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Characterisation of dairy soiled water in a survey of 60 Irish dairy farms

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Abstract

Dairy farming in Ireland generates an effluent known as dairy soiled water (DSW), which consists of a relatively dilute mixture of cow faeces, urine, spilt milk and detergents that is typically applied to grassland. However, relatively little is known about the volumes generated, nutrient content and management factors that influence volume and concentration. Sixty dairy farms that had a separate storage tank for storing DSW were selected for this study. The spatial distribution of the farms reflected the spatial distribution of dairy cows across the 26 counties of the Republic of Ireland, with each farm representing between 10,000 and 20,000 dairy cows. Samples were analysed for biochemical oxygen demand (BOD), ammonium N (NH_4-N), total nitrogen (TN), potassium (K), phosphorus (molybdate-reactive and total) (MRP and TP) and dry matter (DM) content. Management characteristics and parlour properties were quantified. Factors influencing volume and concentration of DSW were determined using mixed model multiple regression analysis. On average, 9784 l (standard error 209 l) of DSW, including rainfall, was produced cow^{-1} year^{-1} and this contained significant quantities of total N, P and K (587, 80 and 568 mg l^{-1}, respectively). A typical Irish dairy farm stocked at 1.9 cows ha^{-1} could therefore supply approximately 13, 2 and 12 kg ha^{-1} of total N, P and K, respectively, across the farm, annually to meet some of the nutrient requirements for herbage production and potentially replace some of the synthetic fertilizer use. Seventy one percent of samples were within the regulated concentration limits of soiled water for BOD (<2500 mg l^{-1}), rising to 87% during the closed period for slurry spreading (mid October to mid-late January), while 81% were within the concentration limits for DM (<1% DM), rising to 94% during the closed period. The efficiency of a milking parlour (cows per unit, time taken) plays a key role in determining the volume of DSW generated. This, in turn, also influences the concentration of nutrients and other chemicals. Large variability was found in nutrient concentrations and this presents a challenge for effective nutrient management to maximise the fertilizer replacement value of DSW.

Keywords

Dairy soiled water • dairy effluent • soiled water • farm effluent • organic fertilizer • dairy parlour management • dilute slurry

Introduction

Dairy soiled water (DSW) is a farm effluent produced from the washing-down of milking parlours and holding areas to maintain hygiene levels in the production of high quality milk. Soiled water is legally defined in Ireland as water from concreted areas, hard standing areas, holding areas for livestock and other farmyard areas where such water is contaminated by contact with livestock faeces or urine, silage effluent, chemical fertilisers; washings such as washings from vegetables, milking parlour, mushroom houses, or farm equipment, has a biochemical oxygen demand (BOD) of less than 2500 mg l^{-1} and less than 1% dry matter (DM) content (S.I. No.31 of 2014) and is stored separate from slurry. Slurry, on the other hand, is legally defined as having a BOD greater than 2500 mg l^{-1} and a DM content greater than 1% (S.I. No.31 of 2014).

The generation of DSW has been estimated to be 50 l cow^{-1} day^{-1} (Department of Agriculture, 1996); however, this value can be greatly exceeded depending on milking parlour efficiency and management of water usage. Slurry and DSW are typically stored in separate storage facilities. DSW facilities usually consist of concrete tanks cast *in situ*; the capacity and type of storage vary considerably from farm to farm (Minogue *et al.* 2010). If DSW is mixed with slurry, legislation requires that the effluent then be regarded as slurry, which, in turn, will have a notable impact on the infrastructure requirements for handling this material on farms.

According to Gibson (1995), DSW (farm dairy effluent) in New Zealand typically consists of 10% excreta, 4% teat washings, and 86% wash water, plus other foreign material. This effluent typically contains nutrients that are potentially plant-available but may also pose a risk of environmental pollution if not managed correctly (Di and Cameron 2002;

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Di *et al.* 1998). Current management of these effluents in Ireland is regulated primarily by the Nitrate Regulations (S.I. No. 31 of 2014) giving effect to the EU Nitrates Directive (Council Directive 91/676/EEC; European Communities 1991). The regulations are focused on decreasing nitrogen (N) loss to ground and surface waters through improved on-farm nutrient management. The Nitrates Directive states that there should be a balance between N supply from animal manures and chemical fertilisers and the N demand of the crop, thus avoiding N surpluses and associated losses to water (Cooper 1993; Wang *et al.*, 2004).

The primary focus of Irish dairy farming is the production of milk through a low cost grassland based system. This is achieved through the synchronisation of lactation with the grass growth curve (February–November). Although the majority of dairy farms operate during this period, a smaller portion (12%; National Milk Agency 2008) operate all year round through a split calving regime (winter milk producers). Calving on these farms takes place during two periods, February–March and August–September, resulting in continuous milk production all year round. Therefore, DSW is produced all year round on some farms but production can be expected to be highly seasonal on others. With this in mind, we can hypothesise that the volumes produced and concentration of nutrients in DSW will vary significantly throughout the year.

On-farm management of DSW mainly involves disposal through land application. Application is, however, limited to 50,000 l ha^{-1} over any 6-week period (25,000 l ha^{-1} in vulnerable karst landscapes) with further restrictions based on soil conditions, slope, proximity to water sources and weather forecast. Unlike slurry, DSW can be applied all year round and is typically perceived to be of no agronomic benefit. Alterations in the guidelines in relation to the storage and land application of DSW could result in a significant increase in the infrastructure required to store this material if it was defined as slurry. A 10-day storage capacity is required for DSW (increasing to 15 days for facilities built after 1 January 2015), while much more significant storage capacities (16–22 weeks) are required for slurry.

Studies have proven the fertiliser potential of DSW for herbage production (Jacobs and Ward 2007). Minogue *et al.* (2010) reported N fertiliser replacement values for DSW ranging between 72 and 90%; however, this was dependent on timing and application rate. Therefore, DSW offers the potential to reduce inorganic fertiliser inputs, improving the environmental and economic sustainability of Irish dairy farming. On the other hand, it has also proven to be a possible source of nutrient leaching and run-off (Di *et al.* 1998: McFarland *et al*. 2003), despite low nutrient concentrations (Table 1).

Table 1 displays nutrient characteristics for DSW from studies across Australia, Ireland, New Zealand, the UK and the United States. Existing nutrient management planning in Ireland does not account for nutrients in DSW. Some limited sampling on a single Irish farm over a 13 week period (Martínez-Suller *et al.* 2010) has shown that the DM content of DSW is relatively low (0.01%) compared with animal slurries (1–10%). Ryan (1990) reported mean concentrations of 227, 44 and 524 mg l^{-1} for total N (TN) total phosphorus (TP) and potassium (K), respectively, for a single Irish farm sampled over 13 weeks. The mean values for N recorded by Martínez-Suller *et al.* (2010; 351 mg l^{-1}) were higher than those recorded by Longhurst *et al.* (2000; 269 mg l^{-1}) in New Zealand. However, the studies carried out by Martínez-Suller *et al.* (2010) and Ryan (1990) involved only single farm means, and they are not likely to have captured the full range of composition of DSW on Irish dairy farms. Other studies have also confirmed that volumes and concentrations of DSW can be expected to vary from farm to farm, depending on a range of farm characteristics and management practices (Longhurst *et al.* 2000; Cumby *et al.* 1999).

It is evident (Table 1) that there is a lack of knowledge on the quantities of DSW produced in Ireland, its nutrient content, and the effect of management practices on DSW production. With this obvious knowledge gap in Irish data regarding DSW, a study across 60 Irish dairy farms was implemented. DSW volume and composition was monitored, monthly, for 1 year. The objective of this study was to characterise the volumes and chemical composition (nutrients and other biochemical parameters) of DSW throughout the year on a representative sample of Irish dairy farms distributed across the country, to relate them to parlour management practices and draw implications for farm nutrient management and policy.

Materials and methods

Farm selection

Sixty dairy farms were selected, assisted by the Teagasc Advisory Service, on the basis that a storage tank solely for the collection of DSW was present on the farm. Storage tanks consisted of reinforced concrete tanks cast *in situ* and had to be in good working order for inclusion in the study. Storage tanks, deemed suitable for the study, were used for collection of effluent from the milking parlour (yard scrapings/faeces/urine and wash water), collecting yard and other hard-standing areas, exclusively. These tanks did not include any input from cattle housing/slurry storage.

The spatial distribution of the farms was structured to reflect the spatial distribution of dairy cows across the 26 counties of the Republic of Ireland (see Figure 1), with each farm representing between 10,000 and 20,000 dairy cows. The number of dairy farms, as a proportion of the 60, allocated to areas/counties directly correlated to the number of

Table 1. Summary of DSW characteristics reported in the literature

Timing	Component								Location	# Farms	Source
	pH	BOD	TN	NH_4-N	NO_2-N	P	TP	K			
					mg l^{-1}						
-	-	2870	227	151	< 0.9	30	44	524	Ireland	1	Ryan (1990
-	-	2077	159	92	1	17	23	210	„	1	Ryan (1991)
-	7.55	-	304	280	-	-	62	383	USA	-[1]	Sweeten and Wolfe (1994)
-	7.3	-	450	42	-	-	<100	350	UK	1	Misselbrook (1995)
Spring	7.6	2660	-	31	-	-	-	-	UK	20	Cumby et al. (1999)
Summer	6.4	9670	95	58	-	-	49	150	„	20	„
Autumn	6.6	7450	70	48	-	-	34	85	„	20	„
-	8.28	1192	290	163	-	-	70	0	Australia	4	Fyfe (1999)
-	-	-	188	84.4	-	-	-	-	Ireland	1	Richards (1999)
-	8	3200	187	83	-	-	26	200	Australia	-[1]	Wrigley (1999)
-	-	-	342	48	-	-	70	370	New Zealand	3	Longhurst (2000)
-	-	1440	-	-	-	-	-	-	UK	1	Cannon et al. (2000)
-	-	2208	-	-	-	-	-	-	Ireland	1	Rodgers, Gibbons and Mulqueen (2003)
Winter	-	2828	-	42	-	-	-	-	„	1	Dunne et al.(2005)
Spring	-	2703	-	53	-	-	-	-	„	1	„
Summer	-	2682	-	36	-	-	-	-	„	1	„
Autumn	-	2303	-	6	-	-	-	-	„	1	„
-	7.4	3000	479	-	-	-	111	-	USA	8	Singh, Crofcheck and Brion (2005)
Summer	-	-	170	89.7	-	14	20	-	Ireland	1	Fenton et al. (2009)
-	6.6	3084	351	32	0.3	8.5	44	415	Ireland	1	Martinez-Suller et al. (2010)

[1]average across a number of farms.
BOD, biochemical oxygen demand; DSW, dairy soiled water; TN, total nitrogen; TP, total phosphorus.

dairy cows in that area/county. As a result, survey farms were concentrated in the south and south-west of Ireland, which corresponds with the concentration of dairy farms in this region. Counties Wicklow, Donegal, Louth, Dublin, Westmeath, Leitrim and Longford were omitted from the study for logistical reasons.

Farm management characteristics

Once a dairy farm suitable for the study was selected, relevant information on the various farm characteristics and management practices that might influence DSW volume and composition were collected. Milking parlour and holding area facilities (where cows are held before and after milking) on Irish dairy farms typically consist of a roofed and concrete-floored parlour building and concreted holding areas that may be unroofed or roofed to varying degrees. DSW is generated from the washing down of these facilities (often including the washings of bulk tanks and milking plant equipment) and rainfall on unroofed areas. Washing regimes of both parlours and holding area can vary among farms and some will use scraping to remove faecal material. Scraping faecal material from yards is likely to reduce the frequency of yard washing and the volume of water used, and affect volumes and concentrations of DSW produced. Most Irish dairy farms are seasonal milk producers with spring-calving herds that have a “dry” period in the winter months and so will not be milking and washing down parlours and holding areas over this period. DSW is typically washed into an underground collection tank for storage. These tanks may consist of a single tank or may have three stages to allow settlement. Soiled water tanks can also receive other farm effluents such as silage effluent. DSW is removed from these tanks by pumping and then land spread. The varying management and facility factors outlined above will influence the volume and concentrations of DSW generated. Accordingly, the management practices and farm characteristics quantified were: area washed (total area washed on daily basis - m^2), area for rainfall (total open area collecting rainfall - m^2), total storage for DSW (storage capacity of DSW tank - m^3), type of storage (single storage tank or 3 stage filtration tank), number of dairy cows (herd size), number of milking units (# milking units present in the milking parlour), duration of milking (minutes), whether silage effluent was collected in the tank (yes, no), parlour wash frequency (# times parlour is washed day^{-1}), scraping frequency (# times $week^{-1}$), collecting yard washed daily (if the collecting yard was washed daily - yes, no), number of cows per milking unit (herd size in relation to parlour size - cows per milking unit) and percentage of the herd for winter milking.

Scraping frequency (method of clearing excess faeces in collecting yard and parlour without using water) was measured as the weekly frequency at which the collecting yard was scraped clean of faeces. Milking duration (minutes) was determined from when the first cow entered to when the last cow exited the milking parlour. The percentage of the herd for winter milking refers to the percentage of the herd employed for winter-milk production. This was measured as the number of cows for winter milk expressed as a percentage of the total herd size. The number of cows per milking unit was determined as the herd size divided by the number of milking units in the milking parlour. Impervious areas washed (washed by the farmer) (m^2) and areas exposed to rainfall (m^2) draining into the DSW storage tank and total storage for DSW (m^3) were measured on site. The remaining farm characteristics were collated in questionnaires completed during a face-to-face interview with the farmers.

Dairy soiled water monitoring

Fifty four of the farmers used vacuum tankers to remove DSW from the storage tank and apply it to the land. In these cases, volumes removed, from the storage tank, were logged on a datasheet on a weekly basis by the farmer. The remaining six farmers employed a pump and irrigator system to remove and land-spread DSW. In these cases, flow meters were installed on the farms and the amount pumped was recorded during the monthly visit to the farm. Rainfall was recorded on farms for the duration of the study using rain gauges (10 l container with an 8-cm diameter funnel). The volume collected was recorded on each visit. For brevity, mean rainfall is summarised for sub-counties and counties.

Figure 1. Geographical location of the 60 dairy farms used in this study. Satellite image courtesy of NASA: http://earthobservatory.nasa.gov/IOTD/view.php?id=6628

Sampling protocol

The 60 farms included in the study were split into four areas for the purpose of sampling. These four areas were then sampled in a consistent order: Week 1 Tipperary, Limerick, Kerry and Clare (18 farms); Week 2 Meath, Kilkenny, Laois, Offaly, Wexford, Carlow and Waterford (17 farms); Week 3 Cork (15 farms); Week 4 Cavan, Monaghan, Sligo, Mayo, Roscommon and Galway (10 farms). Each farm was visited every 28 days for 1 year giving a total of 13 visits. Although different farms were sampled at different times during the day, for consistency within a farm, each individual farm was sampled at the same time on each of the 13 visits. Sampling times ranged from 06.00 to 15.00 hours. The milking, washing and DSW tank pumping regime and rainfall inputs can vary considerably between dairy farms and over the year. Therefore, targeting a particular time in the day or a specific stage in the cycle of milking, washing and pumping for sampling is not possible to plan, nor feasible to implement. The samples taken in this study are representative of DSW in the tank and the composition of that DSW would be reflective of the inputs to the tank over the preceding time (days to weeks, typically). Therefore, these samples would be representative of the typical DSW composition on these farms. No management prerequisites were required for the day of sampling, that is, collecting yards/holding yards were not required to be scraped or washed down and no agitation of the tank was required.

A sample of DSW was collected from the DSW tank by repeatedly puncturing through the crust layer on top of the supernatant (no agitation had taken place), until a clear entry point to the supernatant was present. Two samples were taken at two intermediate depths (total of 4 samples) until 500 ml had been collected as a bulked sample. An extension pole fitted with a perforated 250 ml bottle facilitated the sampling of DSW at various depths. The bottom and top (crust) layer were avoided and the sampling bottle filled as it was lowered, thus sampling across the water column. It was assumed that this sample is representative of the DSW spread on the land. The samples were then chilled to between 2° and 5°C. Due to the time-sensitivity of the BOD_5 test, samples were then dispatched in cool boxes overnight to the laboratory for analysis. The total time between sampling and analysis was approximately 36 h.

Laboratory analysis

Samples were analysed for BOD_5,DM, ammonium N (NH_4-N), TN, K, molybdate-reactive P (MRP) and TP. Samples were mixed for 5 min, using an electric stirrer, prior to the measurement of DM, and then sub-sampled to provide material for chemical analysis. BOD_5 was calculated according to standard methods by subtracting the residual dissolved oxygen concentration, measured after incubation for 5 days at 20°C, from the initial concentration (APHA 1998). For DM determination, approximately 200 g of the raw sample was placed in an oven and dried at 104°C for 24 h (APHA 1998). NH_4-N was measured, using a Konelab 30 discrete analyser (Konelab Corporation, Espoo, Finland). TN and TP fractions were determined colorimetrically by continuous-flow analysis following oxidative digestion with potassium peroxodisulphate as described by Ebina *et al.* (1983). K was analysed by inductively-coupled atomic emission spectroscopy (ICP–AES) according to standard methods (Gottler and Piwoni 2005).

Data processing and statistical analysis

Volume of DSW produced was calculated on 48 of the 60 farms. The 12 remaining farms were excluded from the volume data because volumes recorded by the farmer were unreliable. The volume of DSW produced was initially calculated as a monthly (28 days) total for each farm. The yearly total of DSW produced was calculated by adding all monthly total volumes. Volume of DSW produced cow^{-1} $year^{-1}$, for each farm, was calculated by dividing the yearly total by the herd size on each farm. Total DSW produced cow^{-1} $year^{-1}$ was then calculated by taking the average across all herds included in the study.

On farms with unroofed yard areas draining into the soiled water tank, rainfall contributes a part of the volume of DSW produced. Aside from roofing yards to minimise rainfall input, the management factors that farmers can alter to affect volumes produced are best analysed using volumes that exclude this rainfall. For this reason, we deemed it

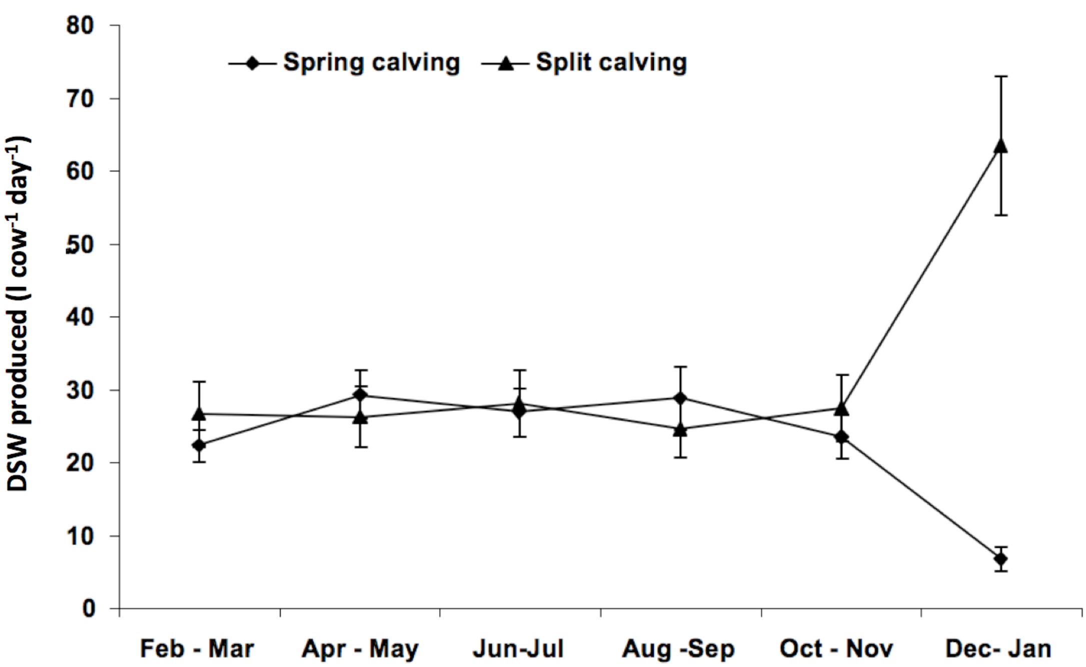


Figure 2. Mean (± standard error) volume of DSW produced cow^{-1} day^{-1}, excluding rainfall, averaged over all farms for the 48 farms that were spring calving and the 12 farms that were split calving. DSW, dairy soiled water.

necessary to separate the contribution of water from rainfall and determine the amounts generated from the dairy unit alone. The contribution of monthly rainfall to DSW volume was calculated by multiplying the rainfall (mm) by the area of open yard draining to the soiled water tank. Monthly volume generated from rainfall was subtracted from the monthly (28 days) total DSW produced to give the volume of DSW generated from the milking parlour alone. Daily average volumes were then calculated for each month. Volume generated cow^{-1} day^{-1}, from dairy washings alone, was calculated by dividing the daily average by the herd size. This was carried out for all farms together and also separately for farms with spring calving herds and split calving herds.

Monthly DSW volume (including rainfall) generated was multiplied by the concentration for that month to give the total loading for that period. Total loadings of BOD, DM, NH_4-N, TN, K, MRP and TP were calculated. Monthly total loads were summed over the year to give an annual load and divided by the number of cows to give a production value per cow per year, as follows:

$$\text{Volume (monthly)} \times \text{concentration} = \text{28-day load}$$

$$13 \times \text{28-day loads} = \text{Yearly load}$$

$$\frac{\text{Yearly load}}{\text{Herd size}} = \text{Production value cow}^{-1}\ \text{year}^{-1}$$

Farm characteristics and management practices associated with DSW volume and chemical parameters were determined using mixed model multiple regression analysis. A multiple regression model was developed for each dependent variable using forward ($P < 0.30$) and backward ($P < 0.05$) stepwise regression. Variables were added and/or removed from the model based on the levels of significance obtained until no further significant variables remained. For this analysis, volume and concentration data were expressed as a daily mean per cow. Total DSW produced, including rainfall, was included in this analysis.

Volume data (including rainfall) were normally distributed. Data used for volume analysis consisted of 48 farms with 13 sample events over time on each farm. Concentration data were positively skewed. Therefore, the natural logarithm of each of the biochemical parameters (except for DM) was obtained after adding a value of 1. For DM, 0.0001 was added before taking the natural logarithm. All of the biochemical parameters were included as dependent variables for analysis but, for reasons of brevity, only DM, BOD, TN and NH_4-N results are detailed here.

In the mixed model analysis, geographical location was included as a random effect (to remove any geographical gradient effect on the data-set) and the significance of the association of the dependent variable was tested against the random effect. Fixed effects considered for inclusion in both the concentration and volume model were: sampling date, area washed (m^2), area for rainfall (m^2), total storage for DSW (m^3), type of storage (single- or three-stage tank), number of dairy cows, number of milking units, duration of milking (minutes), whether silage effluent was collected (y, n), parlour wash frequency (times day^{-1}), scraping frequency (times $week^{-1}$), collecting yard washed daily (yes, no), number of cows per milking unit and percentage of the herd for winter milking. The independent variable 'sampling date' refers to the 52 sampling times throughout the year.

Independent variables were classed into classes of equal range such that a minimum of 10% of the farms were contained within each class. Where this criterion could not be met, the number of classes was reduced accordingly, assigning the remaining farms to the appropriate classes.

Results

Farm characteristics

The mean farm area was 74 ha (standard error (s.e.) 4) with a range of 20–170 ha (Table 2). Mean dairy herd size was 102 cows (s.e. 12) with a range of 30–660 cows. Most of the farms operated a spring calving regime (74%). Eighty-one per cent of farms used a vacuum tanker to spread DSW while the remainder used an irrigation system (consisting of a pump and irrigation gun) for land application of DSW. Average annual volume produced was 916 m^3 (s.e. 105). Mean DSW tank volume was 66 m^3 (s.e. 6), giving a mean storage capacity for DSW of 33 days (s.e. 8).

Composition of DSW produced (not adjusted to exclude rainfall)

The overall mean BOD was 2246 mg l^{-1} (Table 3) with a range of 0–19,085 mg l^{-1}. Seventy-one per cent of DSW samples were below the regulated concentration limit of DSW (2500 mg l^{-1}). Eighty-seven per cent of samples obtained during the closed period for land application of organic manures (mid October to mid-late January, depending on region) were below the concentration limit of DSW. The median (Q2) value was consistently considerably below the concentration limit (Figure 3). The mean value was greatest in March (3114 mg l^{-1}) and lowest in January (1037 mg l^{-1}) (Figure 3). BOD decreased from September (2744 mg l^{-1}) to January (1037 mg l^{-1}), showing a clear trend for lower BOD over the winter period (Figure 3).

The overall mean DM content was 0.5% (Table 3) with a range of 0.01–7.94%. Eighty-eight percent of samples were below the regulated concentration limit of DSW (< 1% DM). Ninety-four percent of samples obtained during the closed period for land application of organic manures were below

Table 2. Characteristics of 60 dairy farms used in a survey of soiled water production and composition.

Parameter	Mean	s.d.[1]	s.e.[2]
Farm size (ha)	74	30	4
Herd size (dairy)	102	90	12
# Milking units	12	7	1
Area washed (m²)	98	82	12
Area for rainfall (m²)	222	235	39
Tank size (m³)	66	52	6

[1] *standard deviation.*
[2] *standard error.*

Table 3. Mean soiled water concentrations and annual production per cow

Nutrient	Mean concentration (mg l^{-1})	s.d.[1]	s.e.[2]	kg cow^{-1} $year^{-1}$ (s.d.)[1]
TN	587	536	19	6.9 (9.1)
NH_4-N	212	206	7	2.2 (2.65)
K	568	513	18	6.3 (7.12)
MRP	36	53	1	0.4 (0.4)
TP	80	68	2	0.92 (1.18)
DM	0.5	0.52	0.02	
BOD	2246	2112	75	

[1] *standard deviation.*
[2] *standard error.*
BOD, biochemical oxygen demand; DM, dry matter; TN, total nitrogen; TP, total phosphorus

the concentration limit. The Q3 value was consistently considerably below the concentration limit (Figure 4). Concentrations were greatest in March (0.91%) and lowest in April/May (0.24%) (Figure 4).

The overall mean for TN was 587 mg l^{-1} (Table 3) with a range of 27–6030 mg l^{-1}. The mean concentration was greatest in March (783 mg l^{-1}) and lowest in July (317 mg l^{-1}) (Figure 5). The overall mean for NH_4-N was 212 mg l^{-1} with a range of 0–2933 mg l^{-1}. NH_4-N made up 25–57% of TN with an overall average of 36%. The mean NH_4-N concentration was greatest in October (308 mg l^{-1}) and lowest in April/May (134 mg l^{-1}). There was a clear increase in TN concentrations from April through June (Figure 5); however, mean NH_4-N concentrations remained relatively stable for the same period (Figure 6). The overall mean for TP was 80 mg l^{-1} (Table 3) with a range of 4–795 mg l^{-1}. Mean concentration recorded for MRP was 36 mg l^{-1} with a range of 0–320 mg l^{-1}. The overall mean for K was 568 mg l^{-1} with a range of 12–7232 mg l^{-1}.

Effect of farm characteristics and management practices on nutrient concentration

A number of farm characteristics and management practices showed significant positive relationships with most of the analysed biochemical parameters (Tables 4 and 5):

a) Number of cows per milking unit (significant with all parameters)
b) Milking duration (significant with all parameters)
c) Scraping frequency (significant with DM, BOD, TN, NH_4-N, and K).

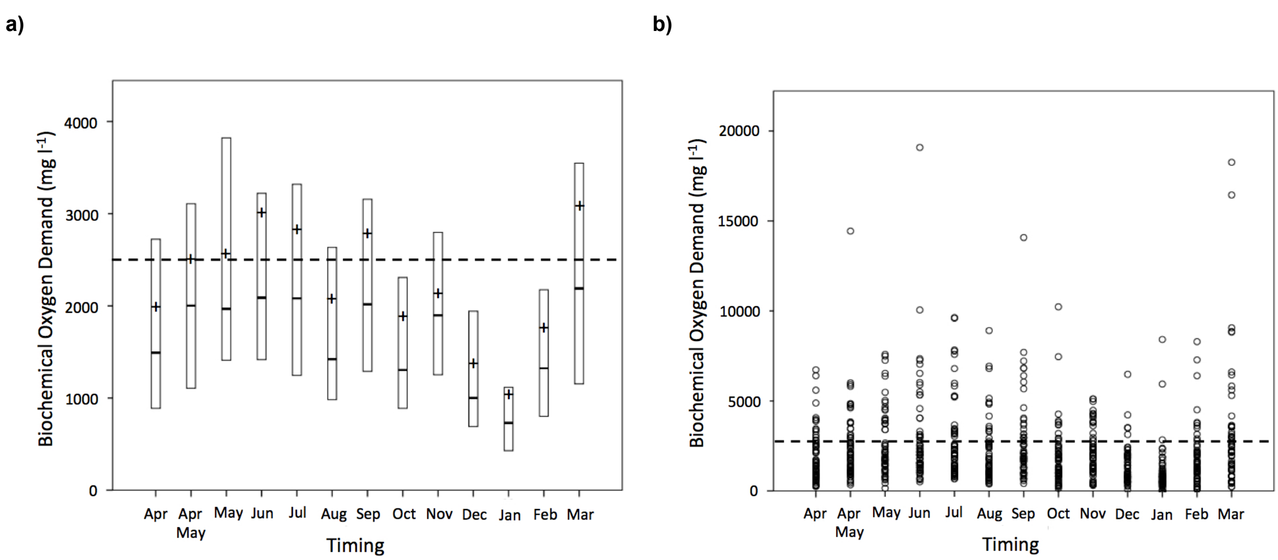


Figure 3. (a) Data summary of BOD concentrations, for all farms at each sampling time, displaying Q1, Q2 (median) and Q3 values and seasonal mean (cross marks), and the regulated BOD concentration threshold for soiled water (dotted horizontal line). (b) Raw BOD concentration data, illustrating the spread of concentrations observed and the regulated concentration threshold (dotted horizontal line). BOD, biochemical oxygen demand.

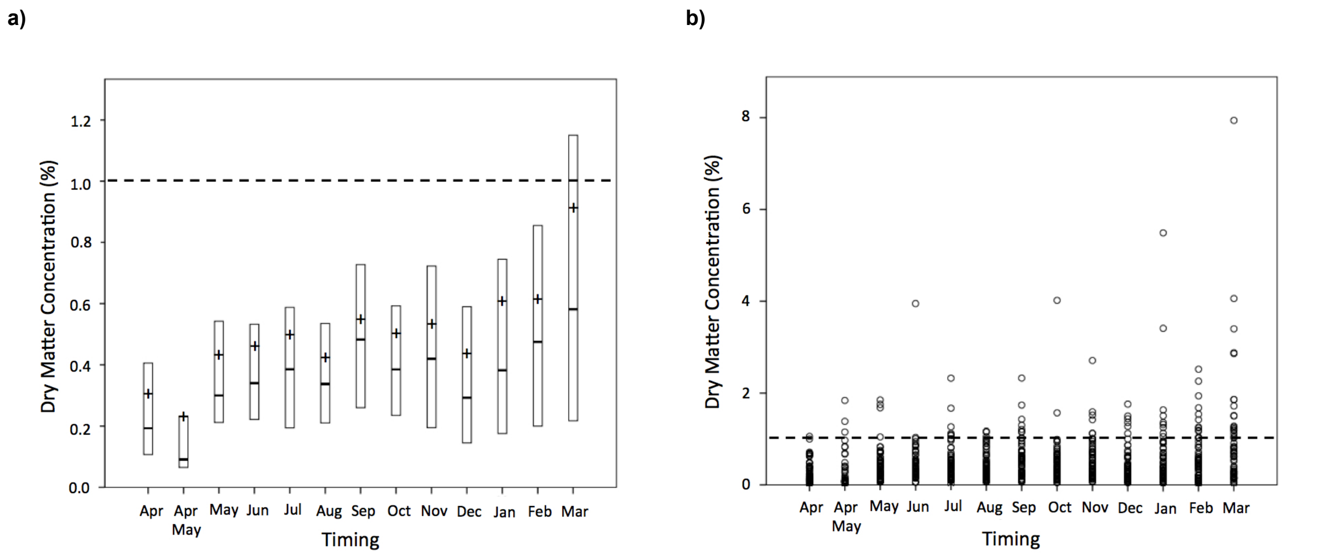


Figure 4. (a) Data summary of DM concentrations, for all farms at each sampling time, displaying Q1, Q2 (median) and Q3 values and seasonal mean (cross marks), and the regulated DM concentration threshold for soiled water (dotted horizontal line). (b) Raw DM concentration data, illustrating the spread of concentrations observed and the regulated concentration threshold (dotted horizontal line). DM, dry matter.

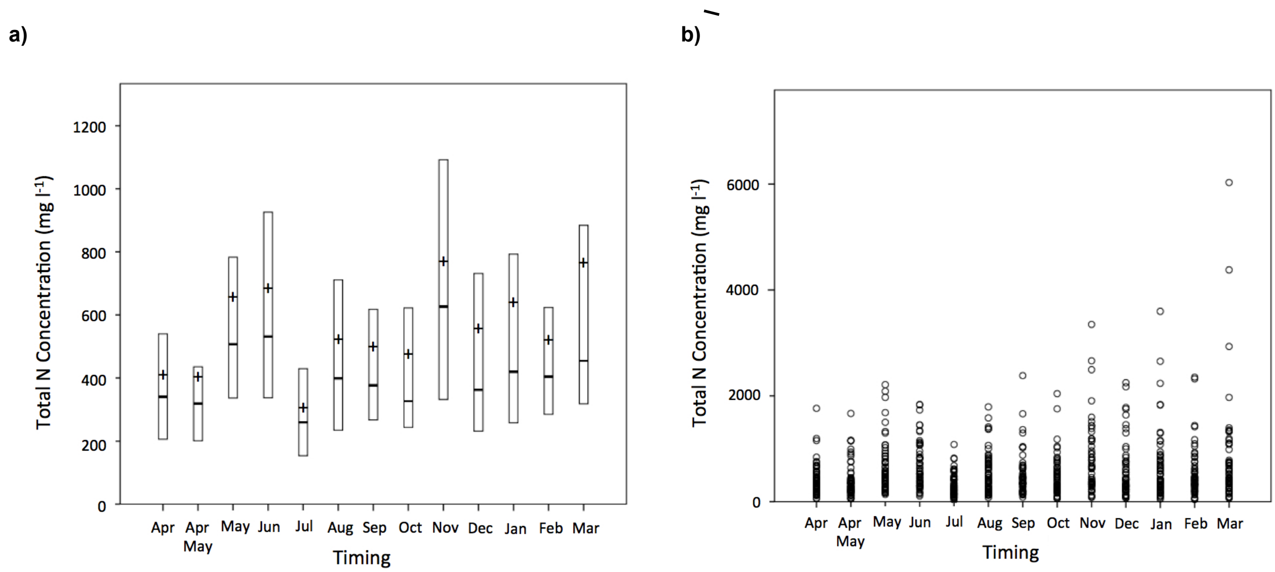


Figure 5. (a) Data summary of TN concentrations, for all farms at each sampling time, displaying Q1, Q2 (median) and Q3 values and seasonal mean (cross marks). (b) Raw TN concentration data, illustrating the spread of concentrations observed. TN, total nitrogen.

There was a clear increase in the concentration of the biochemical parameters as the number of cows per milking unit increased. This relationship was also observed with an increase in milking duration. Scraping frequency (week^{-1}) was also shown to have a significant effect on the concentration of a number of biochemical parameters, while sampling date was significant for all biochemical parameters.

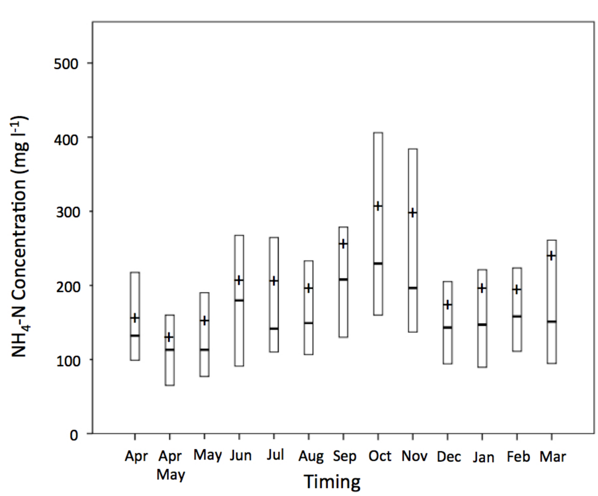
A number of management practices only had significant relationships with some biochemical parameters. Area for rainfall had a significantly negative relationship with NH_4-N concentrations ($P < 0.001$) and a significantly positive relationship with the volume of DSW produced ($P < 0.001$). Silage effluent input increased TN concentrations significantly ($P < 0.001$). Winter milk production also influenced BOD concentrations ($P < 0.001$). BOD increased from herds with no winter milking cows (2633 mg l^{-1}) to herds with less than 30 % winter milking (3450 mg l^{-1}), but then decreased again

Table 4. Description of the main biochemical characteristics of dairy soiled water for different classes of farm management variables across the 60 dairy farms, showing mean lnDM and lnBOD concentrations, with levels of significance[1] from mixed model multiple regression analysis (including rainfall)

Variable	Class	lnBOD[2] (mg l⁻¹)	BOD[3] (mg l⁻¹)	SE	Significance[6]	lnDM[4] (%)	DM[5] (%)	SE	Significance[6]
Cows per milking unit	<5.5	7.42[a]	2331	0.15		8.06[a]	0.6	0.11	
	5.5–8.5	7.62[a]	2683	0.13		8.27[b]	0.72	0.12	
	8.5+	7.88[b]	3034	0.14	***	8.52[c]	0.8	0.09	***
Milking duration	<45	7.25[a]	2095	0.2		7.93[a]	0.64	0.17	
(mins)	45–60	7.61[b]	2482	0.13		8.14[a]	0.62	0.1	
	<60–75	7.65[b]	2720	0.14		8.39[b]	0.78	0.11	
	>75	8.05[c]	3434	0.13	***	8.68[c]	0.79	0.09	***
Scrape frequency	0	7.19[a]	1416	0.13		8.09[a]	0.62	0.1	
(week⁻¹)	1	7.45[b]	2043	0.14		7.97[a]	0.53	0.09	
	2	7.48[b]	2172	0.13		8.22[b]	0.67	0.1	
	7	8.43[c]	5100	0.21	***	8.86[c]	1	0.19	***
Parlour wash	1	-	-	-		8.51[a]	0.9	0.14	
frequency (day⁻¹)	2	-	-	-	NS	8.06[b]	0.52	0.06	***
Winter milk herd (%)	0	7.33[a]	2633	0.07		-	-	-	
	<30	8.29[b]	3450	0.2		-	-	-	
	30–60	7.51[a]	2286	0.29		-	-	-	
	>60	7.41[a]	2362	0.25	***	-	-	-	NS

[1]For each variable, values having the same superscript letter were not significantly different.
[2]Natural log of BOD.
[3]Back transformed BOD (mg/l).
[4]Natural log of DM %.
[5]Back transformed DM %.
*[6]*P = <0.05; **P< 0.01; *** P < 0.001.*
BOD, biochemical oxygen demand; DM, dry matter; SE, standard error.

a)



b)

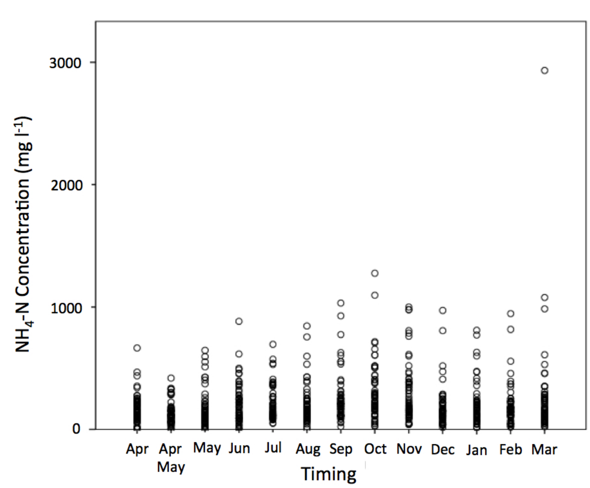


Figure 6. (a) Data summary of NH_4-N concentrations, for all farms at each sampling time, displaying Q1, Q2 (median) and Q3 values and seasonal mean (cross marks). (b) Raw NH_4-N concentration data, illustrating the spread of concentrations observed.

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Table 5. Description of the principle N components in dairy soiled water for different classes of farm management variables across the 60 dairy farms, showing mean lnTN and lnNH$_4$-N concentrations, with levels of significance[1] from mixed model multiple regression analysis (including rainfall)

Variable	Class	lnTN[2] (mg l^{-1})	TN[3] (mg l^{-1})	SE	Significance[6]	lnNH$_4$-N[4] (mg l^{-1})	NH$_4$-N[5] (mg l^{-1})	SE	Significance[6]
Cows milking unit^{-1}	<5.5	5.77 ^{a}	637	0.12		4.43 ^{a}	127.6	0.1	
	5.5-8.5	6.15 ^{b}	757	0.09		4.98 ^{b}	186.2	0.11	
	8.5+	6.35 ^{c}	871	0.11	***	4.92 ^{c}	174.6	0.1	***
Milking duration	<45	5.84 ^{a}	645	0.16		4.44 ^{a}	83.29	0.17	
(mins)	45–60	5.90 ^{a}	642	0.1		4.51 ^{a}	120.7	0.11	
	<60–75	6.15 ^{b}	831	0.11		4.81^b	170	0.1	
	>75	6.47 ^{c}	901	0.09	***	5.34^c	277.2	0.09	***
*Scrape frequency	0	5.88 ^{a}	608	0.09		4.69^a	151.1	0.11	
(week^{-1})	1	5.79 ^{a}	497	0.09		4.59^a	86.4	0.1	
	2	6.02 ^{c}	665	0.1		4.82^b	125.4	0.09	
	7	6.66 ^{c}	1249	0.19	***	5.00^b	288.2	0.21	*
Area for rainfall	roofed	-	-	-		5.31^a	309.1	0.1	
(m^2)	<100	-	-	-		4.82 ^{b}	151	0.13	
	100–200	-	-	-		4.73 ^{b}	182.4	0.12	
	200–300	-	-	-		4.48 ^{c}	48.41	0.15	
	300+	-	-	-	NS	4.54 ^{c}	123	0.13	***
Collecting yard	Y	-	-	-		5.101	265.4	0.07	
(washed daily)	N	-	-	-	NS	4.452	60.15	0.13	***
Parlour wash	1	5.96 ^{a}	614	0.08		-	-	-	
frequency (day^{-1})	2	6.22 ^{b}	895	0.13	***	-	-	-	NS
Silage effluent	Y	6.26 ^{a}	820	0.08		-	-	-	
	N	5.92 ^{b}	690	0.12	***	-	-	-	NS

[1]For each variable, values having the same superscript letter were not significantly different.
[2]Natural log of TN.
[3] Back transformed TN (mg/l).
[4]Natural log of NH$_4$-N.
[5] Back transformed NH$_4$-N (mg/l).
[6]*P = <0.05; **P< 0.01; *** P < 0.001.
TN, total nitrogen; SE, standard error.

for herds with 30–60% (2286 mg l^{-1}) and more than 60% (2362 mg l^{-1}) winter milking.

Volume of DSW produced including rainfall

On average, 9784 l (s.e. 209 l) of DSW, including rainfall, was produced cow^{-1} year^{-1}. On farms where the yard was not covered (69%), rainfall contributed approximately 2739 l (s.e. 410 l) or 28 % of total DSW production, with a range of 391–6450 l.

Volume of DSW produced excluding rainfall

The mean volume produced cow^{-1} day^{-1}, excluding rainfall, that is, DSW exclusively from the milking parlour, was 26 l (s.e. 9) with a range of 3.5–140 l cow^{-1}day^{-1} (Figure 2). DSW produced cow^{-1} day^{-1} for a spring calving herd is relatively consistent through the lactation (February–November) but is substantially lower during the winter. Volumes produced cow^{-1} day^{-1} began lower than the mean in February–March (23 l), increasing to 26–28 l for the remainder of the lactation. These figures were not noticeably different for that of the split calving herds for most of the year. However, volume produced cow^{-1} day^{-1} increases substantially to 63 l (s.e. 10) for split-calving herds during December–January (Figure 2).

Volume of DSW produced and associated management characteristics

There was a significant relationship between the number of cows per milking unit and the volume of DSW produced cow^{-1} day^{-1} (P < 0.001), with volume decreasing as the number of cows per milking unit increased (Table 6). Volume increased with milking duration (P < 0.001). The volume of DSW decreased with increasing scrape frequency (P < 0.05), from 48 to 37 l cow^{-1} day^{-1} with an increase in scraping frequency from 0 to 7 times per week. Volumes produced were also lower for farms that washed twice daily (31 l cow^{-1} day^{-1}) rather than once daily (53 l cow^{-1} day^{-1}) (P < 0.001).

A significant relationship was found between herd size and volume of DSW produced (P < 0.001). Volumes were lower for the 55–110 and 110–200 herd size classes, while there was no significant difference between the highest (200+) and the lowest herd size classes (< 50). A similar trend was observed between area washed and volume cow^{-1} day^{-1} (P < 0.05). The mean volume cow^{-1} day^{-1} was highest for those farms with the smallest areas to be washed and lowest for those with intermediate areas to be washed (50–100 and 100–150 m^2) (Table 6).

Discussion

Results from this study indicate that DSW produced on Irish dairy farms can contain significant quantities of N, P and K. When applied to land, these nutrients are potentially available to plants (Jacobs and Ward 2007). DSW may thus be used as an organic fertiliser, with potential to replace inorganic

Table 6. Mean dairy soiled water volumes generated (including rainfall) for all farms and all sampling times and associated management factors from mixed model multiple regression analysis

Variable	Class	Volume[1] (l cow^{-1}day^{-1})	SE	Significance[2]
Cows per milking unit	<5.5	53^a	3.00	
	5.5–8.5	39^b	2.72	
	8.5+	35^b	2.81	***
Milking duration	<45	39^a	4.14	
(mins)	45–60	46^b	2.63	
	<60–75	52^c	2.82	
	>75[1]	31^d	2.05	***
Scrape frequency	0	48^a	2.91	
(week^{-1})	1	40^b	2.46	
	2	44^b	2.82	
	7	37^{bc}	4.70	**
Parlour wash	1	53^a	3.26	
frequency (day^{-1})	2	31^b	2.06	***
Herd size	<55	49^a	2.63	
	55–110	33^b	2.65	
	110–200	40^c	3.49	
	>200	48^a	4.10	***
Area for rainfall	roofed	33^a	2.69	
(m^2)	<100	40^b	3.31	
	100–200	40^b	3.11	
	200–300	51^c	3.74	
	300+	48^c	3.05	***
Area washed	<50	46^a	3.56	
(m^2)	50–100	39^b	2.41	
	100–150	40^b	2.83	
	>150	45^a	3.67	*
Collecting yard	Y	38^a	2.27	
(washed daily)	N	48^b	3.18	***

[1]For each variable, values having the same superscript letter were not significantly different.
[2]*P = <0.05; **P< 0.01; *** P < 0.001

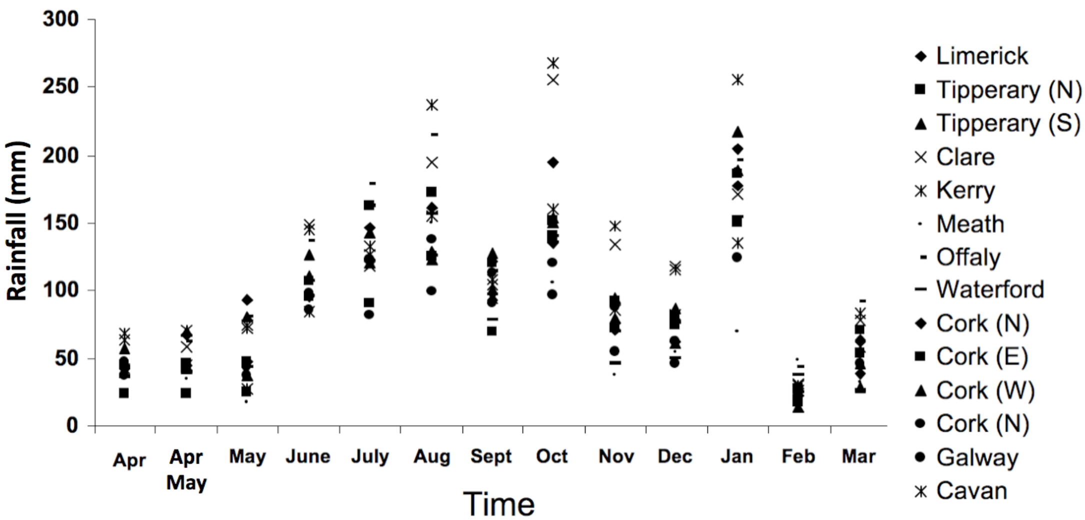

Figure 7. Mean rainfall (recorded by rain gauges on surveyed farms) for farm locations throughout the country, summarised for sub-counties and counties.

fertiliser use on-farm (Minogue *et al.* 2010). The main method of land application was the vacuum tanker with conventional splash plate but 20% of farmers installed pump and irrigation systems for land application of DSW; however, this type of method was employed on the farms with larger herd sizes that produced larger total amounts of DSW.

On average, 9784 l of DSW (including rainfall contributions) are produced cow^{-1} $year^{-1}$, containing 6.9, 0.9 and 6.3 kg of N, P and K, respectively. For a typical Irish dairy farm stocked at 1.9 cows ha^{-1} this DSW could supply approximately 13.1, 1.7 and 12.0 kg ha^{-1} of N, P and K, respectively, across the farm, annually. DSW can therefore play a role in meeting some of the nutrient requirements for herbage production on-farm. The proportion of total N in DSW as NH_4-N (36 %) is not noticeably different to that of slurry (40%) (Balsari *et al.* 2008) and is similar to results reported for DSW by Longhurst *et al.* (2000), Sukias *et al.* (2001) and Ryan (1990) but notably lower than those reported by Richards (1999). Ammonium-N is considered to be more immediately plant available than organic forms of N. There are reasons to suspect that N in DSW will have a relatively high fertiliser replacement value. The dilute nature of DSW might be expected to lead to more rapid infiltration than more concentrated slurries. This may decrease N losses via ammonia volatilisation and deliver nutrients directly to the root zone (Misselbrook *et al.* 1996 and Humphreys 2007). Field plot experiments have found that DSW has a high N fertiliser replacement value of 72–90 % (Minogue *et al.* 2010).

Richards (1999) tested DSW from a single Irish dairy farm for N compounds over a 13-month period and reported seasonal trends in concentrations (highest in summer and lowest in winter). Although the sampling date did have a significant effect on biochemical parameters in the present study, no clear seasonal trend was observed. With 60 dairy farms in the survey, with varying levels of rainwater input and many differing management factors, seasonal trends that may apply to a single farm may be masked by the differing trends in concentration on other farms. It is also possible that the unusually wet summer/autumn recorded for that year (see Figure 7) may have masked any seasonal trend due to rainfall input. Fluctuations observed for TN were not as noticeable for NH_4-N. This would suggest that ammonia is being lost from DSW by volatilisation to maintain a relatively constant average concentration of approximately 150–250 mg l^{-1}. This would then suggest that the conversion rate of organic N to NH_4-N would be similar to the rate at which NH_4-N is being lost. This may make nutrient management planning easier as the immediately-available NH_4-N (mineral N) content of DSW appears to be relatively constant.

As rainfall contributed 28% of total DSW volume on 69% of farms with uncovered yard areas, roofing these yard areas is a potential measure to decrease volumes of DSW produced. The results indicate that the levels of BOD and DM in samples obtained throughout the year did not exceed the regulated concentration limits (1% DM and 2500 mg l^{-1} BOD) that distinguish DSW from slurry in the majority of cases. It is also evident that the vast majority of BOD (87%) and DM (94%) values for DSW samples, recorded during the closed period (mid October to mid-late January, depending on region) for land application of organic manures (slurry), remained below the regulated concentration limits of soiled water. Therefore, most of this DSW effluent may be applied to land throughout the year and a storage capacity of only 10 days is required (15 days for facilities built after 1 January 2015). This may, however, pose at least some degree of risk to water quality. Nitrogen losses from DSW application are likely to be at a minimum during the growing season when crops can take up the applied N (Ryan 1974; Smith and Chambers 1993). However, application of DSW during the closed period is subject to restrictions on application based on ground conditions (waterlogged, frozen, snow-covered), steepness of slope, forecast weather and proximity to surface water, groundwater and karst features (S.I. No. 31 of 2014) that should reduce any risk.

As with all N fertilisers, care must be taken to avoid N application in excess of crop requirements as N surpluses following land application are associated with increased N losses to water (Cooper, 1993; Wang *et al.* 2004). The limited capacity to store DSW found in this study (33 days, on average) for application during periods of greater grass growth and nutrient recovery may result in application during periods of little or no agronomic benefit. This is likely to limit achievement of the optimal soiled water N use and fertilizer replacement value on farms. It should be noted that, on many farms, DSW may be pumped to another storage tank or lagoon for longer storage until more favourable spreading conditions arise. This is a potential strategy to improve N use efficiency and fertilizer replacement value of N in DSW. However, if this DSW is mixed with slurry in such storage, the resultant effluent must be regarded and managed as slurry (S.I. No. 31 of 2014). The large variation in nutrient concentrations (Table 3) also presents a problem for effective nutrient management as this introduces uncertainty in the nutrient content.

The DSW TP concentrations recorded in this study are similar to those recorded by Fyfe (1999) in Australia, Longhurst *et al.* (2000) in New Zealand and Sweeten and Wolfe (1994) in the USA. The ratio of N to P in DSW (7:1) compared to typical grassland requirements (14:1, at a stocking rate of 170 kg ha^{-1} organic N; Coulter *et al.* 2002) means that application rates determined according to pasture N requirements may result in excess P application (Mikkelson and Gilliam, 1995; Edwards and Someshwar, 2000). The ratio of N to K in DSW (1:1) compared to typical grassland requirements (2:1, at a stocking rate of 170 kg ha^{-1}organic N; Coulter *et al.* 2002) may also result in excess K application. Excessive quantities of P and K in soils can result in P and K leaching (mainly through coarse, sandy, well drained soils) (Price, 2006; Murphy, 2007). Excessive K in soils can lead to elevated concentrations in grass that can pose a threat to livestock health, notably calcium deficiency (milk fever or hypocalcaemia) and magnesium deficiency (grass tetany or hypomagnesaemia) (Wang *et al.* 2004). Therefore, care would be needed to monitor P and K application, as well as N, in nutrient management planning to avoid unintended impacts of DSW on environmental quality or herd health.

A winter minimum was observed for BOD. This is likely due to the "drying off period" for spring calving herds in winter, resulting in zero input of faecal matter, urine or spilt milk on spring calving farms, and also to greater dilution from rainfall during winter. Lower BOD concentrations from June to August can be attributed to the high mean rainfall recorded across the country for those months in 2008 (Figure 7). This further highlights the sensitivity of BOD to rainfall events or a change in nutrient input as documented by Hooda *et al.* (2000) and Schofield *et al.* (1990). The peak in values recorded for BOD and DM during March (coincidental with large variability) is attributed to the commencement of the lactation period for spring calving herds.

According to Sukias *et al.* (2001), faecal and urine deposition in the milking parlour generally amounts to approximately 8–10% of the total manure production of the herd. An increase in milking duration will lead to an increase in defecation and urination in the collecting yards. This will lead to higher nutrient inputs to the DSW tank. In general, nutrient and BOD/DM concentrations are a function of the faecal and urine input and the water input (wash water and rain).

Roofed collecting yards were associated with increased NH_4-N concentrations (Table 5). This is most likely attributable to the removal of rainfall input and the sheltering of surfaces from sunlight and wind, inhibiting NH_4-N losses through volatilisation (Balsari *et al.* 2008). Roofed collecting yards also reduced the volume produced (Table 6). Therefore, the roofing of collecting yards may present an opportunity to increase plant-available NH_4-N concentrations in DSW while decreasing volumes produced. The Nitrate Regulations (S.I. No. 31 of 2014) require farmers to minimise soiled water production.

Although environmental factors have a clear influence on the concentration of nutrients and biochemical parameters in DSW, it is clear that milking parlour efficiency (cows per milking unit, time taken) also plays a key role in the composition of nutrients in DSW. Expansion of the herd while maintaining the same yard, parlour and facilities is likely to lead to little change in the volume of water used to wash down; however, it will result in a decrease in the volume of DSW generated per cow and increased concentrations due to the increase in faeces and urine input from the expanding herd. The end result is an increase in nutrient concentration and biochemical parameters and a reduction in the total volume cow^{-1} day^{-1}. This was mainly observed in the 55–110 herd size (Tables 4, 5 and 6), hence the reduction in volume cow^{-1} day^{-1} for this class.

Increases in scraping frequency can also increase concentrations in nutrients and biochemical parameters. This effect may be associated with non-expansion of milking parlour size and DSW storage capacity with an increase in herd size on some farms. Limited storage capacity will force farmers to reduce the total amount of DSW being generated on a daily basis. In addition, non-expansion of the dairy unit in conjunction with an increase in herd size will also reduce volume produced cow^{-1} day^{-1}, which in turn, will increase nutrient concentrations and biochemical parameters. Increased scraping frequency (daily), as a substitute for washing, will reduce the volume of DSW generated per cow, thereby increasing concentrations of nutrients and other biochemical parameters. Farms that increase their herd size but do not increase their milking parlour facilities (number of milking units and tank size being critical), or change management (e.g. volumes of water used to wash down), may be at risk of increasing the concentration of effluent produced, possibly to the point where the regulated concentration limits of DSW are exceeded and the effluent would be considered a slurry.

The fact that BOD concentrations in DSW were greatest for split calving herds with less than 30% of the herd for winter milk may be due to farmers reducing the frequency of washing over the winter. Lower volumes of wash water to dilute the faeces and urine would lead to higher BOD concentrations. During times when a higher percentage of the herd is used for winter milking, farmers will generally employ the same washing regime used during the remainder of the year so that the total volume of DSW remains unchanged while faeces and urine inputs are lower, leading to lower concentrations. Herds with no winter milking will have zero input of faeces or urine during the winter months, and therefore, will tend to have lower concentrations. The parlour and holding areas may not be the only source of nutrient input to DSW. Mixing of silage effluent with DSW is common practice on Irish dairy farms. Silage effluent input increased TN concentrations in this study and others (Leidmann *et al.* 1994).

Conclusions

Results from this study indicate that DSW produced on Irish dairy farms contains significant quantities of N, P and K (587, 80 and 568 mg l^{-1}, respectively). On average, 9784 l (s.e. 209 l) of DSW, including rainfall, was produced cow^{-1} $year^{-1}$. A typical Irish dairy farm stocked at 1.9 cows ha^{-1} could therefore supply approximately 13, 2 and 12 kg ha^{-1} of N, P and K, respectively, across the farm, annually to meet some of the nutrient requirements for herbage production and potentially replace some of the synthetic fertilizer use. Seventy-one percent of samples were within the regulated concentration limits of soiled water for BOD (< 2500 mg l^{-1}), rising to 87% during the closed period for slurry spreading (mid October to mid-late January), while 81% were within the concentration limits for DM (< 1% DM), rising to 94% during the closed period. The efficiency of a milking parlour (cows per unit, time taken) plays a key role in determining the volume of DSW generated. This, in turn, also influences the concentration levels. Large variability was found in nutrient concentrations and this presents a challenge for effective nutrient management to maximise the fertilizer replacement value of DSW.

A Tribute to Dr. Denis Minogue

This work was carried out as part of the PhD thesis of Dr. Denis Minogue. Dr. Minogue was a gifted scientist with a genuine commitment to improving agriculture for the benefit of both farmers and the environment. He made a lasting impact both at University College Dublin and with Teagasc. After a brave battle with cancer, Denis passed away in late 2014. He will be sorely missed by all of his colleagues. Ar dheis Dé go raibh a anam dílis.

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