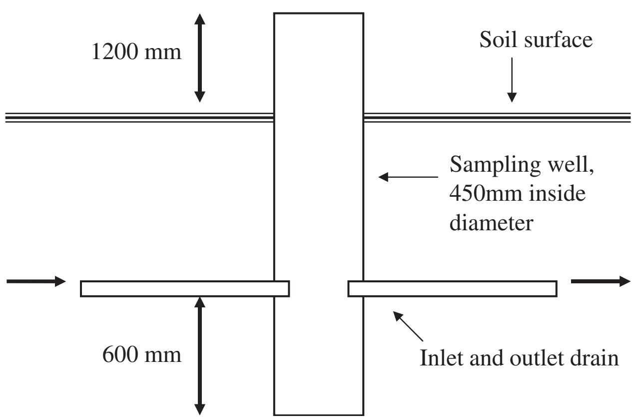

Fig. 2. Profile of the sampling well

3.3. *The experimental plots*

On both farms MH-3 and MH-6, two plots were selected to conduct the tests: the irrigated DE and the control receiving no DE. Maize (*Zea mays*) and mixed cereals (*Tritucum aestivum, Hordeum vulgare* and *Avena sativa*) were grown in 2003 and 2004 on both experimental farms.

On farm MH-3, the soils of the experimental plots were loamy in texture and sloped northwards at a rate of 1·0% over a distance of 150 m. Each plot measured 50 m in width, where the Eastern plot served as the control plot (non-irrigated) and the Western plot received the irrigated DE (*Fig. 1a*). Irrigated DE was applied to cover a plot length of 100 m representing an application area of 0·5 ha.

On farm MH-6, both 50 m wide experimental plots consisted of gravely sandy soils with a southern slope of 2·5 to 3·5% over a distance of 60 m, and soils with higher clay content at the bottom of this slope. The Western plot of 0·3 ha served as the control (non-irrigated) and the Eastern plot, also of 0·3 ha, received the irrigated DE (*Fig. 1b*).

Table 2
Description of experimental farms MH-3 and MH-6

Characteristic	*Farm MH-3*	*Farm MH-6*
Number of cows	42 including 35 in lactation	24 including 20 in lactation
Herd	82 heads	42 heads
Manure storage		
• solid plate-form surface area • seepage collection tank	• 30 m by30 m plus entrance for a total of 960 m^2 • earthen 18 m in diameter at the bottom, 4·3 m deep and side slope of 2 hor: 1 ver	• 21 m × 25 m plus entrance for a total of 525 m^2 • earthen 10 m in diameter at the bottom, 2·1 m deep with side slope of 2·5 hor: 1 ver
Herd feeding	Maize silage, hay	Maize silage, hay
Bulk tank size, *l*	2220	1000
Milk pipeline length, m	61·4	30·3
Solid storage pad, m^2 cow^{-1}	21·8	22·9
Effluent storage, m^2 cow^{-1}	9·1	4·2
Manure storage effluent composition	Milk house wastewater Manure seepage	Manure seepage

The subsurface DE seepage losses on farms MH-3 and MH-6 were monitored using the existing systematic and minimal subsurface drainage systems, respectively. On farm MH-3, two drains under each experimental plot were intercepted and linked by a 100 mm subsurface drain leading into the sampling well (*Fig. 1a*). The sampling wells drained into the field subsurface drainage system with an outlet some 850 m downslope into a watercourse where the seepage losses were measured. On farm MH-6, each experimental plot was drained by a single subsurface drain (*Fig. 1b*) intercepted by a sampling well at their lower edge. On farm MH-6, the outlet of each subsurface drain downstream from the sampling wells was below the ditch water level, and no water course seepage losses could be measured. At the sampling well, the seepage loss was estimated by observing the depth of the liquid flow in the drain.

3.4. *Seepage losses and dairy effluent distribution*

Conducted in July and August of 2003 and 2004 (Tables 3a and b) and with DE application rates of 230–682 $m^3 ha^{-1}$, the trials tested the effect of irrigated volume and soil moisture conditions on the contamination load of groundwater seepage losses. For each irrigation application, the method consisted in visually observing the extent of ground coverage, and measuring the volume applied by irrigation, the losses at the sampling wells and, on farm MH-3, the flow at the subsurface field outlet. During each test, samples were collected from the sampling well of both the irrigation and control plots, at the irrigation pipe and also, on farm MH-3, at the drainage outlet when losses did occur. Samples were collected from the wells before, during and for 3 days after the application session.

During July 2003 and on farm MH-3, the labour and equipment requirements and the cost of operating the irrigation system were compared to that of using a conventional tanker. A time study was conducted while applying DE at a rate of 64 $m^3 ha^{-1}$ on the control plot using a conventional tanker, and on the irrigated plot at a rate of 450 $m^3 ha^{-1}$. The cost of both operations was compared on the basis of disposing all 1000 m^3 of DE for farms MH-3 and MH-6, assuming that the irrigation equipment was shared.

In 2004, two piezometers were installed on farm MH-3 (*Fig. 1a*) to observe the fluctuations in groundwater table with irrigation application. Piezometers could not be installed on farm MH-6 because of stony ground conditions. Thus, in 2004, before and after each irrigation sessions, soil moisture was monitored by sampling the surface 100 mm depth at 20 points plot-1 using a grid system, and the groundwater depth was observed using the piezometers.

3.5. *Analytical procedure*

Soil particle size distribution was determined using sieves and the hydrometer method (Sheldrick & Wang, 1993). Soil moisture content was determined by drying at 60 °C for 48 h.

Table 3a
Irrigation tests conducted on farm MH-3

Year	*Day*	*Rain, mm*	*Irrigation*	*Soil moisture, %*		*Volume applied*		*GWT depth, m*		*Field outlet flow, m^3*
				Before	*After*	*m^3*	*$m^3 ha^{-1}$*			
2003	11th July	0	1st			225	450			
	14th July	30	2nd			115	230			
	29th August	20	3rd			315	630			1·6
Total							655			
2004	15th July	6	1st	20·7	30·6	269	538	0 h: > 1·60 3 h: > 1·.60 20 h:1·12	0 h: > 1·6 3 h: > 1·6 20 h:1·6	
	19th July	12	2nd	24·5	36·1	276	552	0 h: > 1·60 5 h:0·80	0 h:1·26 5 h:0·26	
	2nd August	100	3rd	23·6	40·8	341	682	0 h:1·37 4 h:0·31 6 h:0·45 72 h:1·1	0 h:1·30 4 h:0·28 6 h:0·38 72 h:1·3	4·0
Total							886			

Note: The rainfall spanned a period of 2 days before irrigation; GWT, groundwater table depth. Soil moisture was measured in the top 10 cm layer.

Table 3b
Irrigation tests conducted on farm MH-6

Year	*Day*	*Irrigation*	*Volume applied*		*Rain, mm*	*Soil moisture, %*	
			m^3	$m^3\ ha^{-1}$		*Before*	*After*
2003	22nd Sept	1st	110	367	0		
	25th Sept	2nd	40	133	0		
Total			150				
2004	6th of July	1st	115	383	8	13·5	25·6
	9th of July	2nd	65	217	0	22·6	32·7
Total			180				

Note: The rainfall spanned a period of 2 days before irrigation.

All DE samples were analyzed for total nitrogen (TN), total phosphorus (TP), total potassium (TK) and total suspended and dissolved solids (TS, SS, DS), pH, total and faecal coliforms and faecal streptococci (TC, FC and FS), according to standard methods (APHA *et al*. 1998). All solids (TS, SS and DS) were determined by drying at 103 °C for 24 h. Samples were digested with sulphuric acid and hydrogen peroxide at 500 °C before being analyzed for total kjeldahl nitrogen (TKN) using an ammonia selective probe connected to a pH meter and for TP and TK using a colorimetric method and a spectrophotometer. As the DE exhibited low levels of nitrate and nitrite, measured using a selective probe attached to a pH meter, TN was considered equivalent to TKN. All microbial counts were determined by micro-filtration, the incubation of the filters on a medium and at a temperature specified for each group of organism and the reporting using colony forming units (CFU) ml^{-1}.

The DE nutrient and bacterial loads observed in the sampling well of the irrigated and control plots were compared statistically by means of the student-*t* test (Steel & Torrie, 1986). All significant differences are based on a 95% confidence level.

4. Results and discussion

4.1. *Equipment selection and performance*

The equipment selected was found to deliver up to 600 $m^3\,h^{-1}$ of DE with a total solid content as high as 1·3% without blocking the gates of the irrigation pipe. Applied under the crop canopy, the DE was observed to release a limited amount of odour.

During the field tests, a uniform distribution of DE was achieved over the full length of the gated pipe, by simply adjusting the gate openings. The gated openings were closed when in line with a path of preferential runoff flow, such as a field lane with no vegetation or beside a field ditch. A tractor with a minimum power at the power takeoff of 70 kW was required to pump 600 $m^3\,h^{-1}$ of DE through 200 m of flexible 150 mm diameter polyvinyl tubing and 45 m of gated irrigation pipe.

During all applications, the DE runoff covered from 65%–85% of the soil surface without effect on soil nutrient fluctuation as compared to that of the control plot (Ali *et al*., 2004). Higher coverage was obtained with dryer surface soils because the higher infiltration rate would slow the velocity of DE runoff. The average surface runoff velocity was of the order of 60 $m\,h^{-1}$ on farm MH-3 but ranged from 180 to 300 $m\,h^{-1}$ on farm MH-6 because of higher slopes. For all applications, DE runoff covered the full plot length but some accumulation regularly occurred at the bottom of the slope on farm MH-6, where the slope length at the plot corresponded to L_s, as opposed to farm MH-3, where the slope length exceeded L_s by 50 m.

4.2. *Infiltration capacity of the experimental plots and dairy effluent characteristics*

In the laboratory and on triplicate samples each measured three times after air drying, the loamy soils of farm MH-3 gave an average initial S of 270 $mm\,h^{-1}$ which dropped within 0·5 h to a stable value of $50 \pm 10\ mm\,h^{-1}$. On farm MH-6, the gravelly sandy (top of the slope) and clay soils (bottom of the slope) gave an average initial S of 900 and 200 $mm\,h^{-1}$, which, respectively, dropped to a constant value of $840 \pm 50\ mm\,h^{-1}$ and $50 \pm 10\ mm\,h^{-1}$ after 0·5 h. The irrigation rates I generally recommended (Schwab *et al*., 1986) are conservative values when compared with laboratory S values (Table 1), suggesting that I is equivalent to $(S \times f_s)$.

Table 4
Dairy effluent characteristics for farms MH-3 and MH-6

Parameter	*Farm MH-3*			*Farm MH-6*		
	2002	*2003*	*2004*	*2002*	*2003*	*2004*
Total solids, %	0·23	0·26	0·44	0·75	0·75	1·32
Dissolved solids, %	0·20	0·23	0·37	0·68	0·70	1·12
Suspended solids, %	0·03	0·03	0·02	0·07	0·05	0·05
Settleable solids, %	0·00	0·00	0·05	0·00	0·00	0·14
pH	6·8	7·1	7·2	7·3	7·4	7·2
Total nitrogen, mg l^{-1}	54	136	151	172	311	899
Total phosphorus, mg l^{-1}	19·5	19·1	30·2	14·7	20·7	40·8
Total potassium, mg l^{-1}	777	526	573	338	612	805
Chemical oxygen demand, mg l^{-1}	—	—	2199	—	—	10 449
Total coliforms, CFU ml^{-1}	20	84	42	4·0	81	32
Faecal coliforms, CFU ml^{-1}	1·7	3·0	14	1·0	8·3	15
Faecal streptococci, CFU ml^{-1}	22	1·1	40	120	150	193
FC/FS ratio	0·08	2·73	0·35	0·008	0·05	0·08

Note: FC, faecal coliforms; FS, faecal streptococci.
Farm MH-3, manure seepage and milk house dairy effluent; farm MH-6, manure seepage only.

Table 5
Dairy effluent application rate to meet crop nutrient requirements of 150 kg [N] ha^{-1}, 62 kg [P_2O_5] and 120 kg [K_20] ha^{-1} for a maize silage yield of 30 t ha^{-1} at 35% dry matter content

Year	*Application to meet crop requirements, m^3 ha^{-1}*		
	N	*P_2O_5*	*K_20*
Farm MH-3			
2002	2780	1390	125
2003	1040	1360	185
2004	940	860	170
Farm MH-6			
2002	870	1800	285
2003	500	1000	160
2004	170	660	120

On farms MH-3 and MH-6, 2002 DE were similar to those of 2003, but less loaded than those of 2004 because of the more intensive rainfalls observed during the winter of 2003/04 (Table 4). The DE of farm MH-3 were more diluted than those of farm MH-6 because of the larger storage surface area used per unit solid manure mass, and the fact that the farm MH-3 collected milk house wash waters while farm MH-6 did not. In general, the DE offered TS values under 1·5%, TN between 54 and 899 mg l^{-1}, TP between 14·7 and 40·8 mg l^{-1}, and TK between 338 and 805 mg l^{-1}.

Table 5 calculates the annual land DE application rate based on TP, the most environmentally limiting crop nutrient, for both farms MH-3 and MH-6 (Simard *et al.*, 1995). Because applications are based on TP, TK will be over-applied requiring the yearly rotation of the application plot. In general, DE nutrient loads are much lower than that of typical dairy manures (Westerman *et al.*, 1985).

4.3. *Seepage losses on farm MH-3*

During all irrigation sessions summarised in Table 3a, seepage was observed to start flowing into the plot sampling well 30 min after starting and to stop 90 min after finishing the DE application, but not into that of the control. During August 2003 and 2004, the irrigation sessions resulted in 1·6 and 4·0 m^3 of seepage losses, respectively, at the field outlet. This field outlet started to flow some 140 min after starting and to stop running 90 min after stopping the irrigation session. As observed by other researchers, irrigation leads to seepage losses (Fleming *et al.*, 1990).

Owing to dry climatic conditions in July 2003, the DE applications had no significant impact on the quality of the drainage waster collected at the sampling well of both the control and the irrigated plot (*Fig. 3a*). Also, during the first irrigation session, the control plot received 64 m^3 of DE applied using a conventional tanker, which lead to some well water contamination 3 days later, following a 30 mm rainfall. Nevertheless, the samples from both sampling wells demonstrated TN, TP and bacterial load equivalent to only 10% of that of the DE. On July 11th and 14th, less than 500 l of subsurface seepage flowed into the sampling well, following each applications of 450 and 230 m^3 ha^{-1}, but none was found at the outlet. On August 29th, 630 m^3 ha^{-1} of DE were irrigated after a 20 mm rainfall, which lead to the loss of 1·6 m^3 at the field outlet with on the average, 30% of the TN, TP and TK and 50% of the TC and FC but the same FS load contained in the applied DE.

In 2004, the control plot received no DE and its water samples were significantly less loaded than those collected from the irrigated plot sampling well (*Fig. 3b*). The samples collected from the well of the irrigated plot offered, on an average, only 25% of the load contained in the irrigated DE. On July 15th and 19th, 538 and 552 $m^3 ha^{-1}$ of DE under dry climatic conditions each produced less than 500 *l* of subsurface seepage and no outlet flow. On August 2nd and after a 100 mm rainfall, 682 $m^3 ha^{-1}$ of DE irrigation resulted in the loss of 4·0 m^3 at the field outlet with 20% of the TN, TP and TK load but 100% of the bacterial load contained in the

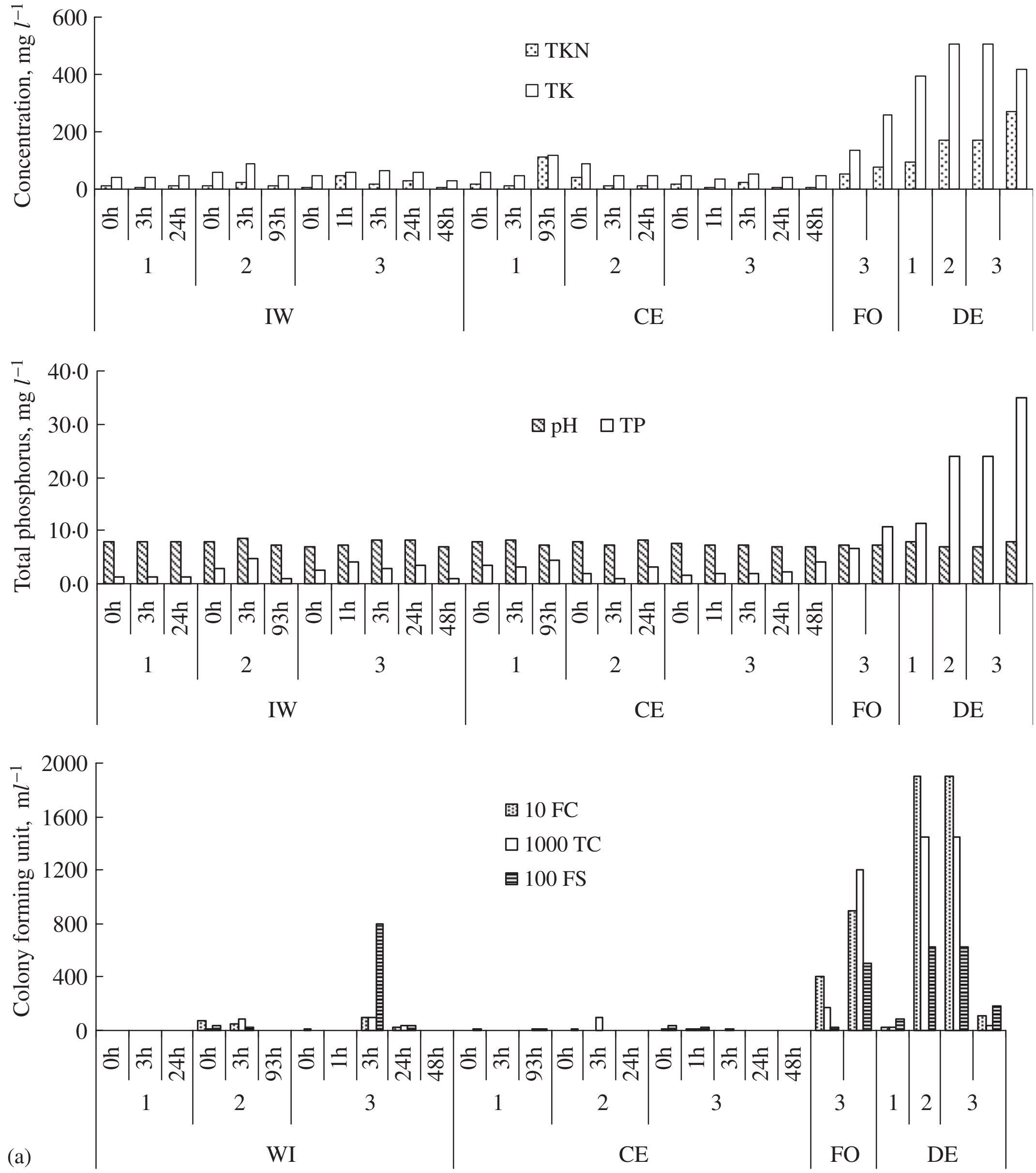

Fig. 3. (a) For farm MH-3 in 2003, water quality for: total kjeldahl nitrogen (TKN) and total potassium (TK); total phosphorus (TP) and pH; total coliforms (TC); faecal coliforms (FC) and faecal streptococci (FS). IW, irrigated plot; CE, control plot; FO, water quality flowing from main field subsurface drainage outlet; DE, dairy effluent applied; 1,2 and 3, irrigation sessions of the 11th and 14th of July and 29th of August, 2003, respectively. (b) For farm MH-3 in 2004, water quality for: total kjeldahl nitrogen (TKN) and total potassium (TK); total phosphorus (TP) and pH; total coliforms (TC), faecal coliforms (FC) and faecal streptococci (FS). IW, irrigated plot; CE, control plot; FO, water quality flowing from main field subsurface drainage outlet; DE, dairy effluent applied; 1,2 and 3, irrigation sessions of the 15th and 19th of July and 2nd of August, respectively

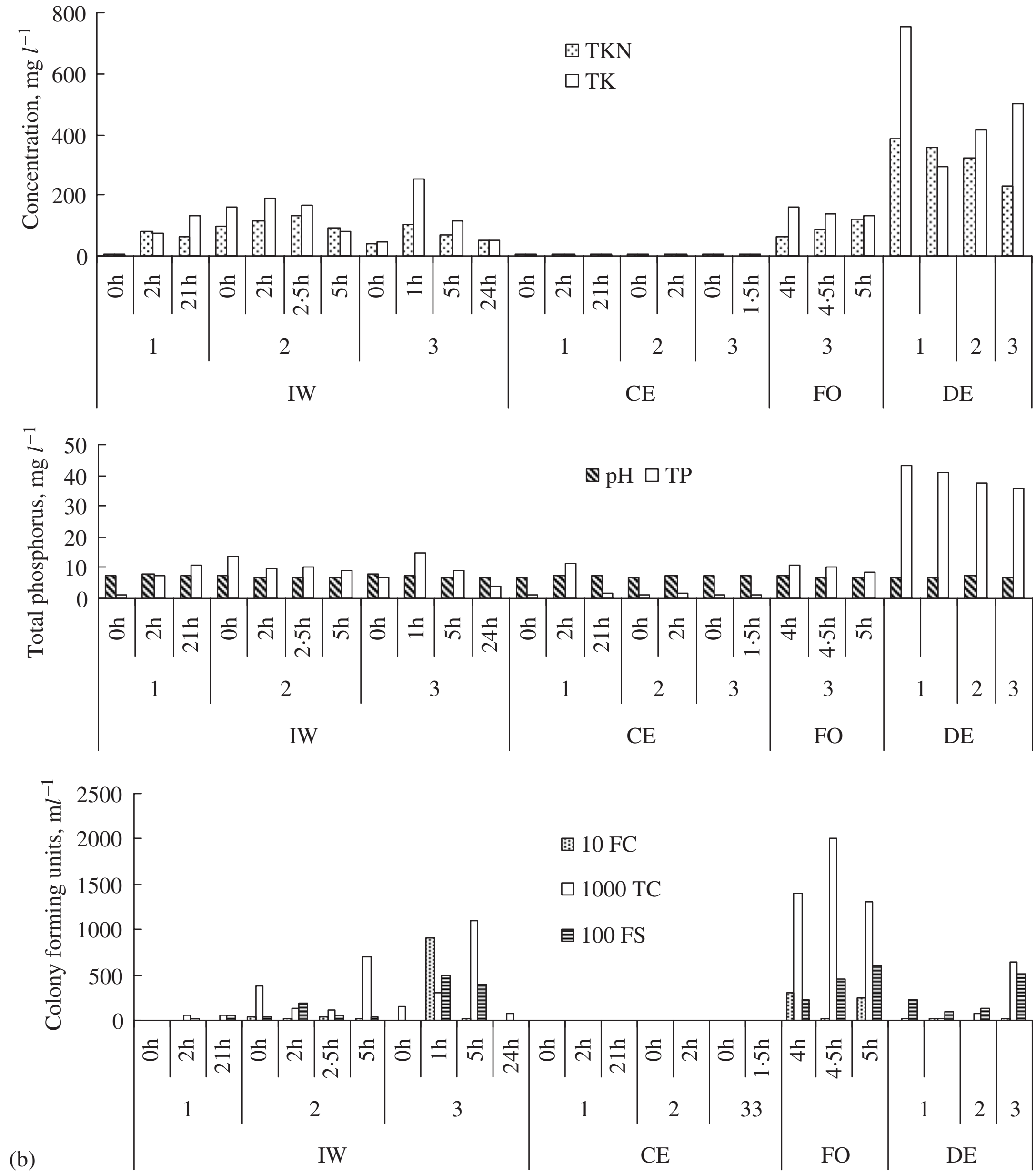

Fig. 3. (Continued)

irrigated DE. This increase in the bacterial count for the soil drainage water was also observed by Toyama *et al.* (1990), following the application of wastewaters.

The soil moisture content and piezometer readings of 2004 indicated why, in some cases, the DE seepage was lost at the subsurface field outlet. In July of both years and under conditions of dry surface soils and a groundwater table depth below the drains except for the irrigated plot after DE applications, only the sampling wells showed DE seepage. In August of both years and after a rainfall wetting the soil surface and raising the groundwater above the subsurface drains for the entire field encompassing the plots, DE seepage was lost at the field subsurface drainage outlet. Thus, when the groundwater is low throughout the field except for the irrigation plot, the subsurface DE seepage can infiltrate the ground as it flows towards, rather than flow out of the subsurface field outlet.

Therefore and during land irrigation, subsurface DE seepage can be minimised by applying recommended rates (Table 1), such as $550 m^3 ha^{-1}$ for farm MH-3 under conditions of low water table and dry surface soils. Under such conditions, less than 1% of the nutrients applied (500 *l* for an application of 225 m^3) will be drained by the subsurface drainage system, representing a treatment efficiency of at least 99%, which exceeds by far the efficiency of any biological treatment (Loerh, 1984).

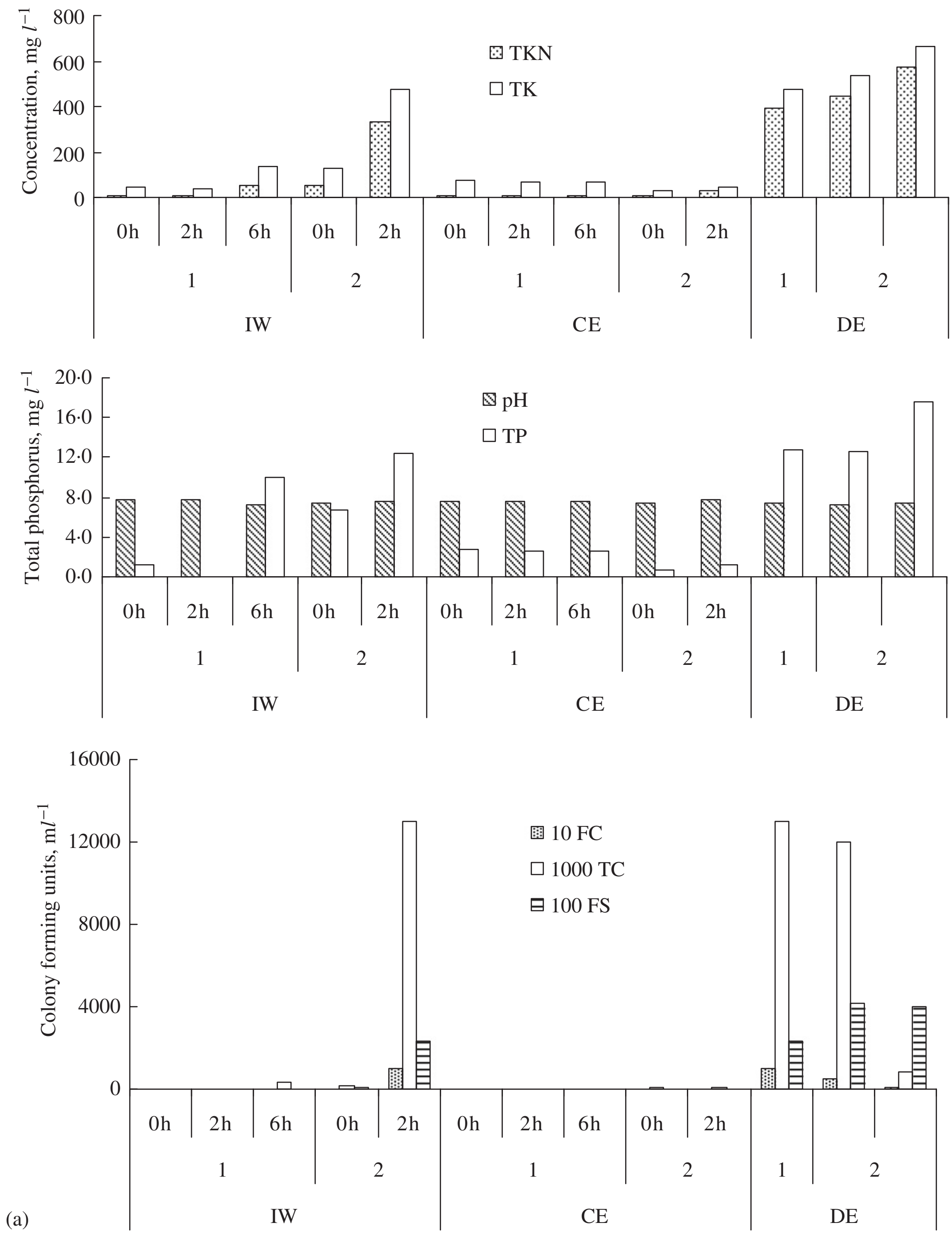

Fig. 4. (a) For farm MH-6 in 2003, water quality for: total kjeldahl nitrogen (TKN) and total potassium (TK); total phosphorus (TP) and pH; total coliforms (TC), faecal coliforms (FC) and faecal streptococci (FS). IW, irrigated plot; CE, control plot; DE, dairy effluent applied; 1 and 2, irrigation sessions of the 22nd and 25th of September, respectively. (b) For farm MH-6 in 2004, water quality for total kjeldahl nitrogen (TKN) and total potassium (TK); total phosphorus (TP) and pH; total coliforms (TC), faecal coliforms (FC) and faecal streptococci (FS). IW, irrigated plot; CE, control plot; DE, dairy effluent applied; 1 and 2, irrigation sessions of the 6th and 9th of July, respectively

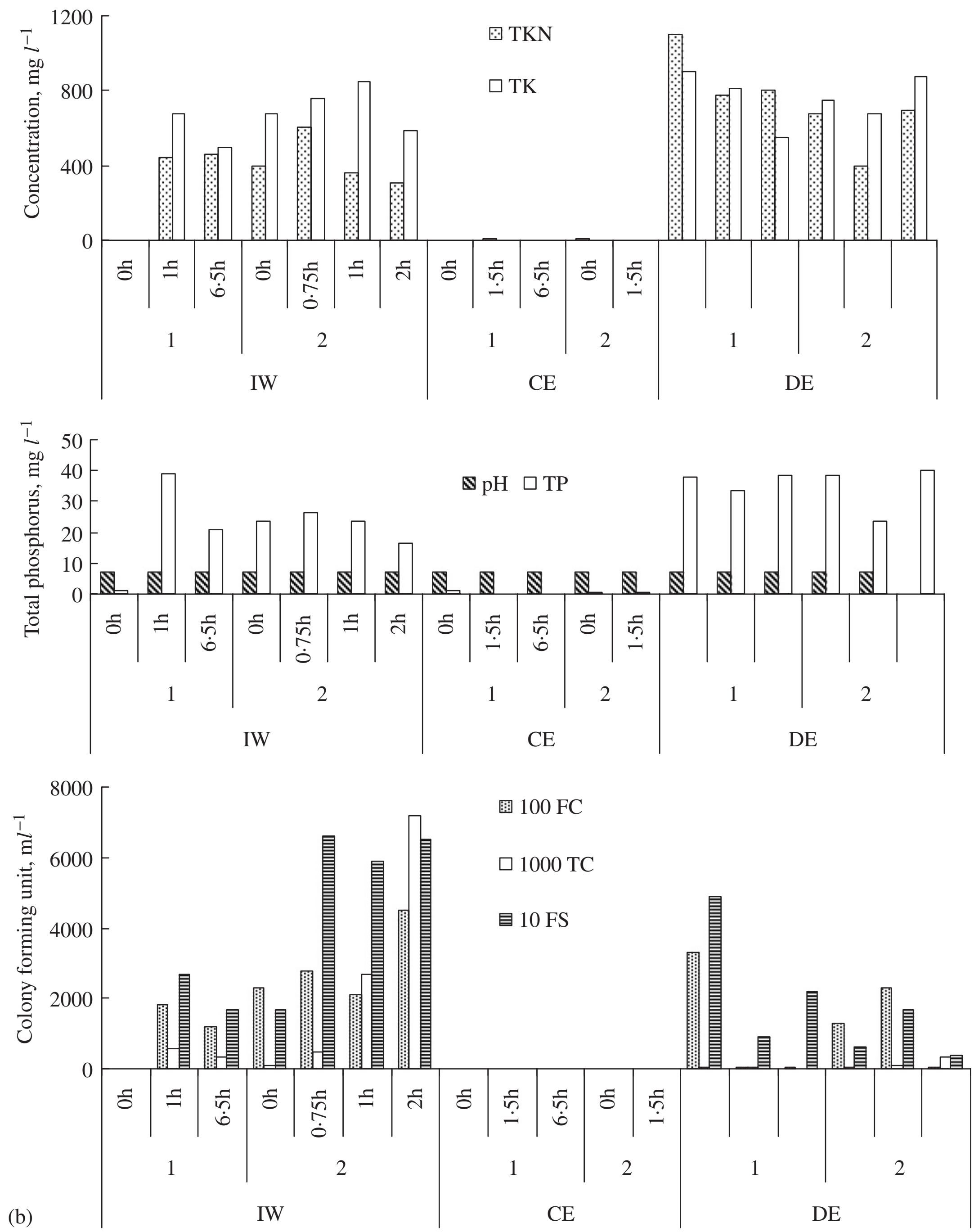

Fig. 4. (Continued)

4.4. *Seepage losses on farm MH-6*

Also on farm MH-6, seepage was observed to start flowing into the sampling well of the irrigated plot 30–45 min after initiating, and to stop 20–30 min after stopping the irrigation process. The DE were applied during 2003 and 2004, at the rate of 367 and 383 $m^3 ha^{-1}$ on the first day, and 130 and 217 $m^3 ha^{-1}$ on the second day, respectively, and seepage losses were always greater and lasted longer on the second day. Nevertheless, only a total of 100 *l* of DE seepage were estimated lost, each year, representing a treatment efficiency of at least 99%.

As no DE was applied to the control plot on both years, the water sampled from the well of the irrigated

Table 6
Dairy effluent application cost using surface irrigation and a conventional tanker

Operation	*Time, h*	*Manpower*		*Equipment*		*DE application rate, m^3 h^{-1}*	*Cost, CAN \$ m^{-3} [DE]*
		Person	*Cost, CAN \$*	*Required*	*Cost, CAN \$*		
Surface irrigation system							
Installation and dismantling	2	2	60·00	30 kW tractor and wagon	100·00		
Application	4	1	60·00	Irrigation pipe, 70 kW tractor, manure pump	850·00	450	
							1·10
Conventional tanker system							
Installation and dismantling	1	2	30·00	Tanker, pump and loading pipe	50·00		
Loading and application	15	1	225·00	2–90 kW tractors, manure pump and tanker	2925·00	64	
							3·25

Note: DE, diary effluent.
Manpower cost of CAN \$15 h^{-1}.
The equipment costs include machinery operating, depreciation and investment costs, and were assessed from the following purchasing and rental costs: CAN \$5000 for the irrigation pump and CAN \$4 000 for the irrigation pipe depreciated over 15 years; CAN \$30 h^{-1} for the 30 kW tractor, CAN \$20 h^{-1} for the wagon carrying the irrigation pipe; CAN \$50 and 65 h^{-1} for the 70 and 90 kW tractor; CAN \$65 h^{-1} for a tanker and manure pump.
The cost was computed on the basis that farms MH-3 and MH-6 sharing the equipment and spreading 1000 m^3 of DE year.

plot was significantly richer in nutrients and bacteria than those obtained from the well of the control plot (*Fig. 4a* and *b*). Generally in 2003, the water collected from the well of the irrigated plot contained 100% of the TP and 10% of the TN and TK of the irrigated DE. In 2004, this water contained the same nutrients but more bacterial load than the irrigated DE. Because of the gravely soil texture found on farm MH-6 as compared to farm MH-3, less DE filtration occurred through the soil macro-pores. Nevertheless, the volume lost represented a treatment efficiency of at least 99%.

4.5. *System operating costs*

On farm MH-3 and July 11th 2003, a conventional tanker was used to apply 32 m^3 of DE to the control plot, or four tanker loads of 8 m^3 applied at a rate of 64 m^3 ha^{-1}. This operation took 40 min and used two tractors, one operator, a tanker and a liquid manure pump. On the same day, the irrigated plot received 225 m^3 (450 m^3 ha^{-1}) of DE using the surface irrigation system, which took 55 min and only one tractor, one operator and a liquid manure pump. Setting up the tanker loading pipe took 15 min as compared to laying the irrigation pipe which took 30 min, both operations requiring 2 persons.

This data was used to compare the cost of spreading DE using a tanker and surface irrigation (Table 6). If the surface irrigation system is shared between farms MH-3 and MH-6, and the irrigation pipe is left in the field until all DE are applied, the surface irrigation system costs CAN \$1·10 m^{-3} of DE applied, as compared to CAN \$3·25m^{-3} when using a custom operator equipped with a tanker. The cost of applying DE by tanker is similar to that observed by Barrington (2002). The cost of the surface irrigation system could be further reduced if shared among more than two farms and if the increase in crop yield resulting from its irrigation was accounted for.

5. Conclusion

The main objective of this study was to establish management practices which limit the environmental impact of surface irrigating DE because the large volumes applied risk seeping in part, into the groundwater. The project also evaluated the cost of surface irrigation *versus* that of a conventional tanker pulled by a farm tractor.

On both farms monitored, subsurface DE seepage occurred relatively quickly, under all ranges of surface soil moisture content and groundwater table height. Nevertheless, these DE losses were minimised when irrigating dry soils, where the groundwater table was below the depth of the subsurface drainage system. Under such conditions, less than 1% of the DE volume, nutrients and bacteria were lost, implying a treatment efficiency of over 99%, which exceeds by far the efficiency of most biological treatment process.

Finally, the irrigation system reduced the cost of land spreading DE to CAN $\$1{\cdot}10\,m^{-3}$, to CAN $\$3{\cdot}25\,m^{-3}$ when using a conventional tanker pulled by a farm tractor. Furthermore, the time required to apply the DE was reduced by 75%.

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