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The composition of dirty water on dairy farms in Ireland

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Considerable quantities of dirty water, composed of milking parlour wash-water, milk spillages, runoff from cattle yard areas and, possibly, effluent from silage and manure, are produced on dairy farms. In Ireland, dirty water from dairy farm facilities is normally managed by spreading on, or irrigation to, land. It has considerable potential to cause water pollution due to its high pH, 5-day biochemical oxygen demand and its N and P concentrations. The objective of the present study was to contribute to better management of dirty water on dairy farms by providing estimates of its composition using rapid methods that can be easily used on farms. During the experiment, 34 samples were collected from the facilities on the dairy farm at Teagasc, Johnstown Castle (Wexford), between 27 January and 1 May, 2006. Dry matter and specific gravity provided the best indicator of biochemical oxygen demand, total nitrogen and phosphorous, and micro and macro nutrients. The nutrient concentration of dirty water can be determined rapidly using either dry matter concentration or specific gravity, enabling farmers to include this information in the nutrient management plan for their farm.

Keywords: dairy; dirty water; predicting nutrient composition; soiled water

Introduction

Ireland has a total land area of about 7×10^6 ha of which agriculture utilises approximately 4.4×10^6 ha. Agriculture is important to the national economy as it

is responsible for over 9% of total exports (Department of Agriculture, Fisheries and Food, 2009). In 2008, the national bovine herd was 6.7×10^6 head including 1.11×10^6 dairy cows; the sheep flock was $5.1 \times$

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10⁶ head of which 2.6×10^6 were ewes; the national pig herd comprised of 1.47×10^6 pigs, and the poultry flock consisted of about 13×10^6 birds (Central Statistics Office, 2009).

Nutrient losses from agricultural systems in Ireland, including those from point sources, has resulted directly or indirectly in the eutrophication of surface waters (Tunney, Beeuwisma and Withers, 1997). Eutrophication is the major threat to Irish water quality and current trends show that water quality continues to decline (Dunne *et al.*, 2005). Point-source pollution from agricultural practices include inappropriately managed dirty water from facilities on dairy farms. In Ireland and the UK, dirty water on dairy farms consists mainly of wash water from milking parlours (milk, sanitizers and other cleaning agents), drainage water from roofs of buildings, silage effluent, runoff from cattle standing yards and occasionally leachate from manure heaps (Cannon *et al.*, 2000; Moir *et al.*, 2005).

A milking parlour operation requires regular washing of equipment and floors, which leads to the production of dirty water. The volume of water used to clean the milking parlour varies daily and depends on: (i) the amount of urine/faeces excreted during milking and (ii) rainfall. The cleaning operation can account for up to 30% of the total wastewater volume from a dairy farm (Wright and Graves, 1998). Various authors have reported ranges for dirty water production on dairy facilities of 11 to 32 (Christopherson *et al.*, 2003), 30 to 49 (Cannon *et al.*, 2000), 20 to 70 (Mantovi *et al.*, 2003) and (in Ireland) up to 240 L cow⁻¹ day⁻¹ (Richards, Ryan and Coxon, 2004). Generally, as the number of cows in the herd increases the volume of dirty water per cow declines.

The chemical composition and quantity of dirty water on dairy farms varies

considerably over time (Cumby, Brewer and Dimmock, 1999; Richards, Ryan and Coxon, 2004). Furthermore, information on the quantity and the physical and chemical composition of this water is scarce. Chemical analysis using standard laboratory methods takes time, is costly and is not practical for most farms. A summary of the literature on the characteristics of dirty water from dairy facilities is in Table 1.

Dirty water is a potential pollutant of ground and surface waters due to its high pH, 5-day biochemical oxygen demand (BOD₅), ammoniacal-nitrogen (NH₄-N) concentration and residues of cleaning and disinfectant chemicals (Cannon *et al.*, 2000; Singh, Crofcheck and Brion, 2005). In Ireland, dirty water is defined in S.I. 378 of 2006 as a liquid with a BOD₅ value of less than 2500 mg/L or a dry matter (DM) concentration of less than 10 g/kg. These regulations require farms to have a minimum of 10 days storage capacity but, unlike manures, dirty water can be spread on grassland at any time of the year subject to the same exclusion zones and code of good practice as for manures. Land-spreading (using spray irrigator or tractor-drawn tanker spreader) is the most widely used practice for managing dirty water on dairy farms in Ireland (Rodgers, Gibbons and Mulqueen, 2003); however, in some cases, this method of management has the potential to cause degradation of surface and ground waters, particularly from application in winter or early spring. The importance of the potential nutrient contribution to crops from applications of dirty water has been highlighted, with up to 1000 kg N per year being landspread as dirty water in Ireland (Richards, Ryan and Coxon, 2004). Improved management of dirty water from dairy facilities could potentially turn a pollution threat into an opportunity for increasing nutrient efficiency due to the high potential loading

Table 1. Summary of dairy dirty water characteristics reported in the literature

Season	Component [†]										Source
	pH	BOD ₅ (mg/L)	TN (mg/L)	NH ₄ -N (mg/L)	NH ₄ -N/TN	NO ₂ -N (mg/L)	P (mg/L)	TP (mg/L)	K (mg/L)		
-	-	2870	227	151	0.66	< 0.9	30	44	524	Ryan (1990)	
-	-	2077	159	92	0.58	1	17	23	210	Ryan (1991)	
-	7.3	-	450	42	0.10	-	-	<100	350	Misselbrook <i>et al.</i> (1995)	
-	-	-	188	84.4	0.45	-	-	-	-	Richards (1999)	
Spring	7.6	2660	-	31	-	-	-	-	-	Cumby <i>et al.</i> (1999)	
Summer	6.4	9670	95	58	0.61	-	-	49	150	Cumby <i>et al.</i> (1999)	
Autumn	6.6	7450	70	48	0.69	-	-	34	85	Cumby <i>et al.</i> (1999)	
-	-	1440	-	-	-	-	-	-	-	Cannon <i>et al.</i> (2000)	
-	-	2208	-	-	-	-	-	-	-	Rodgers, Gibbons and Mulqueen (2003)	
Winter	-	2828	-	42	-	-	-	-	-	Dunne <i>et al.</i> (2005)	
Spring	-	2703	-	53	-	-	-	-	-	Dunne <i>et al.</i> (2005)	
Summer	-	2682	-	36	-	-	-	-	-	Dunne <i>et al.</i> (2005)	
Autumn	-	2303	-	6	-	-	-	-	-	Dunne <i>et al.</i> (2005)	
-	7.4	3000	479	-	-	1.1	-	111	-	Singh, Crofcheck and Brion (2005)	

[†] BOD₅, 5-day biochemical oxygen demand; TN, total N; NH₄-N, ammoniacal N; NH₄-N/TN, ammoniacal N as a proportion of total N; NO₂-N, nitrite N; P, ortho-phosphorous; TP, total P.

of plant available nutrients (Ryan, 1991; Gibbons, Rodgers and Mulqueen, 2005).

The sustainable use of dirty water from dairy facilities, as for animal manures, must be based on accurate information on its characteristics in order to optimise its use, or treatment, and to reduce any potential pollution risk. The objective of this study was to investigate the composition of dirty water from dairy facilities and to evaluate the potential of easily determined physical properties, such as dry matter, specific gravity, pH, and electrical conductivity, as estimators of nutrient composition.

Materials and Methods

Site and sample description

This study was conducted on the dairy facilities at Environmental Research Centre (Teagasc, Co. Wexford), which supports a herd of 137 spring-calving dairy cows. Dirty water from the dairy parlour and yard area was collected and managed separately to the animal manure generated during the winter period when the herd is maintained indoors. The main contributors to dirty water were the wash water from the milking parlour (cleaning milking parlour and holding yard area), wastewater from the cleaning of the milking equipment (milk, sanitizers and other cleaning agents) and the rain water falling on the surface area of the accompanying yards (area ca. 4357 m²).

The volume of water used to clean the milking parlour varied depending on the quantities of faeces excreted by the cows during the milking session. An automatic cleaning system was used for the milking machine, and resulted in the use of relatively constant volumes of water, detergent and chemicals. All the dirty water produced in the dairy unit was collected in a storage tank and solids were removed

in a triple tank sediment trap system. A pump, activated by a float switch, pumped the dirty water from the third tank to a field-based irrigation system. The three sediment tanks were emptied once a month and the sludge applied to land.

A total of 34 samples were collected during a 13-week period (late January to 1 May 2006) at intervals of 2 to 3 days. Samples of dirty water (3 L) were collected from the third dirty-water tank using a simple sampler (Martinez-Suller, Azzellino and Provolo, 2008) and stored in a plastic container (4 L). The first sample was collected on 27 January 2006 and the last one was taken on 1 May 2006. The contents of the tank were agitated manually prior to sampling. The samples were placed immediately in a cold room at 4 °C, pending analysis. The maximum storage time between sampling and analysis was 10 days.

Daily rainfall was recorded at the weather station located at Johnstown Castle, 100 m from the dairy yard (Table 2).

Laboratory analyses

Variables analyzed were pH, specific gravity (SG), electrical conductivity (EC) and the concentrations of dry matter (DM), 5-day biochemical oxygen demand (BOD₅), total nitrogen (TN), ammoniacal nitrogen (NH₄-N), total oxidised nitrogen (TON), nitrite nitrogen (NO₂-N), ortho-phosphorous (P), total

Table 2. Rainfall (mm) during the experimental period (2006)

Period	Daily values		Period total	Monthly average [†]
	Mean	Range		
27 Jan–28 Feb	1.5	0–19	48.1	68
1–31 March	4.8	0–22.2	147.7	67
1 Apr–1 May	0.8	0–6.2	24.0	55
Overall	2.3	0–22.2	219.8	190

[†] Long-term average values at Johnstown Castle Environment Research Centre.

phosphorous (TP), K, Ca, Mg, Na, Cl, Fe, Mn, Cu and Zn.

The raw dirty water samples were mixed for 5 min, using an electric stirrer, prior to the measurement of pH, SG, EC and DM, and then sub-sampled to provide material for chemical analysis. All chemical analyses involved using diluted samples appropriate to the detection limits of the individual methods. Results were accepted for the most suitable dilution factor for each analyte when they were within the analytical range of the specific instrument. BOD₅ was calculated according to standard methods by subtracting the residual dissolved oxygen (DO) concentration, measured after incubation for 5 days at 20 °C, from the initial DO (APHA, 1998).

For DM determination, approximately 200 g of the raw sample were placed in an oven and dried at 104 °C for 24 h (APHA, 1998); specific gravity was measured using a hydrometer with a range of 1000 to 1050 g/L (Stevenson Reeves Ltd., Edinburg, Scotland). The pH and EC values were determined potentiometrically on the raw sample according to APHA (1998). TON, NO₂-N, NH₄-N, Cl and P were measured colorimetrically, 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, Tsutsui and Shirai (1983). All metal fractions were analysed by inductively-coupled optical emission spectrophotometry (ICP) according to standard methods (Gottler and Piwoni, 2005).

Statistical analysis

A simple descriptive analysis was carried out to find the mean, maximum, minimum and s.d. and the simple correlation was

calculated for all pairs of the variables measured. A forward-selection stepwise regression procedure was conducted for each nutrient (BOD₅, TN, NH₄-N, TON, NO₂-N, P, TP, K, Ca, Mg, Na, Cl, Fe, Mn, Cu and Zn) using all of the physical characteristics (pH, SG, EC, DM) as independent variables to determine which of these properties were important in explaining variation in nutrient composition. The values for TN, TON, NH₄-N/TN, NO₂-N, P, K, Mg, Fe, and Zn were log transformed to satisfy the assumption of normality of residuals.

Results and Discussion

Climatic conditions

The temporal relationship between rainfall and DM concentration during the measurement period is shown in Figure 1. During the monitoring period, both the highest monthly and daily rainfalls were recorded in March (147.7 mm and 22.2 mm/day, respectively; Table 2).

Composition of dirty water

Summary statistics for pH, SG, EC and DM are presented in Table 3. The mean pH value is similar to that reported by Cumby, Brewer and Dimmock (1999) for dirty water samples collected from dairy facilities in summer and autumn. However, Cumby, Brewer and Dimmock (1999) and others (Misselbrook *et al.*, 1995; Singh, Crofcheck and Brion, 2005) reported higher mean pH values (7.4 to 7.6) for dirty water collected from dairy facilities in spring.

The mean values for SG, EC and DM were all lower than those reported for cattle slurry (Tunney, 1979; Villar *et al.*, 1979; Scotford *et al.*, 1998b; Moral *et al.*, 2005; Provolo and Martinez-Suller, 2007; Martinez-Suller, Azzellino and Provolo, 2008), probably as a consequence of dilution with rain and wash water.

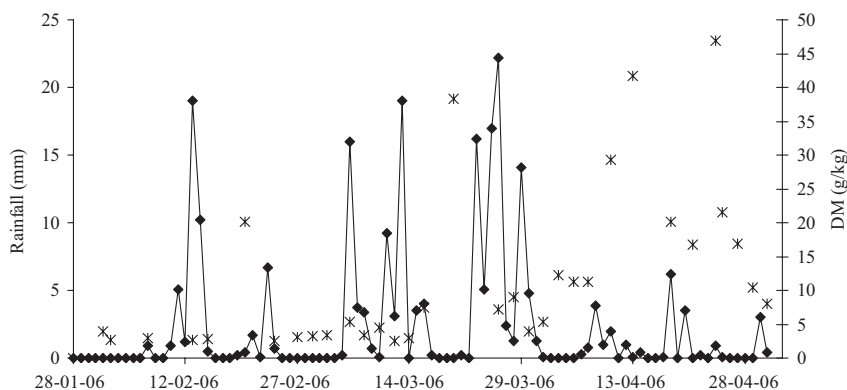


Figure 1. The temporal relationship between rainfall (◆) and dry matter (DM) concentration (*) of dirty water from dairy farm facilities.

Table 3. Summary data on physical properties of dirty water from dairy farm facilities

Variable [†]	Mean	Median	Range	s.d.
pH	6.6	6.5	6.0–7.4	0.33
SG (g/L)	1002	1001	1000–1010	0.003
EC (S/m)	0.22	0.22	0.09–0.34	0.40
DM (g/kg)	12	7	3–47	12

[†] SG, specific gravity; EC, electrical conductivity; DM, dry matter.

The observed values for BOD₅, TN, NH₄-N, TON and NO₂-N, summarised in Table 4, are all within the range reported by others (see Table 1). Singh, Crofcheck and Brion (2005) observed wide variations among farms, and from day to day within farms, for BOD₅ but no seasonal variation was detected. However, Cumby, Brewer and Dimmock (1999) reported wide variations in BOD₅ concentrations with seasonal variations reflecting the degree of dilution. According to Rodgers, Gibbons and Mulqueen (2003), most of the inorganic N was in the NH₄-N form, as the concentrations of NO₂-N and TON were very low. The low mean NH₄-N/TN proportion (0.13) in the present study may have been a consequence of the season (late winter/spring) when the measurements

Table 4. Summary of the concentration of BOD₅, N, P and K in dirty water from dairy farm facilities

Variable [†]	Mean	Median	Range	s.d.
BOD ₅	3084	2410	1570–8400	1739
TN	351	252	128–987	231
NH ₄ -N	32	31	0–106	25
NH ₄ -N/TN	0.13	0.11	0–0.60	0.12
TON	0.3	0	0–1.6	0.47
NO ₂ -N	0.3	0.2	0–1.0	0.27
P	8.5	6.3	0.7–24.9	6.49
TP	44	37	21–103	22
K	415	359	231–977	169

[†] See footnote Table 1.

were made, as spring-calving cows were dry during the winter (out of the milking parlour), thus eliminating milking and reducing urine excretion, the main sources of NH₄-N. Richards (1999) tested dirty water from dairy facilities for N compounds over a 13-month period and reported seasonal variations (highest in summer and lowest in winter).

Dairy washings contain a number of organic N forms, which have a high BOD₅, as well as the inorganic forms NH₄-N, NO₃-N and NO₂-N (Moir *et al.*, 2005). Ammonia is readily lost from dirty water and slurry by volatilisation or by nitrification. Nitrification of the ammonia would normally lead to the

transient formation of $\text{NO}_2\text{-N}$ and/or $\text{NO}_3\text{-N}$. Traces of these oxidised nitrogen compounds were found in only a few samples, indicating that relatively little nitrification had occurred during the generation and storage of the dirty water.

Most of the cleaning and disinfectant chemicals used on dairy farms are sources of chloride, sulphate and phosphate ions. The TP concentration of dirty water is of concern since P is usually the limiting nutrient in fresh water eutrophication. The mean TP value observed in the present study (Table 4) is similar to values previously reported (Ryan, 1990; Cumby, Brewer and Dimmock, 1999) and the K concentration is also in line with other reports (Cumby, Brewer and Dimmock, 1999; Cannon *et al.*, 2000; Christopherson *et al.*, 2003).

Data on concentration of the micro and macro nutrients are summarised in Table 5. The nutrients Na and Cl are associated with specific agronomic and environmental risks (Moral *et al.*, 2005), though cases of this rarely arise in the context of waste water from Irish dairy farms (Gibbons, Rodgers and Mulqueen, 2005; Ryan *et al.*, 2005). High Cl concentrations affect the chemical forms of metal in soils, and could enhance the availability of metal cations by the formation of complexes

with a progressively more negative charge (Burton and Turner, 2003), which would reduce immobilisation of cations on the surface of colloidal soil particles. In addition to Na toxicity for plants, sodium salts could disperse soil colloids, giving rise to a weak and often compact soil structure (Moral *et al.*, 2008). Ca and Mg are two macro nutrients not usually considered in indirect estimation procedures, but they probably play an important role in the dynamics of other nutrients, especially P.

Cu and Zn are commonly-occurring micro nutrients in agricultural wastewaters and arise from their inclusion in concentrate diets because of animal nutritional requirements and their antimicrobial properties (Moral *et al.*, 2008). Despite their essential role in plant nutrition, high concentrations of Cu, and to a lesser degree Zn, in available forms in soils can induce phytotoxicity in crops (Moral *et al.*, 2008), and Cu deficiency in animals (McGrath, Fleming and Culleton, 2008). However, the Cu and Zn concentrations observed in the present study do not give cause for concern. Mean concentrations of Fe and Mn were associated with very high temporal variability which was also observed for Cu and Zn.

Correlations between physical properties and nutrient concentration

The significance of the correlations amongst all of the components measured is displayed in Table 6. The pH was significantly correlated with all other variables, except $\text{NH}_4\text{-N}$, $\ln(\text{NO}_2\text{-N})$, P, $\ln(\text{K})$ and Na. This contrasts with the results obtained in previous work with animal manure (Scotford *et al.*, 1998a,b; Moral *et al.*, 2005; Provolò and Martínez-Suller, 2007; Martínez-Suller, Azzellino and Provolò, 2008). The DM concentration was not significantly correlated with $\text{NH}_4\text{-N}$, $\ln(\text{NO}_2\text{-N})$ or $\ln(\text{P})$, but was correlated

Table 5. Summary of the concentration¹ of metals and chloride ions in dirty water from dairy farm facilities

Element ¹	Mean	Median	Range	s.d.
Ca	188	171	61–430	84
Mg	51	49	22–96	17
Na	60	58	27–94	18
Cl	278	269	126–605	103
Fe	17.7	9.3	2.0–96.7	20.7
Mn	1.4	1.0	0.4–4.1	0.9
Cu	0.3	0.1	0–1.5	0.4
Zn	1.1	0.6	0.2–6.0	1.4

¹ mg/L.

Table 6. Correlation coefficients among all measured variables

Variable [†]	Variable																		
	pH	SG	EC	DM	BOD ₅	ln(NH ₄ -N (TN))	ln(NH ₄ -N (TN))	ln(NH ₄ -N/TN)	ln(TON-N)	ln(NO ₂ -N)	ln(P)	ln(K)	ln(Ca (Mg))	ln(Na)	ln(Cl)	ln(Mn)	ln(Cu)		
SG	-0.49																		
EC	0.37	0.00																	
DM	-0.62	0.97	-0.07																
BOD ₅	-0.60	0.93	-0.02	0.93															
ln(TN)	-0.54	0.87	0.06	0.90	0.81														
NH ₄ -N	0.16	-0.14	0.36	-0.11	-0.14	0.00													
ln(NH ₄ -N/TN)	0.54	-0.36	0.55	-0.37	-0.31	-0.34	0.66												
TON	0.40	-0.31	0.23	-0.35	-0.23	-0.39	-0.09	0.20											
ln(NO ₂ -N)	0.23	-0.03	0.44	-0.03	0.07	0.14	0.00	0.24	0.68										
ln(P)	0.09	0.27	0.27	0.26	0.36	0.13	0.08	0.26	0.16	0.51									
TP	-0.61	0.94	0.05	0.97	0.93	0.91	-0.02	-0.25	-0.32	0.15	0.36								
ln(K)	0.32	0.10	0.47	-0.01	0.11	0.04	0.28	0.37	0.38	0.24	0.03	0.01							
Ca	-0.63	0.94	0.05	0.94	0.88	0.87	-0.07	-0.29	-0.37	-0.06	0.17	0.90	0.10						
ln(Mg)	-0.43	0.73	0.33	0.70	0.69	0.67	0.13	-0.03	-0.24	0.13	0.31	0.75	0.10	0.84					
Na	-0.25	0.37	0.33	0.31	0.32	0.31	0.23	0.01	0.02	0.13	-0.05	0.34	0.33	0.54	0.77				
Cl	-0.46	0.88	0.28	0.86	0.85	0.73	0.00	0.01	-0.21	0.19	0.38	0.86	0.29	0.88	0.76	0.41			
ln(Fe)	-0.69	0.86	-0.09	0.89	0.80	0.93	-0.14	-0.46	-0.25	0.11	0.05	0.86	0.14	0.83	0.54	0.27	0.69		
Mn	-0.62	0.97	0.02	0.96	0.90	0.86	-0.12	-0.35	-0.31	-0.01	0.28	0.92	0.09	0.96	0.78	0.44	0.89	0.86	
Cu	-0.66	0.95	-0.06	0.97	0.92	0.84	0.04	-0.21	-0.34	-0.24	0.28	0.94	0.05	0.91	0.70	0.33	0.88	0.82	
ln(Zn)	-0.76	0.90	-0.15	0.94	0.83	0.94	-0.07	-0.44	-0.41	-0.11	0.09	0.92	-0.11	0.90	0.71	0.38	0.71	0.92	0.90

[†] See footnotes Tables 1, 3, 5.

All correlation coefficients in bold were significant at $P < 0.05$; critical values varied slightly due to some missing values (below detection limit).

($P < 0.001$) with $\ln(\text{TN})$ and TP. Similar results have been reported by other workers for cattle manure (Villar *et al.*, 1979; Scotford *et al.*, 1998a,b; Provolò and Martínez-Suller, 2007; Martínez-Suller, Azzellino and Provolò, 2008). With the exception of Na and $\ln(\text{K})$, correlations between DM and the micro/macro nutrients were highly significant ($P < 0.001$). The correlations between SG and the chemical composition variables were similar to those for DM. This is not surprising considering the highly significant correlation recorded between SG and DM in this study, and as reported previously for slurry (Tunney, 1979).

EC should be a useful indicator for the concentration of ions such as $\text{NH}_4\text{-N}$, K, Cl and Na, but not for organic-dependent components such as P, organic N, Ca or Mg (Moral *et al.*, 2005). In the present study, EC was significantly correlated with $\text{NH}_4\text{-N}$, $\ln(\text{NH}_4\text{-N}/\text{TN})$, $\ln(\text{NO}_2\text{-N})$ and $\ln(\text{K})$, but the corresponding correlations for the latter variable with either SG or DM were not as high. Similar results have been obtained for cattle and pig slurry by others (Bellotti, 1997; Scotford *et al.*, 1998a,b; Moral *et al.*, 2005; Provolò and Martínez-Suller, 2007; Martínez-Suller, Azzellino and Provolò, 2008).

Highly significant correlations were observed between easily measured physical characteristics (pH, SG and DM) and BOD_5 and N compounds, indicating that these physical characteristics can be used to estimate BOD_5 concentration in dirty water. This is especially important because BOD_5 is the major criterion used in water pollution control. The results also suggest that EC is not a useful indicator of BOD_5 concentration.

Total nitrogen, $\ln(\text{TN})$, was correlated ($P < 0.001$) with pH, SG and DM but not with EC. In the present work, EC was the only physical characteristic that showed

a significant correlation with $\text{NH}_4\text{-N}$ and $\ln(\text{NO}_2\text{-N})$. This is interesting from a water quality perspective as both $\text{NH}_4\text{-N}$ and $\text{NO}_2\text{-N}$ are highly toxic in aquatic ecosystems, leading to very low water concentrations being set for these compounds.

There were no significant correlations between pH, EC, SG or DM and the ortho-P concentration (Table 6). However, TP was significantly correlated with DM, SG, pH, BOD_5 , $\ln(\text{TN})$ and all macro and micro nutrients, except $\ln(\text{K})$ and Na. This agrees with previous results (Scotford *et al.*, 1998a,b; Provolò and Martínez-Suller, 2007; Martínez-Suller, Azzellino and Provolò, 2008; Moral *et al.*, 2008). In line with the reported results of Bellotti (1997), Martínez-Suller *et al.* (2008), Moral *et al.* (2005) and Provolò and Martínez-Suller (2007), $\ln(\text{K})$ was significantly correlated with EC, and with $\ln(\text{TON})$ and $\ln(\text{NH}_4\text{-N}/\text{TN})$. No other significant correlations involving $\ln(\text{K})$ were found.

All macro and micro nutrients showed similar correlations with pH, SG and DM, to those already published. Moral *et al.* (2008) observed highly significant correlations of EC with Na and Cl concentrations in pig slurry ($P < 0.001$), but this was not observed in the present study.

Regression between physical properties and nutrient concentration

Results from stepwise linear regression analysis of the relationship between easily determined physical properties and nutrient concentrations are presented in Tables 7 and 8. Although the stepwise regression procedure selected DM as the best explanatory variable for BOD_5 , $\ln(\text{TN})$ and TP, SG often had similar predictive power, reflecting the high correlation between SG and DM, even though DM had a numeri-

Table 7. Estimated regression equations for predicting, from physical characteristics, key aspects of the composition of dirty water from dairy facilities

Dependent variable [‡] (mg/L)	Equation element	Estimate	s.e.	Significance	Partial R ²
BOD ₅	Intercept	15	158.2	***	0.87
	DM (g/kg)	1350	96	***	
ln(TN)	Intercept	5.16	0.062	***	0.82
	DM (g/kg)	0.4	0.04	***	
NH ₄ -N	Intercept	-27.12	27.557	n.s.	0.13
	EC (S/m)	2.63	1.206	*	
ln(TON)	Intercept	0.13	0.117	n.s.	0.79
	DM (g/kg)	-0.4	0.07	***	
ln(NO ₂ -N)	Intercept	-2.87	0.803	**	0.19
	EC (S/m)	0.076	0.0351	*	
TP	Intercept	6.06	5.993	n.s.	0.94
	DM (g/kg)	18.2	0.74	***	
	EC (S/m)	0.73	0.257	**	
ln(K)	Intercept	4.92	0.344	***	0.22
	EC (S/m)	0.045	0.151	**	

[‡]See footnotes Tables 1, 3.

Table 8. Estimated regression equations for predicting, from physical characteristics, the concentration of macro and micro nutrients in dirty water from dairy facilities

Dependent variable [‡] (mg/L)	Equation element	Estimate	s.e.	Significance	Partial R ²
Ca	Intercept	-29,324	1955.1	***	0.88
	SG (g/L)	29.44	1.950	***	
ln(Mg)	Intercept	-84.86	13.003	***	0.54
	SG (g/L)	0.09	0.013	***	
	EC (S/m)	0.03	0.099	**	
Na	Intercept	-2413	1050.2	*	0.14
	SG (g/L)	2.429	1.047	*	
	EC (S/m)	1.68	0.810	*	
Cl	Intercept	-34,120	2612.2	***	0.78
	SG (g/L)	34.13	2.606	***	
	EC (S/m)	8.51	2.015	***	
ln(Fe)	Intercept	8.47	0.109	***	0.79
	DM (g/kg)	0.7	0.07	***	
Mn	Intercept	-344,216	15,133.4	***	0.94
	SG (g/L)	344.82	15.098	***	
Cu	Intercept	-78.94	21.782	***	0.94
	DM (g/kg)	287.3	13.14	***	
ln(Zn)	Intercept	10.49	1.967	***	0.88
	DM (g/kg)	0.67	0.07	***	
	pH	-0.74	0.293	*	

[‡]See footnotes Tables 1, 3.

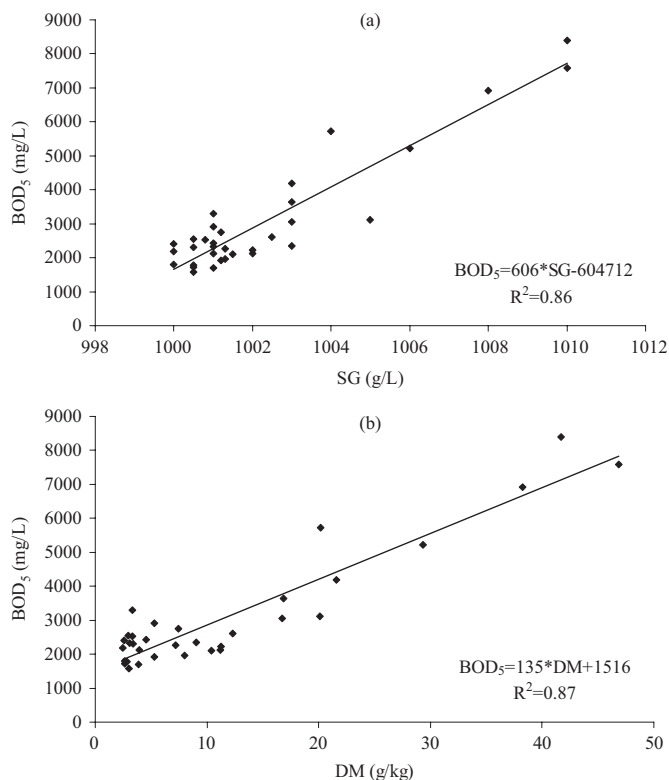


Figure 2. The relationship between biochemical oxygen demand (BOD_5) and a) specific gravity (SG), b) dry matter concentration (DM).

cally higher R^2 value. This suggests that both DM (R^2 0.87) and SG (R^2 0.86) are good estimators of the most important water quality parameter, namely BOD_5 (Figure 2), and the two most important fertilizer elements applied to crops in agricultural wastes, namely TN (DM; R^2 0.82) and TP (DM; R^2 0.94). Plant available NH_4-N and $\ln(NO_2-N)$ were related to EC ($P < 0.05$), but both had low R^2 values (Table 7). Although $\ln(TON)$ was related to DM (R^2 0.79), this is of no practical use because the TON concentration of dirty water is low (Table 4). The $\ln(P)$ was not significantly related to any of the physical properties, but $\ln(K)$ was related to EC (R^2 0.22).

All macro and micro nutrients displayed highly significant correlations with both SG and DM and SG was identified as the best single predictor for Mn, Ca, Cl, $\ln(Mg)$ and Na. DM was a good estimator of some plant nutrients, such as Fe, Cu and Zn.

The stepwise procedure identified a number of cases where additional variables significantly improved the prediction equation. In some of these, the additional variables only slightly improved the R^2 value ($P < 0.05$). For example, the prediction of TP was significantly ($P < 0.01$), but only slightly (R^2 increased by 0.01), improved by the inclusion of EC (Table 7). Likewise, R^2 for the prediction of $\ln(Zn)$

was significantly improved ($P < 0.05$), but only by 0.02, by the inclusion of pH. The inclusion of more than one independent variable significantly increased the R^2 by 0.08 to 0.11 for Na, $\ln(\text{Mg})$, Cl (Table 8). The small additional predictive power offered by multiple variables does not warrant their inclusion, because the improvement is either small, or it relates to the agronomically less important components. The results indicate that either DM or SG can be used to provide satisfactory quantification of the nutrient concentration of dirty water. As a practical tool for farmers and farm advisors, SG has the added advantage that instantaneous results can be obtained in the field.

Conclusions

The finding that mean BOD_5 and DM concentrations in dirty water observed in this study exceeded the maximum values set in Irish legislation highlights the difficulties in selecting limits for legally defining dirty water in terms of its biological or physical characteristics. The macro and micro nutrient concentrations observed were lower than those reported for slurry, but values were highly variable. This supports the suggestion of Ryan *et al.* (2005) that dirty water applications should be integrated into the farm nutrient management planning process.

DM and SG provided the best indicator of BOD_5 , $\ln(\text{TN})$, TP, and micro and macro nutrients. So, the nutrient concentration of dirty water can be determined rapidly using either DM concentration or SG, enabling farmers to include this information in the nutrient management plan for their farm.

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