Biosystems Engineering (2006) **95** (4), 547–556
doi:10.1016/j.biosystemseng.2006.08.002
SE—Structures and Environment

Surface Irrigation of Dairy Farm Effluent, Part I: Nutrient and Bacterial Load

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(Received 21 December 2005; accepted in revised form 8 August 2006; published online 13 October 2006)

When handled separately from manures, dairy farm effluents (DE) are costly to manage because of their low nutrient content and large volume. In anticipation of using surface irrigation to lower the land application cost of DE, this projects investigated the impact, on DE characteristics, of different sources and storage systems. Milk house wastewaters were monitored on two farms using a 500 *l* manhole intercepting these before entering the septic tank. Manure runoff, with and without milk house wastewater, was also characterised on six farms for 1 yr, and on two farms for three consecutive years, where each farm used a different management system. The results indicated that DE containing milk house wastewater, manure runoff or a mixture of both had a relatively low nutrient load, confirming that their application rate needed to range between 205 and 2050 $m^3 ha^{-1}$, depending on the management system used. Stored along with solid manure, DE generally had a higher total solids (TS), nutrient loads and bacterial count, as compared to that drained away from the solid manure. Furthermore, for effluent drained away from solid manures, rainfall rather than snow occurring from October to May, inclusively, tended to increase their TS and nutrient load. The ratio of faecal coliforms to faecal streptococci (FC/FS) was greater than 1·0 when milk house wastewaters were stored along with the manure runoff because milk house wastewaters increased the death rate for FS compared to FC.

1. Introduction

Worldwide, dairy farms generate large volumes of wastewaters or effluents (DE) which, if discharged directly into watercourses, can have significant environmental impacts (Ribaudo *et al.*, 2003; Mbwele *et al.*, 2003; Barrington & Piché, 1992; Craggs *et al.*, 2003). For every 24 $m^3 cow^{-1} yr^{-1}$ of manure generated, from 10 to 25 $m^3 cow^{-1} yr^{-1}$ of wastewaters must also be properly disposed. While some dairy farms use this wastewater to transform manures into slurries, others with as many as 200 dairy cows such as in the North West USA, manage solid manures separately from milk house and manure seepage effluents (Ribaudo *et al.*, 2003; Wright & Graves, 1990).

Dairy farm effluents have a relatively low nutrient load compared to dairy slurries (Table 1). Considering the typical nutrient load of DE (Table 2), their application using a conventional tanker at rates of 50–100 $m^3 ha^{-1}$ only contributes 2–14 $kg ha^{-1}$ of phosphorus when a forage crop requires 30 $kg ha^{-1}$ (CRAAQ, 2003). Thus, conventional manure-spreading equipment is time consuming and costly when used to land spread DE generated on these farms, while not fully meeting crop fertiliser requirements.

Dairy farm effluent could be discharged directly into watercourses if a cost-effective treatment strategy was developed to sufficiently reduce their contaminant load. Constructed wetlands were tested for this purpose in Europe, New England and Eastern Canada. Schaafsman *et al.* (2000), Newman *et al.* (2000), Knight *et al.* (2000), Cronk (1996) and Tanner *et al.* (1995a, 1995b) found that constructed wetlands for DE generally reduced ammonium by 95%, total phosphorus (TP) by 55% and total solids (TS) by 95%. In contrast, nitrite/nitrate levels were increased by up to 80%, although the nitrite/nitrate fraction was generally less than 10% of the total nitrogen (TN) load. Nevertheless, constructed

Table 1
Reported nutrient load of dairy farm effluent (DE) and dairy slurry

*Nutrient**	*DE*		*Dairy slurry*
	Milking wastewater	*Manure runoff*	
Total solids (TS), %	0·21	0·72	5·7
Total nitrogen (TN), kg m^{-3}	0·055	0·205	2·7
Total phosphorus (TP), kg m^{-3}	0·14	0·035	0·6
Total potassium (TK), kg m^{-3}	—	—	1·6
Land application rate†, m^3 ha^{-1}	220	890	52

*According to Loehr (1984) and Westerman *et al.* (1985).
†Application rate for 31 kg ha^{-1} of total phosphorus required by a forage crop (CRAAQ, 2003).

Table 2
Reported of dairy farm effluent (DE) nutrient load

Reference	*Total solids g l^{-1}*	*Total nitrogen, mg l^{-1}*	*Total phosphorus, mg l^{-1}*	*Total potassium mg l^{-1}*	*Biological oxygen demand, mg l^{-1}*	*Total chemical oxygen demand g l^{-1}*	*Bacteria 10^6 cell counts ml^{-1}*		
							Faecal coliforms	*Total coliforms*	*Faecal streptococci*
Luostarinen and Rintala (2005)	NA	30	24	16	NA	596	NA	NA	NA
Newman *et al.* (2000)	+ 1·3	103	26	NA	2683	NA	0·6	NA	NA
Schaafsman *et al.* (2000)	1·6	170	52·5	NA	1914	NA	NA	NA	NA
Knight *et al.* (2000)	+ 1·1	102	NA	NA	442	NA	NA	NA	NA
Wright and Graves (1990)	2·8–15	720–7500	230–830	570–3330	8370	25–41	NA	NA	NA
Tanner *et al.* (1995a, 1995b)	+ 0·2	75	15	NA	57	NA	0·002	NA	NA
Sweeten and Wolfe (1990)	3·0	170	24	170	NA	4269	NA	NA	NA
Loehr (1984)*	0·2	55	14	NA	NA	NA	NA	NA	NA
Loehr (1984)†	0·72	205	35	NA	NA	NA	NA	NA	NA

Note: NA, data not available.
*Milk house wastewater.
†For manure runoff.

wetlands were found to be non-sustainable by accumulating non-volatile elements such as phosphorus, and thus, introducing the risk of groundwater contamination. Besides requiring the dredging of the wetland's sediments after a number of years, the nutrients retained are not recycled for crop production.

Alternative options have been tested for the on-site load reduction of DE, such as anaerobic fermentation (Luostarinen & Rintala, 2005), reverse osmosis (Reimann, 1997), aerobic digestion (Craggs *et al.*, 2003), septic tank systems (Lens *et al.*, 2001) and a combination of these. Even if a 90% treatment efficiency is reached by such systems, the effluent is still too highly loaded in nitrogen and phosphorus to be discharged directly into a watercourse.

In an effort to offer dairy farms a more economical, practical and sustainable system for the disposal of their effluents, while using the full nutrient value and the water for irrigation, Ali *et al.* (2005) have adapted surface irrigation for their land application. As opposed to vegetative filters which treat wastewaters during rainstorms, surface irrigation enables wastewater applications on dry soils to minimise the risk of effluent leaching to the groundwater and to optimise the irrigation value of the water applied. Furthermore, the crop yield can be improved as a result of the water applied. Nevertheless, the quantity of effluent applied to farmland must not exceed crop nutrient requirements, and especially that of phosphorus, to comply with agro-environmental regulations (MENQ, 2002). According to Table 2, the nutrient content of DE can be quite variable and requires defining in terms of farm management system.

The objective of this paper was therefore to investigate the impact, on DE characteristics, of the source and the type of manure management system used. The seven farms surveyed had a variety of effluent composition (milk house wastewaters, manure runoff or a mixture of both) and used different manure storage systems, which tested their impact on the volume and characteristics of DE.

2. Method

2.1. *Milk house wastewater effluent*

From July 2003 to June 2005, milk house wastewaters were monitored on two different farms using a pipeline as milking system (Table 3), the first with a 50 cow herd (farm MH-1) and the second with a 40 cow herd (farm MH-2). The volume of milk house wastewater produced daily was measured by installing a flow meter on the water line supplying the milk house. The milk house wastewaters were collected and sampled using a manhole measuring 1·2 m in diameter and 1·8 m in depth, installed upright before the septic tank (*Fig. 1*). The volume retained in the manhole corresponded to at least one milking, and the inlet and outlet piping were designed to retain sediments and milk fat.

Wastewater samples were collected from the manholes on a monthly basis, except for January to March. On both farms, the manhole content was mixed with a sewage spoon before sampling. On farm MH-1 where sediments did accumulate in the manhole, the wastewater was sampled before mixing to measure its load and, after mixing, to characterise the sediment load by comparing values before and after mixing. In contrast to farm MH-1, milk fat accumulated at the surface of the manhole wastewaters on farm MH-2 and this milk fat was therefore measured, sampled and analysed separately.

All wastewaters were analysed for TS, suspended solids (SS), dissolved solids (DS), pH, TN, TP and total potassium (TK). All sediments and milk fat were analysed for all the above except for SS and DS. Milk fat was also analysed for chemical oxygen demand (COD).

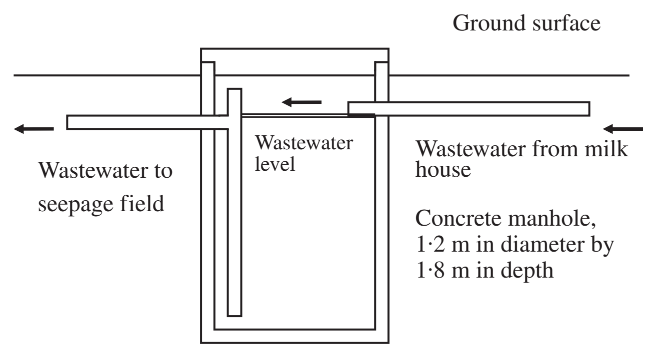

Fig. 1. Manhole used to collect milk house wastewaters intercepted before the septic tank system

Table 3
Description of dairy farms participating in the survey

Parameter	*Farm MH-1*	*Farm MH-2*	*Farm MH-3*	*Farm MH-4*	*Farm MH-5*	*Farm MH-6*	*Farm MH-7*
Cow number	50	40	44	52	50	24	60
Average cow weight, kg	625	575	600	650	625	650	650
Cow breed	Holstein	Holstein and Jersey	Holstein	Holstein	Holstein	Holstein	Holstein
Solid storage pad, m^2 cow^{-1}	14·1	None	21·8	13·5	10·1	22·9	11·2
Effluent storage, m^2 cow^{-1}	None	None	9·1	5·9	20·2	4·2	None
Total storage area, m^2 cow^{-1}	14·1	0	30·9	19·4	30·3	27·1	11.2
Manure storage effluent composition	MR	NA	MH MR	MR	MR	MR	MR
Basic ration	Maize silage, dry hay and alfalfa haylage	Maize silage and dry mixed hay	Maize silage and dry mixed hay	Maize silage and dry mixed hay	Maize silage and dry mixed hay	Maize silage, dry hay and alfalfa haylage	Maize silage and dry mixed hay
Average milk production, *l* cow^{-1} yr^{-1}	9500	8000	8250	8500	8250	9500	9250

MR, manure runoff; MH, milk house wastewater; NA, not applicable.

2.2. *Effluent containing manure runoff alone or mixed with milk house wastewater*

To evaluate the impact of various factors on DE nutrient load, each monitored farm offered a different combination of effluent type and manure storage facility. From 2002 to 2004, DE was sampled from the storage facility of six farms for 1 yr and from that of two of these six farms for 3 yr (Table 3).

There are two general ways of storing solid manures and DE [*Fig. 2*(*a*) and (*b*)]. The dairy effluents consist of contaminated precipitations collected from the solid manure storage facility, and manure liquids originating from urine and manure decomposition, plus, in some cases, milk house wastewater. Solid manure piles and DE can be stored separately, using a low wall pad (less than 2·4 m high) for the solids and a separate deep pit (walls of 3·6–6·1 m) into which the DE are drained, such as in system A [*Fig. 2*(*a*)]. Also, the DE can be stored along with solid manures, such as in system B [*Fig. 2*(*b*)], where the storage structure offers a wall height limited to 2·4 m because of the ramp (slope of 1 vertical to 10 horizontal) used to access and remove the solids with a loader. System A is more costly to build and generally accumulates more precipitation because of its greater surface area, but its content is easier and cleaner to handle as the solids are drier. With system B, the effluents are in contact with the solid manure during the entire storage period and are therefore harder to drain and pump out while the manure remains wetter and sloppier to handle (Barrington & Piché, 1992).

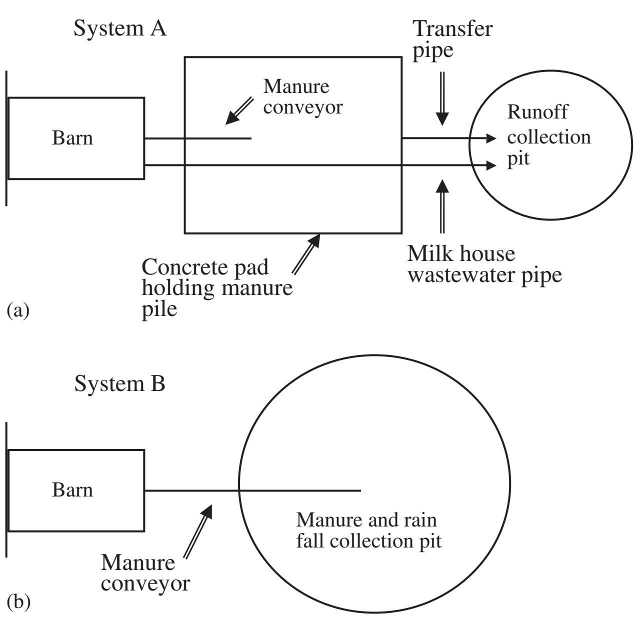

Fig. 2. Manure and milk house wastewater management on experimental farms. Farms MH-3, MH-4, MH-5 and MH-6 used the first system A (separate manure pile and effluent storage) while farms MH-1 and MH-7 used the system B (same manure pile and effluent storage)

With herds of 50 and 60 cows, respectively, both farms MH-1 and MH-7 stored solid manures and only its runoff within the same structure [*Fig. 2*(*b*)]. With herds of 44, 50 and 24 cows, respectively, farms MH-3, MH-5 and MH-6 stored their manure on a concrete pad and their effluent in an earthen basin such as in system A [*Fig. 2*(*a*)], but the effluent on farm MH-3 consisted of both milk house wastewater and manure runoff while that of farms MH-5 and MH-6 consisted of manure runoff only. With a herd of 52 cows, farm MH-4 used system A where solid manures were accumulated on a concrete pad and manure runoff only was drained into a concrete tank.

Owing to the settling which can occur in these storage facilities, effluent samples were collected at three different depths (bottom, centre and surface) using a 1 *l* bottle with a removable cap. The bottle was inserted at the required depth and the cap was pulled off to fill the bottle. At the same time, the size of the storage facility, the depth of effluent it contained and the date of the last emptying operation were measured and obtained to compute the volume produced annually.

The sampling of DE on six different farms (all farms except for MH-2) during 1 yr (2002) provided data pertaining to the effect on effluent characteristics, of the storage system (system A *versus* system B) and the source of wastewater. The sampling of DE on two farms (MH-3 and MH-6) for 3 yrs, provided information on the variation of nutrient load with climatic conditions. All effluent samples were analysed for TS, SS, DS, pH, TN, TP, TK and bacteria (total coliforms, TC; faecal coliforms, FC; and faecal streptococci, FS).

2.3. *Analytical procedure*

All analyses were conducted using standard methods (APHA, 1998). Total solids were determined gravimetrically after drying for 24 h at 103 °C. Suspended solids were separated from the DS by filtering using a 0·45 μm filter, and then quantified by drying for 2 and 24 h, respectively, at 103 °C. After digesting all samples at 500 °C using 18 M sulphuric acid and 50% hydrogen peroxide, total kjeldahl nitrogen (TKN) was determined using an ammonia-sensitive probe connected to an Orion pH meter, and TP and TK were determined colorimetrically using a spectrophotometer. Total nitrogen was obtained by adding the TKN concentration to that of nitrite and nitrate-N (NO_2-N and NO_3-N). Where levels of NO_2-N and NO_3-N were low, TKN was assumed equal to TN. Sample nitrite and nitrate levels were determined using an ion selective probe connected to an Orion pH meter.

Chemical oxygen demand was determined colorimetrically after oxidising with potassium chromate at 140 °C. The pH of all samples was determined using a pH probe connected to an Orion meter. The bacterial counts were conducted by filtering diluted DE samples using a micropore filtration method, by incubating the filters at a temperature and in an agar appropriate for the individual groups of organisms to be identified, namely TC, FC and FS (APHA, 1998) and by reporting the counts in colony forming units (CFU) ml^{-1}.

2.4. *Statistical procedure*

Excel (Microsoft 2003 software) was used to correlate the effluent load (TS, TN, TP and TK) to the size of manure storage system and winter precipitation, and to calculate the standard deviation of the effluent analytical values. For the 24 samples of milk house wastewater collected on each one of the two farms, during 3 yr, the standard deviation of the loads was computed using Excel (Microsoft 2003 software).

3. Results and discussion

3.1. *Characteristics of effluent composed of milk house wastewaters*

Based on the monthly water meter readings, the average daily volume of wastewater produced on farm MH-1 varied between 12·0 and 15·0 l cow^{-1}, while that of farm MH-2 varied from 12·5 to 13·0 l cow^{-1}. On farm

Table 4a
Average milk house wastewater characteristics for farm MH-1

Parameter	*Year 1*			*Year 2*			*Year 3*		
	ww	*sed**	*fat*	*ww*	*sed**	*fat*	*ww*	*sed**	*fat*
TS, %	0·29 (0·09)		0	0·28 (010)		0	0·23 (0·05)		0
SS, %	0·04 (0·03)		0	0·04 (0·03)		0	0·03 (0·02)		0
DS, %	0·24 (0·08)		0	0·28 (0·10)		0	0·20 (0·04)		0
pH	7·6 (0·3)		0	8·3 (1·1)		0	7·4 (0·51)		0
NH_4-N, mg l^{-1}			0			0			0
TKN, mg l^{-1}	72 (29)	—	0	39 (21)	1943	0	67 (29)	1448	0
TP, mg l^{-1}	97 (70)	—	0	105 (85)	1227	0	99 (24)	504	0
TK, mg l^{-1}	383 (212)	—	0	152 (161)	1366	0	71 (27)	395	0

Note: ww, wastewater; sed, sediments; fat, milk fat.
TS, total solids; SS, suspended solids; DS, dissolved solids; TKN, total kjeldahl nitrogen; TN, total nitrogen; TP, total phosphorus; TK, total potassium.
*TN, TP and TK for the sediments are expressed in terms of g kg^{-1} [dm].
The value in parenthesis is the standard deviation computed from eight values for each year.

Table 4b
Average milk house wastewater characteristics for farm MH-2

Parameter	*Year 1*			*Year 2*			*Year 3*		
	ww	*sed**	*fat*	*ww*	*sed**	*fat*	*ww*	*sed**	*fat*
TS, %	0·51 (0·55)	0	19·7 (2·3)	0·32 (0·17)	0	20·6	0·32 (0·17)	0	12·8 (1·4)
SS, %	0·07 (0·12)	0	—	0·12 (0·10)	0	—	0·10 (0·10)	0	—
DS, %	0·20 (0·16)	0	—	0·26 (0·21)	0	—	0·21 (0·16)	0	—
pH	6·0 (0·3)	0	—	6·1 (0·4)	0	—	6·2 (0·4)	0	—
TKN, mg l^{-1}	133 (64)	0	5463 (980)	88 (49)	0	1062	132 (102)	0	598 (219)
TP, mg l^{-1}	105 (31)	0	101 (54)	85 (35)	0	130	107 (28)	0	93 (28)
TK, mg l^{-1}	229 (123)	0	187 (120)	270 (156)	0	219	100 (48)	0	341 (107)
COD, g kg^{-1}	—	—	460 (27)	—	—	611	—	—	644 (38)

Note: ww, wastewater; sed, sediments; fat, milk fat.
TS, total solids; SS, suspended solids; DS, dissolved solids; TKN, total kjeldahl nitrogen; TN, total nitrogen; TP, total phosphorus; TK, total potassium; COD, chemical oxygen demand.
*TN, TP and TK for the sediments are expressed in terms of g kg^{-1} [dm].
The value in parenthesis is the standard deviation computed from eight values for each year.

MH-1, sediments accumulated in the sampling manhole, but no milk fat was observed while on farm MH-2, an important amount of milk fat was collected, but no sediments were observed. Thus, wastewater characteristics are presented separately from those of milk fat and sediments (Tables 4a and b).

On farm MH-2, the total amount of milk fat produced by the milk house wastewaters could not be quantified because some was transported into the septic tank and even into the sewer pipes of the seepage field. Also, milk fat accumulation varied, reaching 12 mm month^{-1}, during the first year, disappearing during the next winter and accumulating at a rate of 8 mm month^{-1} during the following year. The build up of milk fat on farm MH-2 was attributed to the dumping of wasted milk and the absence of a water softener. On farm MH-1, all wasted milk was diverted to the manure storage facility, thus reducing the risk of milk fat build up, and a water softener helped soaps better dissolve fats.

On farm MH-1, the accumulation of sediments also varied with season and from one year to the next, as a result of their decomposition and as confirmed by the monthly variation in TS load of the mixed wastewater samples.

Table 5a
Dairy farm effluent characteristics—effluents stored in a separate pit (system A)

Parameter	*Farm MH-3*			*Farm MH-4*			*Farm MH-5*			*Farm MH-6*		
	Bottom	*Mid*	*Surface*	*Bottom*	*Mid*	*Surface*	*Bottom*	*Mid*	*Surface*	*Bottom*	*Mid*	*Surface*
TS, %	0·23	0·24	0·22	1·32	1·01	1·00	1·55	0·59	0·43	0·79	0·77	0·69
SS, %	0·19	0·21	0·19	1·06	0·81	0·80	1·47	0·56	0·41	0·71	0·70	0·62
DS, %	0·03	0·03	0·03	0·26	0·20	0·20	0·08	0·03	0·02	0·08	0·07	0·07
pH	6·8	6·8	6·9	7·1	7·5	7·5	7·0	7·0	7·2	7·2	7·3	7·3
NH_4-N, mg l^{-1}	34·1	37	15·5	460	444	435	677	183	53	147	143	106
TKN, mg l^{-1}	53·7	65	43·7	644	639	508	1149	310	111	192	173	151
TP, mg l^{-1}	24·1	20	14·0	89	69	18·4	39·4	14·4	5·1	15·6	12·2	16·5
TK, mg l^{-1}	1352	762	218	487	545	437	333	236	83	498	312	204
TC, CFU ml^{-1}	50	500	50	2300	2100	1200	2700	2700	1600	20	50	50
FC, CFU ml^{-1}	10	30	10	1800	1800	1200	2100	50	460	20	5	5
FS, CFU ml^{-1}	5	55	5	16 000	500	400	1300	15 000	50	50	400	40
FC/FS	2	0·55	2	0·113	3·6	3·0	1·62	0·003	9·2	0·4	0·013	0.13

Note: bottom, mid and top, effluent sampled at the bottom 0·3 m, middle and top 0·3 m depth of the pit.
TS, total solids; SS, suspended solids; DS, dissolved solids; TKN, total Kjeldahl nitrogen; TN, total nitrogen; TP, total phosphorus; TK, total potassium; CFU, colony forming units.
Only farm MH-3 stored both milk house wastewaters and manure runoff; all other farms stored only manure runoff.

Table 5b
Dairy farm effluent characteristics—effluents stored in the same pit (system B)

Parameter	*Farm MH-1*			*Farm MH-7*		
	Bottom	*Mid*	*Surface*	*Bottom*	*Mid*	*Surface*
TS, %	1·35	2·22	3·27	4·38	2·93	2·56
SS, %	1·29	2·11	3·11	3·94	2·63	2·31
DS, %	0·06	0·11	0·16	0·44	0·30	0·25
pH	6·8	6·7	7·1	6·7	6·7	6·8
NH_4-N, mg l^{-1}	359	1025	1503	1881	1327	1084
TKN, mg l^{-1}	561	1030	1594	2234	1666	1459
TP, mg l^{-1}	142	126	135	188	148	86
TK, mg l^{-1}	686	1081	813	1331	1088	807
TC, CFU ml^{-1}	1200	1200	7100	3400	5400	21000
FC, CFU ml^{-1}	1200	1200	4200	2800	3200	9300
FS, CFU ml^{-1}	10^5	46 000	68 000	61 000	10^5	22 000
FC/FS	0·012	0·026	0·069	0·044	0·032	0·43

Note: bottom, mid and surface, effluent sampled at the bottom 0·3 m, middle and surface 0·3 m depth of the pit.
TS, total solids; SS, suspended solids; DS, dissolved solids; TKN, total Kjeldahl nitrogen; TN, total nitrogen; TP, total phosphorus; TK, total potassium; COD, chemical oxygen demand; CFU, colony forming units.

In general, the nutrient load of the milk house wastewaters remained within the same range for both experimental farms (Tables 4a and b). The TS ranged between 0·2% and 0·4%, and the nutrients, namely TKN, TP and TK, ranged respectively between 40–110, 70–130 and 125–350 mg l^{-1}. Compared to farm MH-1, the wastewaters of farm MH-2 contained slightly more solids and also more TN and TP, and their pH was slightly lower, as a result of wasted milk being discharged into the system and the absence of a water softener. On both farms, the wastewater pH remained above 6·0, indicating that the strong soaps did not acidify to the extent of inhibiting microbial activity.

Based on an average production rate of 13·5 l cow^{-1} day^{-1}, for farms MH-1 and MH-2, and their average TP load of 100 mg l^{-1}, the milk house wastewaters could fertilise 1·5 ha of forage crop (100 dairy cows)$^{-1}$, at 30 kg of TP ha^{-1}, if applied at a rate of 300 m^3 ha^{-1} (CRAAQ, 2003).

3.2. *Dairy farm effluent with and without milk house wastewater*

The characteristics of the DE sampled from the six farms, each with a different type of management system for manures and milk house wastewaters, are summarised in Tables 5a and b. In general, the effluent stored along with the solid manure (system B) had higher TS, nutrients and bacterial counts, than that drained and stored in a separate pit (system A), as a result of their prolonged contact with solid manures.

For the farms storing their effluent in a separate structure, the TS levels were generally under 1·5% and there were little differences in nutrient concentrations and bacterial counts among the bottom, centre and surface samples (Table 5a). On farms where the effluent was stored in the same structure as the solid manure, the TS averaged over 2·0% and the level of TS, TN and TP was found to increase with sampling depth (Table 5b).

For the sampling of year 1, the following relationship was found between DE total solids T_s in % and total storage area A in m^2:

$$T_s = -2{\cdot}56 \times \mathrm{Ln}(A) + 9{\cdot}18 \quad (1)$$

with a high value for the coefficient of determination R^2 of 0·92, indicating that the total area directly affects the amount of rainfall collected by the storage, with or without milk house wastewaters, because these also affect the size of the storage structure. Since some DE originates from urine and manure decomposition, besides contaminated precipitations, a maximum value for T_s of 9·18% was reached in the absence of an area receiving precipitations.

Also, the following relationships between effluent total solids T_s in % and nutrient in mg l^{-1} such as total nitrogen T_N, total phosphorus T_P, and total potassium T_K, respectively, were found through regression equations:

$$T_N = 63{\cdot}5\mathrm{e}^{0{\cdot}787}T_s \quad (2)$$

$$T_P = 16{\cdot}68\mathrm{e}^{0{\cdot}220}T_s \quad (3)$$

$$T_K = 493\mathrm{e}^{0{\cdot}122}T_s \quad (4)$$

where the respective values for R^2 are 0·91, 0·47 and 0·18, respectively. The high correlation between T_N and T_s results from the fact that T_N is found in both the solid and liquid fractions of the DE. Despite the fact that phosphorus is generally contained in the solids, the poor correlation between T_P and T_s implies that a relatively high fraction of T_P is soluble. The poor relationship

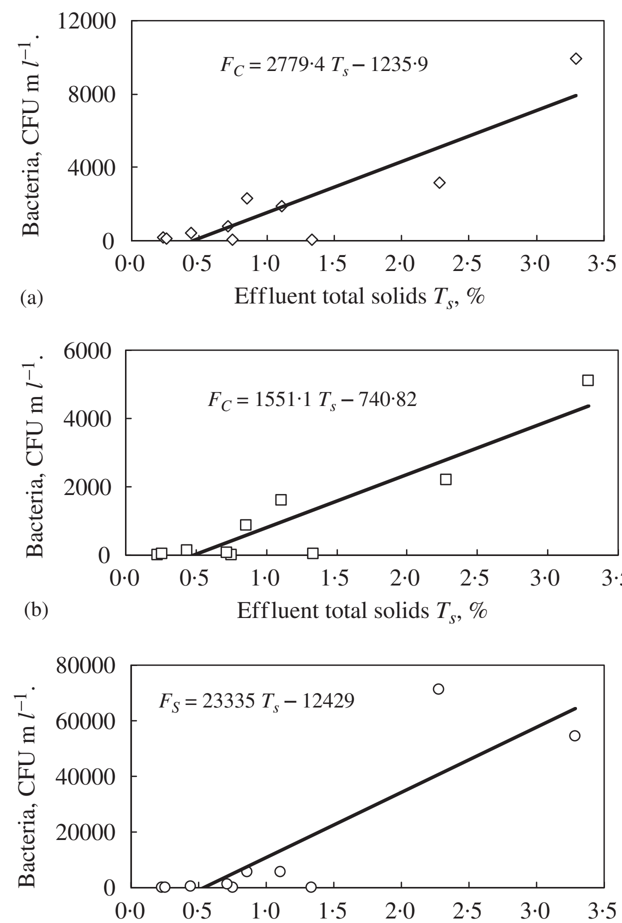

Fig. 3. Effect of dairy farm effluent total solids (TS) on: (a) total coliforms, T_C, coefficient of determination R^2 of 0·79; (b) faecal coliforms, F_C, coefficient of determination R^2 of 0·85; (c) faecal streptococci F_S, coefficient of determination R^2 of 0·75; CFU, colony forming units

between T_K and T_s is justified by the fact that potassium is generally soluble and not found in T_s.

For all six farms monitored, the bacterial counts increased linearly with effluent total solids, regardless of the effluent composition and the type of manure storage system (*Fig. 3*). Also, the presence of milk house wastewater generally resulted in a FC/FS ratio greater than 1·0 while that consisting of solely manure runoff has a ration under 1·0, regardless of the storage system. The ratio of FC/FS is generally above 1·0 for fresh human wastewaters while that of livestock is generally under 1·0 (Loehr, 1984). It therefore appears that ageing manure runoff with milk house wastewaters increases the death rate for FS compared to FC, resulting in a FC/FS ratio above 1·0.

The DE characteristics for farms MH-3 and MH-6 (Tables 6a and b) were similar for years 1 and 2 but of higher concentrations for year 3. Also, year 3 produced DE where TS were relatively high up to the centre depth, as compared to years 1 and 2 where the TS content was

Table 6a
Characteristics of dairy farm effluent for farm MH-3 (system A with milk house wastewaters)

Parameter	*Year 1*			*Year 2*			*Year 3*		
	Bottom	*Mid*	*Surface*	*Bottom*	*Mid*	*Surface*	*Bottom*	*Mid*	*Surface*
TS, %	0·23	0·24	0·22	0·36	0·22	0·19	0·59	0·45	0·28
SS, %	0·19	0·21	0·19	0·33	0·19	0·15	0·50	0·37	0·25
DS, %	0·03	0·03	0·03	0·03	0·03	0·04	0·02	0·08	0·03
Set S, %	—	—	—	—	—	—	0·07	0·00	0·00
pH	6·8	6·8	6·9	7·0	7·1	7·3	0·07	0·08	0·02
NH_4-N, mg l^{-1}	34·1	37	15·5	—	—	—	6·9	6·9	7·9
TKN, mg l^{-1}	53·7	65	43·7	194	115	98	231	153	71
TP, mg l^{-1}	24·1	20	14·0	24·7	18·0	14·7	40·8	31·2	18·6
TK, mg l^{-1}	1352	762	218	503	520	554	754	583	382
COD, mg l^{-1}	—	—	—	—	—	—	3200	2106	1292
TC, CFU ml^{-1}	50	500	50	90	120	230	300	870	100
FC, CFU ml^{-1}	10	30	10	60	20	9	280	130	10
FS, CFU ml^{-1}	5	55	5	20	13	$<$10	1100	100	2
FC/FS	2	0·55	2	3	1·54	1	0·25	1·3	5

Note: bottom, mid and top, effluent sampled at the bottom 0·3 m, middle and top 0·3 m depth of the pit.
TS, total solids; SS, suspended solids; DS, dissolved solids; See s, settle-able solids; TKN, total kjeldahl nitrogen; TN, total nitrogen; TP, total phosphorus; TK, total potassium; COD, chemical oxygen demand; CFU, colony forming units.

Table 6b
Characteristics of DE for farm MH-6 (system A without milk house wastewaters)

Parameter	*Year 1*			*Year 2*			*Year 3*		
	Bottom	*Mid*	*Surface*	*Bottom*	*Mid*	*Surface*	*Bottom*	*Mid*	*Surface*
TS, %	0·79	0·77	0·69	0·85	0·68	0·62	1·54	1·58	0·89
SS, %	0·71	0·70	0·62	0·86	0·65	0·60	1·38	1·28	0·71
DS, %	0·08	0·07	0·07	0·09	0·03	0·02	0·05	0·23	0·18
Set S, %	0	0	0	0	0	0	0·11	0·07	0·00
pH	7·2	7·3	7·3	7·3	7·5	7·5	7·0	7·0	7·6
NH_4-N, mg l^{-1}	147	143	106	—	—	—	—	—	
TKN, mg l^{-1}	192	173	151	451	269	215	1008	1375	313
TP, mg l^{-1}	15·6	12·2	16·5	27·0	21·4	13·8	36·6	51·8	34·1
TK, mg l^{-1}	498	312	204	635	605	596	713	752	948
COD, mg l^{-1}	—	—	—	—	—	—	13744	13636	3966
TC, CFU ml^{-1}	20	50	50	2000	340	100	29	55	12
FC, CFU ml^{-1}	20	5	5	90	100	60	29	15	1·0
FS, CFU ml^{-1}	50	400	40	850	1800	400	270	300	10
FC/FS	0·4	0·013	0·013	0·106	0·056	0·150	0.110	0.050	0.100

Note: bottom, mid and top, effluent sampled at the bottom 0·3 m, middle and top 0·3 m depth of the pit.
TS, total solids; SS, suspended solids; DS, dissolved solids; Set s, settle-able solids; TKN, total kjeldahl nitrogen; TN, total nitrogen; TP, total phosphorus; TK, total potassium; COD, chemical oxygen demand; CFU, colony forming units.

Table 7
Effluent volume produced annually as a function of precipitation

Parameter	*Farm MH-3*			*Farm MH-6*		
October to May inclusively	*Year 1*	*Year 2*	*Year 3*	*Year 1*	*Year 2*	*Year 3*
Effluent volume produced, m^3	652	687	886	150	150	180
Average effluent TS, %	0·23	0·26	0·44	0·75	0·72	1·33
Rainfall, mm	458	456	599	458	456	599
Snow, mm	128	177	208	128	177	208
Total precipitation, mm	586	633	807	586	633	807
Effluent collected, $m^3 m^{-2}$ of storage surface area	0·480	0·505	0·652	0·231	0·231	0·261

Note: the effluent of farm MH-3 contains milk house wastewaters and manure runoff while that of farm MH-6 contains only manure runoff. The effluent volume was measured annually at the same time and just before emptying the tank.
TS, total solids.

high at the bottom only. For farms MH-3 and MH-6, a high correlation was found between the amount of rainfall rather than snow, occurring from October to May of each year (Table 7). Equations (5) and (6) correlate the average DE total solids T_s in % with winter rainfall from October to May inclusively r in mm for farms MH-3 and MH-6 respectively:

$$T_s = 0{\cdot}0015r - 0{\cdot}475 \quad (5)$$

$$T_s = 0{\cdot}006r - 2{\cdot}0156 \quad (6)$$

where the value for R^2 is 0·99 in both cases. Thus, winter rainfall rather than snow impacts the amount of solids washed into the effluent storage. In Eqns (5) and (6), T_s is negative when r is zero, indicating that a certain amount of rainfall is requires to wash away some manure solids. Thus, when A is small, DE is mainly composed of urine and manure seepage originating from its decomposition [Eqn (1)], but this DE will not accumulate in the seepage pit unless a certain amount of rainfall occurs. The volume of effluent collected was quite different, between farms MH-3 and MH-6, per m^2 of storage area, because farm MH-3 stored milk house wastewaters along with manure runoff, whereas farm MH-6 stored only manure runoff.

In general and for the farms storing their manure using system A as storage, the DE offered an average TP load of 15–90 mg l^{-1} implying that 330–2000 $m^3 ha^{-1}$ of effluent are required to fertilise a forage crop requiring 30 kg ha^{-1} of phosphorus. For those farms using system B as storage and for DE with an average TP of 150 mg l^{-1}, some 200 $m^3 ha^{-1}$ of effluent are required for the same fertilisation. To limit the bacterial load applied along with the DE, milk house wastewaters should be stored along with manure runoff. The DE should also be sampled and analysed annually, before land application, as nutrient load can vary especially during winters with heavy rainfalls.

4. Conclusion

The objective of this paper was to investigate the impact, on dairy form effluent (DE) characteristics, of its source and the type of manure management system used. Dairy farm effluent was therefore characterised on seven farms offering a variety of management system.

The storage system, whether A or B, had a greater influence on the nutrient load of the dairy farm effluents, as compared to the presence or absence of milk house wastewaters, because of its effect on the length of contact time between the DE and the solid manure. Accordingly, effluents obtained from storage system A need to be applied at much higher rates of 330–2000 $m^3 ha^{-1}$ to fertilise a forage crop requiring 30 kg ha^{-1} of phosphorus, compared to those obtained from storage system B where a rate of 200 $m^3 ha^{-1}$ would suffice. Nevertheless, both storage systems produce an effluent which requires an application rate exceeding that generally applied by tanker of 50–100 $m^3 ha^{-1}$. Milk house wastewaters alone would require an application rate of 300 $m^3 ha^{-1}$, for the same fertilisation level, indicating that their phosphorus load falls within the range of DE. Considering these application rates, surface irrigation is better suited for the land application of DE, as compared to using a conventional tanker.

The nutrient load of DE was influenced by the surface area of the storage facility and the amount of winter (October to May) rainfall rather than snow or total precipitation. The storage of milk house wastewaters along with manure runoff can lower the DE faecal coliforms to faecal streptococci ratio. Finally, system A as storage facility generally produced effluents with a total solids load under 1%, which developed a lower bacterial load.

Acknowledgements

This project was financed by the Council for the Development of Agriculture in Quebec (CDAQ) and the Natural Science and Engineering Research Council of Canada. The authors are also grateful to all the dairy farms who contributed their operations and to Cemagref for sponsoring the visit of Dr Martinez during the summer of 2004.

References

Ali I; Barrington S; Martinez J; Whalen J (2005). Surface irrigation adapted to dairy wastewater land spreading. CSAE paper 05-093. Masonville, Quebec, Canada

APHA (1998). Standard Methods for the Analysis of Water and Wastewater, 20th Edn. American Public Health Association, American Water Works Association and World Pollution Control Federation, Washington, DC, USA

Barrington S; Piché M (1992). Research priorities for the storage of solid dairy manures in Québec. Canadien Agricultural Engineering, **33**(2), 393–399

CRAAQ (2003). Crop Fertilisation Guide, 1st Edn. Quebec Centre for Research in Agriculture and Agro-Food, Ste Foy, Québec, Canada

Craggs R J; Tanner C C; Sukias J P S; Davis-Colley R J (2003). Dairy farm wastewater treatment by an advance pond system. Water Science Technology, **48**(2), 291–297

Cronk J K (1996). Constructed wetlands to treat wastewater from dairy and swine operations: a review. Agriculture Ecosystems & Environment, **58,** 97–114

Knight R L; Payne V W E; Borer R E; Clarke R A; Pries J H (2000). Constructed wetlands for livestock wastewater management. Ecological Engineering, **15,** 41–55

Lens P; Zeeman G; Lettinga G (2001). Decentralized Sanitation and Reuse—Concepts, Systems and Implementation. IWA Publishing, UK

Loehr R (1984). Pollution Control for Agriculture, pp 450–454. Academic Press, Orlando, FL, USA

Luostarinen S A; Rintala J A (2005). Anaerobic on-site treatment of black water and dairy parlour wastewater in UASB-septic tanks at low temperatures. Water Research, **39,** 436–448

Mbwele L; Rubindamayugi M; Kivaisi A; Dalhammar G (2003). Performance of small wastewater stabilisation pond system in tropical climate in Dar es Salaam, Tanzania. Water Science Technology, **48**(11–12), 187–191

MENQ (2002). Bylaw for the operation of livestock facilities in Quebec. Law on Environmental Quality, Article 35 and Annexe 1·3. Quebec Ministry of Environment, Quebec Government, Quebec, Canada

Newman J M; Clausen J C; Neafsey J A (2000). Seasonal performance of a wetland constructed to process dairy milk house wastewater in Connecticut. Ecological Engineering, **14,** 181–198

Reimann W (1997). Influence of organic matter from wastewater on the permeability of membranes. Desalination, **109,** 51–55

Ribaudo M N; Gollehon N; Aillery M; Kaplan J; Joahnson R; Agapoff J; Christensen V (2003). Manure management for water quality: cost to animal feeding operations of applying manure nutrients to land. USDA Economic Research Service, Report AER-824. Washington, DC, USA

Schaafsman J A; Baldwin A H; Steb C A (2000). An evaluation of a constructed wetland to treat wastewater from a dairy farm in Maryland, USA. Ecological Engineering, **14,** 199–206

Sweeten J M; Wolfe M L (1990). Runoff and wastewater management systems for open lot dairies. 1990. In: Agricultural and Food Processing Waste. Proceedings of the 6th International Symposium on Agricultural and Food Processing Wastes, pp 361–375. ASAE, St. Joseph, MIC, USA

Tanner C C; Clayton J S; Upsdell M P (1995a). Effect of loading rate and planting on treatment of dairy farm wastewaters in constructed wetlands—I. Removal of oxygen demand, suspended solids and faecal coliforms. Water Research, **29**(1), 17–26

Tanner C C; Clayton J S; Upsdell M P (1995b). Effect of loading rate and planting on treatment of dairy farm wastewaters in constructed wetlands—II. Removal of nitrogen and phosphorus. Water Research, **29**(1), 27–34

Westerman P W; Safley L M; Barker J C; Chescheir G M (1985). Available nutrients in livestock wastes. In: Agricultural Waste Utilization and Management. Proceedings of the Fifth International Symposium on Agricultural Wastes. pp 191–210. ASAE, St. Joseph, MI, USA

Wright P E; Graves R R (1990). Guideline for milking center wastewater. Northeast Regional Agricultural Engineering Service, Cooperative Extension. Ithaca, NY, USA