Science of the Total Environment 542 (2016) 854–863

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Septic tank discharges as multi-pollutant hotspots in catchments

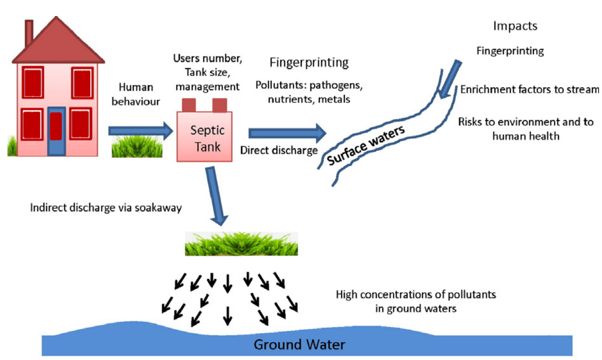
Samia Richards [a,*], Eric Paterson [a], Paul J.A. Withers [b], Marc Stutter [a]

[a] The James Hutton Institute, Craigiebuckler, Aberdeen, AB15 8QH, Scotland, UK
[b] Bangor University, Bangor, Gwynedd LL57 2UW, UK

HIGHLIGHTS

- Physicochemical and microbial fingerprinting of effluent discharges are presented.
- STE continues to pose risks to stream ecology, water quality and human health.
- Effluent enrichment factors of NH_4–N, P and Cu were 1486, 261 and 30, respectively.
- Effluent quality was linked with tank condition, management and user number.
- Detection of tryptophan by fluorescence can be used to trace STE contamination.

GRAPHICAL ABSTRACT



Septic tank discharges; as multi-pollutant hotspots in catchments

ARTICLE INFO

Article history:
Received 28 July 2015
Received in revised form 30 October 2015
Accepted 30 October 2015
Available online xxxx

Editor: D. Barcelo

Keywords:
Septic tank effluent
Water quality
Nutrients and metal concentrations
Bacteria
Tracers

ABSTRACT

Small point sources of pollutants such as septic tanks are recognised as significant contributors to streams' pathogen and nutrient loadings, however there is little data in the UK on which to judge the potential risks that septic tank effluents (STEs) pose to water quality and human health. We present the first comprehensive analysis of STE to help assess multi-pollutant characteristics, management-related risk factors and potential tracers that might be used to identify STE sources. Thirty-two septic tank effluents from residential households located in North East of Scotland were sampled along with adjacent stream waters. Biological, physical, chemical and fluorescence characterisation was coupled with information on system age, design, type of tank, tank management and number of users. Biological characterisation revealed that total coliforms and *Escherichia coli* (*E. coli*) concentration ranges were: 10^3–10^8 and 10^3–10^7 MPN/100 mL, respectively. Physical parameters such as electrical conductivity, turbidity and alkalinity ranged 160–1730 μS/cm, 8–916 NTU and 15–698 mg/L, respectively. Effluent total phosphorus (TP), soluble reactive P (SRP), total nitrogen (TN) and ammonium-N (NH_4–N) concentrations ranged 1–32, <1–26, 11–146 and 2–144 mg/L, respectively. Positive correlations were obtained between phosphorus, sodium, potassium, barium, copper and aluminium. Domestic STE may pose pollution risks particularly for NH_4–N, dissolved P, SRP, copper, dissolved N, and potassium since enrichment factors were >1651, 213, 176, 63, 14 and 8 times that of stream waters, respectively. Fluorescence characterisation revealed the presence of tryptophan peak in the effluent and downstream waters but not detected upstream from the source. Tank condition, management and number of users had influenced effluent quality that can pose a direct risk to stream waters as multiple points of pollutants.

* Corresponding author.
E-mail address: samia.richards@hutton.ac.uk (S. Richards).

http://dx.doi.org/10.1016/j.scitotenv.2015.10.160

1. Introduction

Septic tank systems (STS) are the most widely used collection systems for onsite treatment and disposal of domestic wastewater around the world. Their use is particularly common in rural areas where connection to main sewerage network system is not available, or impractical and costly (Dudley and May, 2007). In the UK, only 4% of the population are served by small private treatment works or septic tanks (ST), (DEFRA, 2002), but over one third of dwellings in Ireland (400,000) use them (Gill et al., 2004). Approximately 13% of the Australian population and 25% of households in the United States are served by onsite systems (Dawes and Goonetilleke, 2003; D'Amato et al., 2008). The efficiency of these systems is reflected in the quality of septic tank effluent (STE) and the functioning of the soakaway. STE poses potential risks to human health and aquatic ecosystems if it reaches surface or ground waters without effective treatment (Withers et al., 2014) which depends on tank performance, effluent retention time and the physical, biological and chemical processes inside the tank. Effluent quality also depends on wastewater organic matter content and use of chemicals in the household, which affects bacterial growth and activity in the tank (Brandes, 1978).

Historically, ST were made from bricks or concrete and comprised of one rectangular chamber connected with an inlet pipe (receiving influent from the house) and an outlet pipe (discharging effluent to the soakaway) (May et al., 1996). Septic tanks should be designed to accommodate vertical soil pressure and should be large enough to provide a minimum effluent retention time of 24 h (Seabloom et al., 2005). The primary functions of ST are solids removal from wastewater, accumulation and storage of sludge and scum, breakdown of solid material in an anaerobic digestion process and finally discharge the partially treated effluent to soakaway soil for further treatment (D'Amato et al., 2008). Most STS are capable of treating domestic wastewater effectively at low cost if situated, designed, constructed and maintained appropriately (Environment Alliance PPG4, 2006).

Septic tank effluent is thought to have become to hold negligible or less impact on water quality compared to diffuse pollution (Sharpley et al., 1993; Haygarth et al., 2005). However, domestic wastewater contains a wide variety of potential pollutants including pathogens, faecal bacteria, organic matter (OM), phosphorus (P), nitrogen (N), ammonia (NH_4–N), biochemical oxygen demand (BOD) and suspended solids (SS) as well as pharmaceutical organic compounds and household detergents and chemicals (Gill et al., 2004; Wilhelm et al., 1994; Siegrist et al., 2012) that pose a risk to contaminate fresh waters. Many studies have linked P contamination of surface waters to STE (Bowes et al., 2010; Edwards and Withers, 2008). Bacterial contamination of watercourses from untreated STE is of major concern and poses a risk of disease outbreaks if it contaminates drinking water in nearby water wells (Harris et al., 2013). Lusk et al. (2011) stated that pathogenic bacteria present in STE such as *Escherichia coli* (*E. coli*), *Salmonella* and *Shigella* can cause infections in humans (diarrhoea, nausea, dysentery and hepatitis) in much lower dosage than their actual concentration in STE. Domestic wastewater may contain a number of trace organic chemicals derived from cleaning products, washing detergents and other human activities including caffeine, pharmaceutical compounds, hormones and endocrine disrupting compounds contributing to environmental and human health risks from STE (Kusk et al., 2011).

Although most STs discharge their effluents to soil soakaways for secondary treatment, some STs discharge their effluents and contaminants directly to surface waters or to soakaways that are sited too close to watercourses, (Dudley and May, 2007). Efroymson et al. (2007) declared that the STs that are located within close proximity of watercourses and those with hydraulic failures have direct impacts on water quality. Withers et al. (2011) considered that effluent discharges during low flow periods in summer would have the greatest ecological impact and risk to human health. There is little data on the composition of STE in the UK with which to assess the risk to both water quality and human health. And the variability in effluent quality between different types of tanks and due to effects of management factors is currently poorly known. For example, very few studies have looked across a range of nutrient, metal and microbiological parameters, yet the knowledge of these combinations of contaminants will inform impact, tracing techniques to quantify STE emissions and future control.

In the UK, onsite waste water treatment systems are unregulated and not monitored for performance. In the absence of this knowledge of their true impact, we propose that STE enrichment to freshwaters can pose significant risks at catchment scales acting as small inputs of multiple pollutants. The current study examined the effluent composition of thirty two STE from residential households located in the North East of Scotland. The main hypothesis is that STE compositions indicate they are a major environmental source of physical, chemical and microbial pollution. Knowledge is required on septic tank management and landscape factors that may control effluent composition and potential pollution impact. Therefore, we further hypothesise that 1) STE composition, and hence impact on receiving waters, can be related to tank management factors that may provide risk descriptors and 2) composition factors can be identified to inform development of future environmental tracing methodologies to quantify STE risks.

2. Materials and methods

2.1. Study sites

Thirty two conventional residential septic tank systems serving permanently occupied dwellings located in four rural river catchments in the North East of Scotland were selected for effluent sampling and analysis. Site location, tank management and catchment information is reported in supplementary material (Table S1) and (Fig. S1): Lunan water ($n = 5$), River Dee ($n = 14$), River Don ($n = 8$) and Ythan River ($n = 5$). Selection of sites was based on a survey previously sent to ST users to gain information on their ST system and to acquire permission and agreement to participate in the study. Sites were visually assessed for tank access and for signs of system failure before sampling. Twenty one sites were serviced with individual conventional concrete septic tanks and eleven sites with reinforced fibre glass/polyethylene tank type. Five sites were within 2–10 m from water courses. Three tanks discharged their effluent directly without soakaway secondary treatment to water courses, five discharged the effluent through an undersoil surface soakaway and eventually to streams, and two discharge their effluent to ditches, while others discharged their effluents to surface soil beds or to fields. The ages of the tanks varied from 1 to over 100 years. Management of the tanks also varied; from being emptied yearly to never having been emptied, while some users did not know the history of their tanks. Six of the 32 sites did not use dishwashers. The number of people served by individual ST in this study varied from 1 to 7 people in a household and sampling occurred between February and June 2014.

2.2. Effluent sampling and analyses

Two separate effluent samples were collected from each site: 40 mL was sampled into a sterile vial for microbial, chemical oxygen demand (COD) and biochemical oxygen demand (BOD) characterisation; 1 L was sampled into polyethylene bottle for physical and chemical characterisation. Where possible, stream water samples of the study sites were also collected ($n = 10$). Effluent and water samples were kept in a cold box during transportation to the laboratory then in a cold room at 4 °C until processing. Microbial, BOD and COD analyses were performed within 12 h while processing for physical and chemical analyses were within 36 h. Total viable counts (TVC) of heterotrophic bacteria were performed using a spread plating technique. Serial dilution was made and diluted samples were spread aseptically on top of solidified nutrient agar, (Standard methods for the examination of water and wastewater, 1999). Plates were incubated at 37 °C for 24 h then bacterial colonies were counted and colony formed units (CFU) were calculated in 1 mL of effluent or water.

For total and faecal coliforms and *E. coli* detection, effluents were diluted appropriately using sterilised saline phosphate buffer (pH 7.3) and the diluted effluents were screened using IDEXX Colilert-18 kits and Quanti-Tray/2000 (IDEXX Laboratories, Westbrook, ME, USA). Samples were mixed with Colilert substrate then poured into Quanti-Tray, sealed and incubated for 18–22 h at 37 °C for total coliforms and *E. coli* and at 44 °C for faecal coliforms. The number of positive yellow wells was counted for coliforms enumeration and ultra violet (UV) blue fluorescence for *E. coli* and then converted into most probable number (MPN) according to manufacturer's instructions.

Five day BOD (BOD_5) was determined using Hach Lange cuvette tests with a nitrification inhibitor. Appropriate dilutions of STE were prepared using aerated buffer solution and added to BOD_5 cuvette tests before incubating for 5 days at 20 °C. BOD_5 was detected at 620 ηm wavelength (DR2800 spectrophotometer, Hach, Colorado, USA). COD was performed using Hach Lange cuvette tests by oxidising the effluent with sulphuric acid and potassium dichromate solution for 2 h at 150 °C. The detection of the green chromic ion (Cr^{3+}) was quantified at 605 ηm wavelength (DR2800 spectrophotometer, Hach, Colorado, USA).

Turbidity was determined using a turbidity meter (Hach 2100P, Turbidimeter, Camlab) and calibration standards measured in nephelometric turbidity units (NTU). Electric conductivity (EC) was determined using a Hanna HI-98312 conductivity tester. Alkalinity, NH_4–N and SRP were determined in triplicate with appropriate blanks using automated colorimetry (Konelab Aqua 20, Thermo Scientific, Vantaa, Finland). Bromide, Cl, F, NO_3 and SO_4 were determined by ion chromatography (Dionex DX600, Dionex, California, USA). Total nitrogen (TN) was determined using automated colorimetry (TOC-VCSH analyser, Shimadzu, Japan). Effluent pH was measured using Hanna pH 210 meter.

Total suspended solids (TSS), was determined gravimetrically on prewashed GF/F (0.7 μm) filters which were dried at 105 °C for 18 h and reweighed. To investigate total particulate phosphorus (TPP) and nitrogen (TPN) retained on the filter papers, a persulphate digestion was used with subsequent colorimetric analyses (Methods for Chemical Analysis of Water and Wastes, U.S. EPA, 1983). Effluent and water samples were filtered through 0.45 μm cellulose membrane and the filtrates were scanned for carbon species between 200–700 ηm wavelengths using Shimadzu UV Probe, UV-1800 Spectrophotometer, Shimadzu, Japan and UV Probe 2.33 software. The filtrates were also analysed for dissolved organic carbon (DOC) concentration using automated total organic carbon analyser (Shimadzu TOC-VCSH, Tokyo, Japan). Specific UV absorbance at 254 ηm ($SUVA_{254}$) was normalised for DOC concentration and reported in (L/mgC/m). Effluent and water filtrates were also analysed for OM fluorescence (Gilden Photonics Fluorimeter, fluoroSENS 1.88.7, Glasgow, UK). Excitation emission matrices (EEMs) were obtained at wavelength intervals ranged (Ex 200–450 ηm) at 2 ηm increments (Em 270–500 ηm) at 5 ηm increment, band pass width was 5 ηm and 0.1 s integration time to cover both UV and visible fluorescence regions. Effluent spectra were Raman normalised against Millipore water at 397 ηm. Dissolved OM peaks were picked and determined using a Gilden Photonics Contour Visualiser (V. 1.0) to provide the relative intensity of fluorescence at various wavelengths for tryptophan-like fluorophores (amino acids) and fulvic and humic-like fluorophores peaks in fluorescence intensity units (FIU).

Major elements (Al, Ca, Cu, Fe, K, Mg, Na, P as TDP, S, Si and Zn) were determined in triplicate by ICP-OES (Agilent 7500ce, Tokyo, Japan).

Table 1
STE parameter ranges, mean, standard of errors and skewness for all tanks (n = 32), compared with the mean of upstream waters and calculated STE enrichment factors (EFs) (n = 10).

		STE	STE		Stream waters[g]	STE
Parameter	Unit	Range	Mean ± 1 s.e.	Skewness[e]	Mean ± 1 s.e.	EF[d]
pH		6.37–7.68	7.01	N	7.26	1
EC	μS/cm	160–1730	866 ± 69	N	259 ± 56	4
Turbidity	NTU	8–916	198 ± 34	Sk+	3.42 ± 0.69	76
TSS	mg/L	14–3895	384 ± 167	Sk++	6.10 ± 0.78	103
COD	mg/L	48–5514	655 ± 164	Sk++	15.18 ± 5.37	40
BOD	mg/L	16–565	234 ± 26	N	6.33 ± 3.06	41
Alkalinity	mg/L	15–698	303 ± 27	N	42 ± 11	9
DOC	mg/L	5–179	48 ± 7	Sk+	6.06 ± 1.34	11
$SUVA_{254}$	L/mg/m	0.39–4.28	1.70 ± 0.13	Sk+	4.24 ± 0.96	0.4
TP	mg/L	1.13–32.49	14.55 ± 1.46	N	0.16 ± 0.05	98
TDP	mg/L	0.22–26.43	9.46 ± 1.18	N	0.05 ± 0.02	213
SRP	mg/L	0.15–25.68	8.37 ± 1.06	N	0.05 ± 0.03	176
TPP	mg/L	0.59–22.25	4.77 ± 0.69	Sk++	0.10 ± 0.05	53
TN	mg/L	11–146	68 ± 6	N	5.77 ± 1.02	13
TDN	mg/L	5–125	59 ± 6	N	4.61 ± 1.08	14
NH_4–N	mg/L	2–144	55 ± 6	N	0.04 ± 0.01	1651
NO_3–N	mg/L	0.01–3.85	0.44 ± 0.15	Sk+	4.40 ± 1.01	<0.1
TPN	mg/L	0.01–12.46	4.80 ± 0.57	N	0.26 ± 0.04	12
SO_4	mg/L	0.53–20.78	6.21 ± 0.89	Sk+	8.07 ± 4.16	0.7
Br	mg/L	0.018–0.062	0.02 ± 0.00	N	0.07 ± 0.02	0.4
Cl	mg/L	18–94	51 ± 4	N	27 ± 5	2
F	mg/L	0.02–7.37	0.36 ± 0.23	Sk++	0.08 ± 0.01	12
Total coliforms	MPN/100 mL[a]	10^3–10^8	2.3×10^7	Sk++	2.3×10^4	312
Faecal coliform	MPN/100 mL[a]	10^3–10^7	3.2×10^6	Sk++	9.8×10^2	1340
E. coli	MPN/100 mL[a]	10^3–10^7	1.3×10^6	Sk++	1.7×10^3	691
TVC	CFU/mL[b]	10^5–10^6	2.7×10^6	N	1.1×10^4	234
Tryptophan	FIU[c]	6.6×10^3–1.8×10^5	7.6×10^4	–	1.7×10^3[f]	–

[a] Most probable number in 100 mL.
[b] Colony formed unit in 1 mL.
[c] Fluorescence intensity unit.
[d] Enrichment factor = $\sum([STE_{n=10}] / [upstream_{n=10}]) / n$.
[e] Skewness: (−1 to +1) is N, (1 to 3) is Sk+, (>3) is Sk++, (−3 to −1) is Sk−.
[f] Only detectable in downstream waters.
[g] n = 10 as only possible where receiving watercourse present.

Trace elements concentrations (As, B, Ba, Co, Cr, Li, Mn, Nb, Pb, Sn, Sr, Ti, W and Zr) were also analysed by ICP-MS (Agilent 7500i, Shield-Torch System).

2.3. Statistical analysis

Effluent and water data were subjected to descriptive statistical analysis using GenStat 17 and Minitab 17 and Anderson–Darling normality tests applied with log 10 transformations where necessary. One way analysis of variance (ANOVA) was performed ($P < 0.05$) to examine the significance of ST management/categorised factors. Tanks were categorised as: *Compromised* n = 5 (tanks with broken or no lids, do not maintain anaerobic condition, leaking and effluent is exposed to the environment) vs *Intact* tanks n = 27 (no obvious sign of broken structure); *Receive* n = 6 (tanks that receive roof runoff) vs *Not receive* n = 26; *Dishwasher* n = 26 (tanks that receive dishwasher waste) vs *No dishwasher* n = 6; *Concrete* tanks n = 20 vs *Polyethylene* tanks n = 12; *Desludging* < 2 years n = 14 (tanks reported desludging every 2 years or less) vs >2 years n = 18 (desludging frequency is more than 2 years or never been emptied); *No of users* ≤ 2 people n = 20 (tank serves up to 2 persons) vs *More* n = 12 (tank serves more than 2 persons). Multifactor analysis was not applied due to the unbalanced data in some categories. The enrichment factor of STE was calculated based on the mean STE concentration (n = 10) divided by the mean of upstream water concentration (n = 10) from the source. Box and whisker plots were used to illustrate the distribution of data and to evaluate the difference between the two levels of each grouping factor. Principal component analysis (PCA) based on the correlation matrix was performed on the data and a biplot of the loading in the first two PCs for STE indicators and metals were used to evaluate major and trace element fingerprints.

Tank residence time calculations were made to understand the impact of receiving roof runoff on septic tank processes. It was not possible to determine septic tank volumes accurately or to distinguish volumes between categories of older concrete and modern polyethylene tanks. Therefore, in the calculation of residence time (t_{res}) for a typical household of 2.7 persons (t_{res} = tank volume / $flow_{in,\ out}$) the local building standards recommended 2720 L was applied. Flow was assumed by calculation of 150 L/day/person to be 405 L/day/household, giving $t_{res} = 6.7$ days without the tank receiving roof runoff. In the case of roof runoff the average annual regional rainfall of 1126 mm on a modelled roof of 100 m^2 gave an additional average daily flow of 308 L/day/household and a reduced $t_{res} = 3.8$ days. The worst case scenario for accelerated flushing from rain was based on a 24 h 1 in 5 years modelled regional rainstorm (FEH, 1999) prediction of 48 mm (4800 L/day on the 100 m^2 roof) giving $t_{res} = 0.5$ days.

3. Results

3.1. Effluent quality and enrichment factor

Means, concentration ranges and degree of skewness for the physicochemical, microbial parameters and metals of STE including stream waters are shown in Tables 1 and 2. STEs contained large concentrations of NH_4–N, SRP, DOC, TSS and very little NO_3–N and Br (Table 1). The pH of STE was generally neutral with mean of 7.01 and range 6.37–7.68. STEs were also high in EC, BOD, COD, turbidity and alkalinity with means 866 µS/cm, 234 mg/L, 655 mg/L, 198 NTU and 303 mg/L, respectively. The effluents contained large bacterial concentrations (mean total coliforms, faecal coliforms, *E. coli* and TVC (2.3×10^7, 3.2×10^6, 1.3×10^6 MPN/100 mL and 2.7×10^6 CFU/mL, respectively). Trace metals such as B, Ba, Cu, Fe, Mn, Sr, W and Zn were found to have concentrations that ranged from 45–366 µg/L (Table 2).

The enrichment factors (EFs) of STE relative to upstream water (n = 10) are listed in Tables 1 and 2. The highest EF were shown for NH_4–N (1651), faecal coliforms (1340), *E. coli* (691), total coliforms (312), TVC (234), TDP (213), SRP (176) and TSS (103), whereas, TP, Turbidity, Cu, TPP, BOD and COD had only moderate to high EF (40–100). A moderate EF (10–39) suggests that TDN, TN, TPN, F and DOC were of lesser risk to stream waters. A low EF (2–10) was obtained for alkalinity, K, W, Ti, B, turbidity, Zn, Na, Al, Mn, Ba, Co, Cr, Cl, Fe, Nb, Pb and Zr. The loading scatter plot (Fig. 1) represented STE variables in terms of indicators, major and trace metals. The indicators in Fig. 1a, showed a strong positive correlation between TN, TDN, Cl, NH_4–N, SRP, TDP, EC, DOC, TP and alkalinity which collectively have weak correlation with TSS and negative correlation with SUVA and NO_3–N and TPN. Total coliforms have positive correlation with pH, weak correlation with turbidity, TPP and negative correlation with SUVA, TSS and NO_3–N. Fig. 1a, also showed that TP, EC, alkalinity, TDP, TDN, NH_4–N and TSS hold the highest values while Br, TVC, SO_4, total coliforms and *E. coli* hold the lowest values. The major and trace metals biplot (Fig. 1b) showed a strong positive correlation between K, P, Na, Ba, Cu, Al and Zn which are collectively have negative correlation with Fe, Mn, Ca, Sr, Co and Zr. Phosphorus, Na and K hold the highest values followed by As, Ba, B, Cr, Cu, Li, Nb and Ti.

Table 2
STE major and trace metals ranges, mean, standard of errors and skewness for all tanks (n = 32), compared with the mean of upstream waters and calculated STE enrichment factors (EFs) (n = 10).

Parameter	Unit	STE Range	STE Mean ± 1 s.e.	Skewness[b]	Stream waters[c] Mean ± 1 s.e.	STE EF[a]
Al	mg/L	<0.01–0.20	0.06 ± 0.01	Sk+	0.02 ± 0.01	4
Ca	mg/L	6–67	21 ± 3	Sk+	24 ± 6	1
K	mg/L	3–42	24 ± 2	N	3.31 ± 1.71	8
Mg	mg/L	1.40–27.72	6.60 ± 0.86	Sk+	8.08 ± 2.12	1
Na	mg/L	17–113	53 ± 5	N	17 ± 3	4
P	mg/L	0.27–26.43	9.30 ± 1.16	N	0.05 ± 0.02	215
S	mg/L	2.42–35.63	9.13 ± 1.14	Sk+	10.90 ± 6.44	1
Si	mg/L	1.36–15.72	6.58 ± 0.57	N	7.27 ± 0.82	1
As	µg/L	0.50–5.00	1.20 ± 0.24	Sk+	0.50 ± 0.00	3
B	µg/L	19–244	111 ± 10	N	27 ± 3	5
Ba	µg/L	26–925	366 ± 38	N	165 ± 44	3
Co	µg/L	0.05–3.95	0.45 ± 0.13	Sk++	0.14 ± 0.07	3
Cr	µg/L	0.25–3.49	1.05 ± 0.15	Sk+	0.40 ± 0.07	3
Cu	µg/L	5–637	109 ± 29	Sk+	1.85 ± 0.53	63
Fe	µg/L	<1–1486	198 ± 49	Sk++	188 ± 159	2
Li	µg/L	1.00–10.00	2.21 ± 0.45	Sk+	2.95 ± 0.87	1
Mn	µg/L	10–312	74 ± 13	Sk+	31± 21	3
Nb	µg/L	2.50–25.00	5.38 ± 1.10	Sk+	2.50 ± 0.00	2
Pb	µg/L	0.50–6.67	1.68 ± 0.31	Sk+	0.57 ± 0.07	2
Sn	µg/L	2.50–25.00	5.05 ± 1.09	Sk+	2.50 ± 0.00	1
Sr	µg/L	27–236	89 ± 10	Sk+	119 ± 21	1
Ti	µg/L	2–65	11 ± 2	Sk+	2.50 ± 0.00	5
W	µg/L	5–346	45 ± 13	Sk++	5.46 ± 0.46	7
Zn	µg/L	18–287	150 ± 13	N	32 ± 6	4
Zr	µg/L	2.00–20.00	3.81 ± 0.80	Sk++	2.00 ± 0.00	2

[a] Enrichment factor = $\sum([STE_{n=10}] / [upstream_{n=10}]) / n$.
[b] Skewness: (−1 to +1) is N, (1 to 3) is Sk+, (>3) is Sk++, (−3 to −1) is Sk−.
[c] n = 10 as only possible where receiving watercourse is present.

3.2. Tank management factors

The significant effects of tank and system design and management on STE composition are given in Table 3. Fig. 2, box plots show some of the major differences in effluent composition between the two levels in each group factor. The results revealed that STE quality varied according to system design (ie. roof water infiltration) and management. Tanks that *Received roof runoff* exhibited significantly ($P < 0.05$) reduced values for a large number of parameters (Table 3). Effluent pH, alkalinity, EC, turbidity, COD, BOD and DOC, total coliforms and nutrients concentrations with the exception of NO_3 were all much higher in tanks that did not receive roof runoff (Fig. 2). In the *Dishwasher* category, systems that received dishwasher wastes, effluent properties showed significant difference ($P < 0.05$) in TVC, TN, TPN, TSS, COD and TPP concentrations (Table 3). Metal concentrations also exhibited

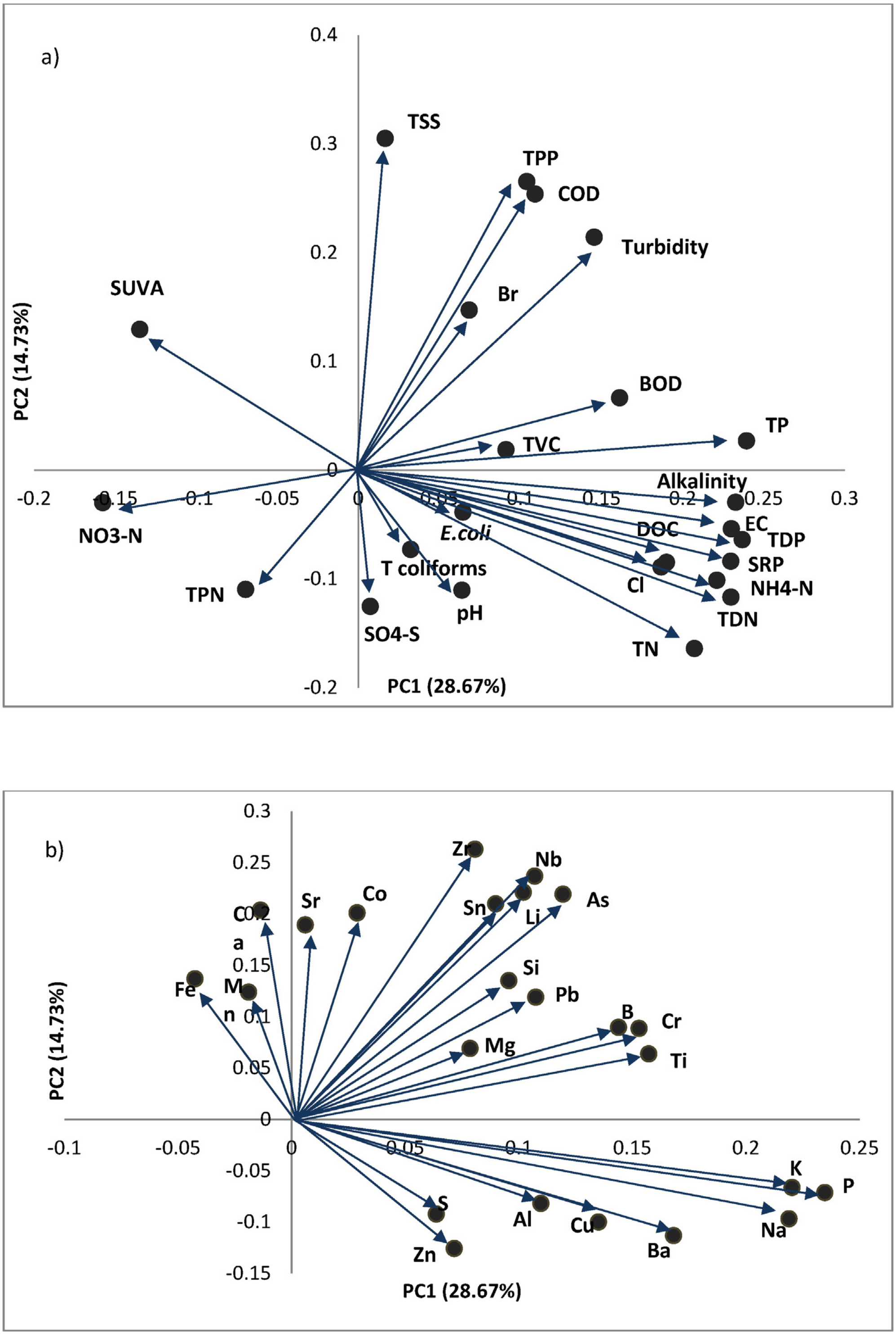


Fig. 1. a) Loading plots of weights assigned to each of STE indicator variables and, b) specifically to STE major and trace metal variables. Points show loadings positions, length of lines and arrows represent the strength and the direction of loading of each parameter in relation to others.

significant differences ($P < 0.05$) in As, Sn, Li, Nb and Zr. Effluent from *frequently desludged* systems (<2 years) exhibited a significant difference ($P < 0.05$) in pH and TPN concentrations with high pH, EC, coliforms and *E. coli* populations, while nutrient concentrations were much higher in effluents from tanks that were not frequently desludged.

In the *Tank Type* category (*Concrete* vs *polyethylene*), no significant difference was found between the two types of tanks ($P > 0.05$). However, STE from concrete tanks ($n = 21$) exhibited high pH, alkalinity, TSS, EC and BOD. Nutrient concentrations (TP, TDP, TPP, TN and NH_4–N) and metal concentrations (Na, Ca, Fe, Ba and Sr) were also high in effluent from concrete tanks. *Number of Users* category, exhibited a significant difference ($P < 0.05$) in total coliforms and Si (Table 3). Total coliforms and *E. coli* concentrations were much higher in effluent that served >two people (Fig. 2). The same trend was observed in pH, EC, alkalinity, DOC, Na and Ca concentrations. There were no significant differences in *Compromised*/*Intact* category ($P > 0.05$), although generally TVC, TN, NH_4–N concentrations were higher in intact tanks. Anions in STE such

Table 3
The number of tanks in each factor and parameters ANOVA results of significant differences ($P \leq 0.05$). Parameters with no significant difference ($P > 0.05$) not included.

Parameter	ANOVA results P-value			
Factor A	Receive[a] (n = 6)	Dishwasher (n = 26)	Desludging < 2 years (n = 14)	No users ≤ 2 (n = 20)
Factor B	Do not receive (n = 26)	No dishwasher (n = 6)	Desludging > 2 years (n = 18)	No users > 2 (n = 12)
PH	0.015		0.017	
EC	0.002			
Alkalinity	0.001			
TVC		0.028		
TP	0.001			
TN	<0.0001	0.026		
TDN	<0.0001			
TDP	0.001			
TPN		0.051	0.001	
SRP	0.001			
NH_4–N	<0.0001			
Cl	0.001			
SUVA	0.001			
K	<0.0001			
P	0.001			
Si				0.034
Fe	0.048			
As		0.009		
Ba	0.022			
Sn		0.001		
Turbidity[b]	0.008			
TSS[b]		0.007		
COD[b]	<0.0001	0.014		
BOD[b]	0.009			
T coliforms[b]	0.003			0.047
TPP[b]		0.015		
NO_3–N[b]	0.003			
DOC[b]	<0.0001			
Al[b]	0.02			
Na[b]	<0.0001			
S[b]	0.012			
Cu[b]	0.02			
Ba[b]	0.001			
Cr[b]	0.012			0.004
Li[b]		0.007		
Nb[b]		0.01		
Ti[b]	0.006			
Zr[b]		0.004		
PC1	<0.0001			
PC2	0.08	0.005	0.08	

[a] Receive roof runoff vs Do not receive roof runoff.
[b] Transformed data.

as SO_4 and F showed no significant difference ($P > 0.05$) in all grouping factors and ranged between 0.53–20.78, 0.03–7.37 mg/L (Table 1).

3.3. Effluent fluorescence

Effluent organic matter (OM) characterisation by fluorescence excitation emission matrices (EEMs) produced a three dimensional contour map of STE and showed a tryptophan-like peak (T) in the UV region present in all STE at excitation range 270–290 ηm and emission range 330–370 ηm, (Fig. 3). Anthropogenic input in the form of tryptophan-like fluorophores intensities ranged between 6.6×10^3–1.8×10^5 and the average was 7.6×10^4 fluorescence intensity unit (FIU). A tryptophan peak was also present in downstream but not detected in upstream waters (Table 1). A fulvic-like peak (C) was also detected in effluent from *Compromised* tanks and those that *Received roof runoff* categories at excitation emission ranges of 300–340 ηm and 390–450 ηm, respectively, (Fig. 3) with average intensities of 4.29×10^4 FIU.

4. Discussion

This study provides the first comprehensive analysis of STE in the UK, combining physical, chemical and microbial compositions of effluent from households across North East of Scotland. The 32 sites covered a range of different tank type, age, condition, size, number of users and tank management and were considered representative of the wider population of tanks in use. Septic tank effluent is rich in nutrients, metals and microbial populations which pose great risk to stream waters. Although most onsite waste water treatment systems discharge their effluent to soil soakaways for contaminant removal, it should be noted that 25% of STS tested in this study discharged their effluent directly to surface waters or to soakaways which are too close to watercourses and therefore pose a risk to water quality and human health (Dudley and May, 2007).

4.1. Effluent impacts and tank management

4.1.1. Nutrient composition

The analysis showed that most STs have high nutrient concentrations of inorganic N, P and C in their effluent (Table 1). The anaerobic condition that functional tanks should maintain allows the heterotrophic bacteria to convert organic N and P to NH_4–N and SRP, while the TN and TP remain unchanged (Canter and Knox, 1985; Seabloom et al., 2005). The study showed that tank design and management play a critical role in effluent quality and may reduce effluent residential time in the tank with the risk of discharging unprocessed effluent to the environment. Although TN exhibited a similar range (11–146 mgN/L) to the values found by Lowe et al. (2009) and Gross (2005), however, the mean across all sites of TN concentration of 68 mgN/L was lower than 107 mgN/L reported by O'Luanaigh et al. (2012). This may be associated with dilution from roof runoff or broken lids exposing effluent to the environment. Tank management on effluent quality was also apparent when considering only STE not receiving roof runoff which increased the mean TN concentration to 80 mgN/L. Ammonium range in the effluent was increased when considering tank management (not receiving roof runoff and with intact lids). An opposite trend was observed on nitrate concentrations which were three times greater in effluents that were exposed to the environment. Tank management (*Receiving roof runoff*) created an association between high concentrations of NO_3–N/low NH_4–N which can be explained by nitrification of NH_4–N to NO_3–N in the presence of oxygen. High NO_3–N levels and the nitrification of NH_4–N as the effluent is discharged from the tank are of environmental concern, due to the high mobility of nitrate and its role in eutrophication of surface and ground waters and public health concern for drinking waters (Ward et al., 2005).

This study revealed that STE may continue to pose a risk on stream water health, as most organic P and polyphosphate in STE are converted to soluble phosphate (TDP) by microorganisms. Effluent TDP levels in this current work constitute 65% of TP concentration; however, controlling P discharge from onsite waste water treatment system is crucial to combat eutrophication since the effluent is dominated by soluble reactive forms of P. Moreover, STEs are discharged persistently throughout the year and their risk to water quality can be greater during critical summer periods when ecology is most sensitive to elevated nutrient concentrations (Withers et al., 2011). Total P concentration of STE in this study (range 1.13–32.49 mgP/L, mean of 14.55 mgP/L), (Table 1) are greater than (10–20 mg/L) reported by Wilhelm et al. (1994); EPA, Ireland (2000); Gross (2005); Idaho, department of Environmental Quality (2012), but agree with the values reported by Lowe et al. (2009). Tank management (*Receiving roof runoff*) influenced P concentrations as TP range and mean were greater (6.37–32.49 and 16.54 mgP/L) when we consider only tanks that do not receive roof runoff and with intact lids. It is well recognised that, with legislation on P contents of some household cleaning products, dishwasher detergents remain a key domestic source of phosphates, (Richards et al., 2015), alongside human

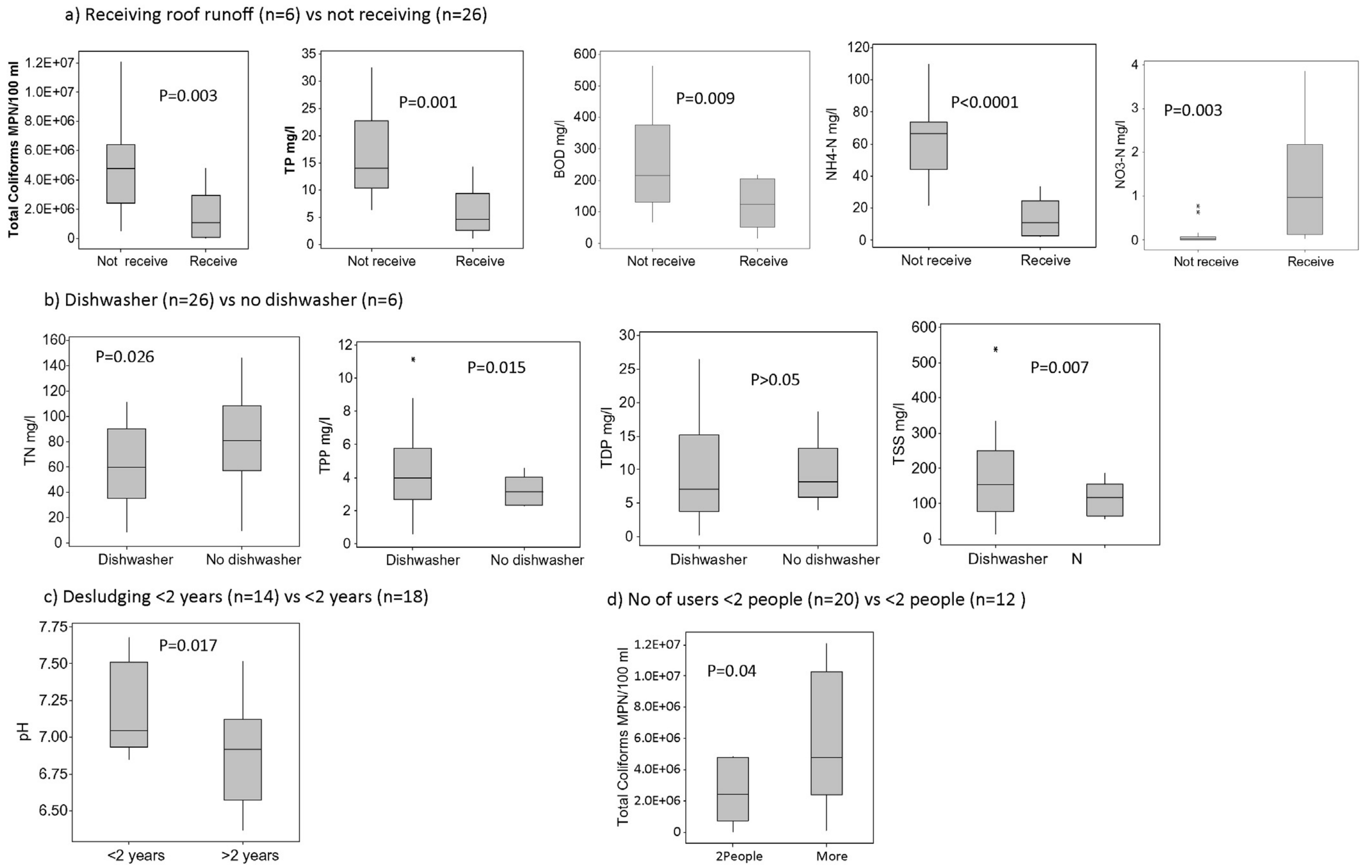


Fig. 2. STE indicators grouped as: a) *Receiving roof runoff*, b) *Dishwasher*, C) *Desludging*, and d) *No of users*. P-values for variables are <0.05 except for dishwasher TDP, P > 0.05.

sewage. Notably, effluent from tanks that do not receive dishwasher wastes exhibited relatively low TDP concentration (ranged 4.01–11.40, mean 7.26 mgP/L) and significantly decreased TPP ($P < 0.05$), (Table 3).

Most literature reports BOD and COD rather than dissolved organic carbon (DOC) and associated $SUVA_{254}$ as a measure of C content of STE. In this work, DOC concentrations, (Table 1) can be compared with values reported by Lowe et al. (2009) and by Robertson et al. (1998, 1991). Although OM (colloids or particles) can settle within the sludge layer, considerable concentrations of DOC can be transported with effluent discharges. These dissolved and particulate organic C discharges, form part of effluent BOD load with resulting impacts on decreasing dissolved oxygen in receiving waters where effluent is discharged directly. Despite the fact that there are not many literature data on STE ($SUVA_{254}$) the value reported by this current work 1.7 L/mg/m agrees with the mean value reported by Conn and Siegrist (2009) of 1.5 L/mg/m.

The enrichment factors (EFs) of BOD and COD are 41 and 40 times greater than stream waters, and most tanks tested in this study had high BOD and COD concentrations, which is an indication of the high proportion of OM content of the effluent. Human behaviour on effluent quality was evident in the high COD values from tanks that did receive dishwasher wastes ($P = 0.014$), (Table 3). The implication of high BOD and COD and their associated OM of STE is of concern for water quality since if these parameters were not reduced in soil system, they may reach surface waters and may result in reduction of dissolved oxygen in watercourses.

4.1.2. Effluent physical composition

Physical properties such as turbidity, TSS, EC, alkalinity and pH are useful indicators for effluent characterisation and can indicate tank failure and effluent discharge to watercourses. Effluent turbidity is an indicator of the suspended matter and the relationship between turbidity and TSS is highlighted by the positive correlation; person correlation coefficient of 0.627 ($P = 0.001$). Surprisingly, there are not many STE turbidity values reported in the literature, however, Mandal (2014) and Igbinosa and Okoh (2009) reported wastewater turbidity levels of 43 and 159 NTU, respectively, being lower than the mean turbidity value of 198 NTU found in STE of this current work. The EF of STE turbidity is 76 times of stream waters and when discharged directly to watercourses, it can cause increase in stream turbidity affecting stream sunlight level and its associated stream habitats (Lloyds et al., 2011). Effluent pH influences its chemical and biological interactions as low or high pH reduces the ability of the microorganisms to break down OM. Excess of hydrogen ions can cause the denaturing of a key enzyme protein and excess of hydroxide ions exert toxic effect on the microorganisms. In this current work, typical pH of 7.0 is comparable to Patterson (2003) and the optimum pH range for bacterial growth reported by Rowe and Abdel-Magid (1995) of 6.8–7.7 agrees well with this current data.

4.1.3. Effluent microbial concentrations

This work showed that STE have large microbial abundances, the mean abundance of both faecal coliforms and *E. coli* are one and two order of magnitude higher than that reported by Lowe et al. (2009), respectively. TVC of STE in this work of 10^6 CFU/mL agrees with that reported by Toor et al. (2011). The large microorganism populations in ST discharges such as faecal coliforms and *E. coli* are of concern as their EF are 1340 and 691, respectively, and their survival periods in groundwater are 20–30 and 90–110 days, respectively, (Crites and Tchobanoglous, 1998; Flint, 1987). The effect of human behaviour on STE was evident in the significantly increased total coliforms concentrations ($P = 0.04$) as number of tank users increased to >2 people, (Fig. 2). This can be an indication of unsuitable tank size for the household.

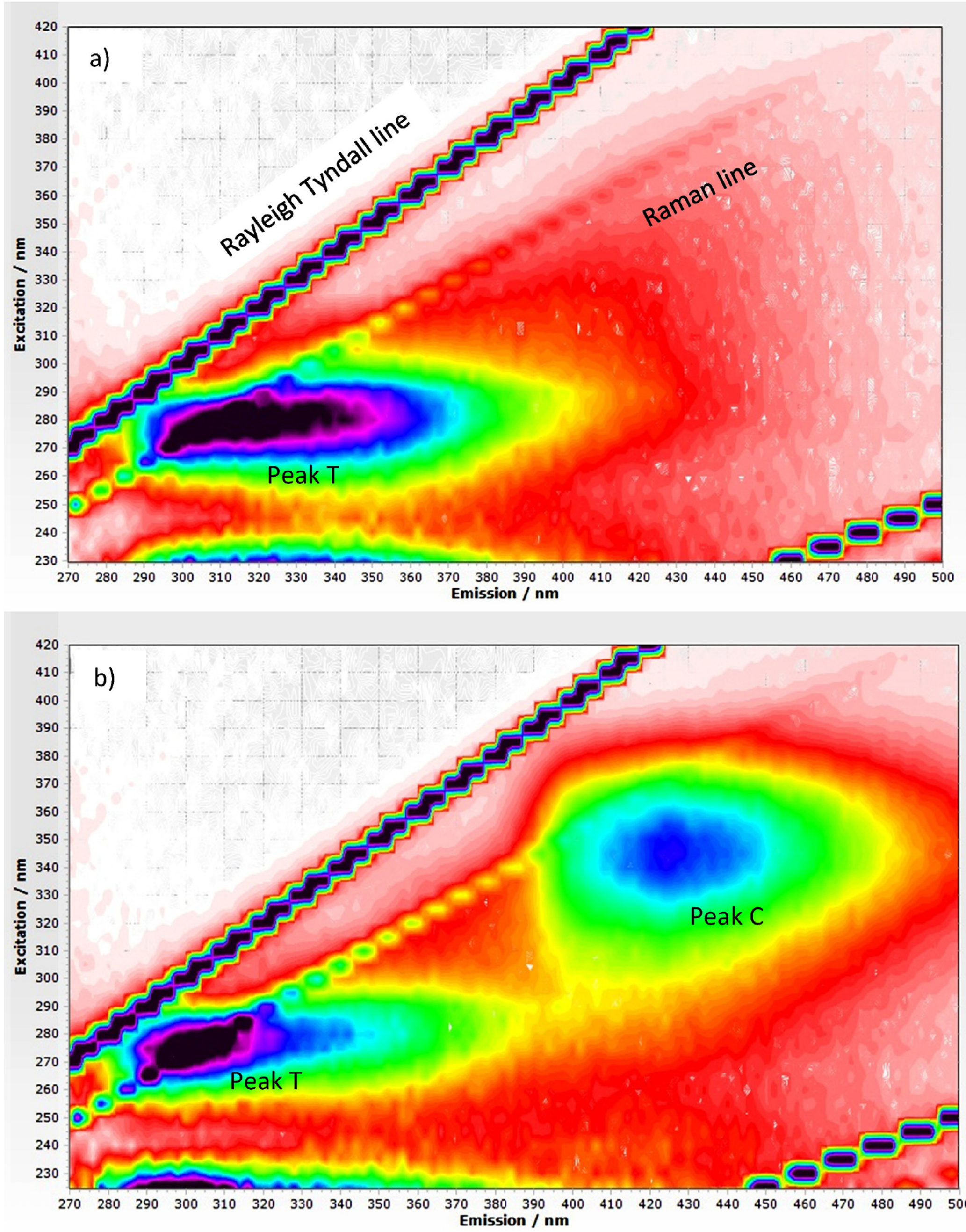


Fig. 3. a) Fluorescence excitation emission matrices (EEMs) for septic tank effluent with the dominant protein like peak attributed to tryptophan fluorophore (Peak T). b) An extra peak attributed to the fulvic fluorophore (Peak C) in tanks that receive roof runoff or have broken lids.

4.1.4. Metal concentrations

There are limited data available in the literature on trace metals in STE, however, in this current study the major and trace metal EF for P, Cu, K, W, Ti, B, Na, Al and Zn (Table 2) were 215, 63, 8, 7, 5, 5, 4, 4 and 4 times of stream waters, respectively. Effluent mean concentrations of Cu (0.11 mg/L) and Zn (0.15 mg/L) were double the values reported by Whelan and Titamnis (1982). Elevated levels of Cu are toxic in aquatic environments and in drinking waters. The presence of other elements in STE such as Br, Ca, Li, Mg, S, Si, Sn and Sr are of no concern as their mean concentrations were below or equal to that of upstream waters (Tables 1 and 2). It is clear that STE is enriched in most major and heavy metals and if discharged untreated, it poses a threat to water quality and aquatic ecosystems due to their persistence and accumulation (Edem et al., 2008). A possible source of these metals is household chemicals that were previously reported to contain high concentration in trace metals (Richards et al., 2015).

4.2. Effluent compositional indicators as potential tracers of impact

The use of tracers is a useful tool to determine pathway of pollutants in natural waters, the source and the impact. A fluorescence excitation emission matrix (EEMs) is a novel tool that was utilised to detect STE discharge. Excitation emission matrices of STE showed a distinct high intensity for the tryptophan (peak T), (Table 1 and Fig. 3) which is a known marker in environmental samples for contamination with STE or sewage effluent (Hudson et al., 2007). The presence of a tryptophan peak in the receiving surface water downstream from the source that was also undetectable upstream is an indication of effluent discharge.

Thus, fluorescence EEMs may be used as a potential tracer for effluent contamination to water courses. This work also highlighted the presence of humic substances (peak C) in some STEs (Fig. 3b) associated with tanks that receive roof and/or field runoff. Therefore, EEMs may also be used to detect tank failure or poor tank management.

5. Conclusion

The composition of residential STE was characterised to provide full and integrative data to provide the knowledge of their impact with respect to ST type, management and user behaviours. The characterisation of domestic effluent revealed that not only are STE rich in nutrients, organic matter and metals, but also high proportions of these parameters are present in the soluble reactive forms and pose great risk to stream waters. Factors such as tank condition, management in terms of frequent desludging and maintenance, use of dishwasher and number of tank users significantly influenced the quality of STE, in turn affecting risk to stream eutrophication and water quality especially during periods of ecological sensitivity. Receiving roof runoff was linked to reduction in effluent retention time in the tank. Infrequent desludging was linked to increased organic matter, bacterial abundance, alkalinity and phosphorus. Dishwasher use caused increased suspended solids and particulate phosphorus, while tanks that served larger number of users had effluent with high dissolved phosphorus and nitrogen. The presence of tryptophan fluorescence peaks in receiving water downstream from STs indicated effluent discharge and potential for future source loading tracing approaches. There is a need for better tank management through possible legislation (possibly to remove direct connections to streams) and/or to consider an additional treatment for STE before discharge to surface waters or reaching ground waters. This would be beneficial in protecting and improving stream water quality and guarding against human health impacts.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2015.10.160.

Acknowledgments

This work was funded by the Scottish Government Rural and Environmental Sciences and Analytical Services (RESAS). The authors are thankful to all the householders in Rivers Dee, Don, Lunan and Ythan Catchments in the North East Scotland for their cooperation and assistance with survey data and allowing sampling effluent. The authors also thank F. Sturgeon, C. Thomson, C. Curran and H. Watson for analytical work at James Hutton Institute. The authors also thank L. Beesly, M. Troldborg and D. Richards for their assistance with field work.

References

(DEFRA) Department of Environment, Food and Rural Affairs, 2002. Sewage treatment in the UK. Waste water collection and treatment, and disposal of sewage sludge — United Kingdom 2000. (http://www.defra.gov.uk/publications/files/pb6655-uk-sewage-treatment-020424.pdf. Last accessed January 2015).
Bowes, M.J., Neal, C., Jarvie, H.P., Smith, J.T., Davies, H.N., 2010. Predicting phosphorus concentrations in British rivers resulting from the introduction of improved phosphorus removal from sewage effluent. Sci. Total Environ. 408 (19), 4239–4250.
Brandes, M., 1978. Characteristics of effluents from gray and black water septic tanks. Water Pollut. Control Fed. 50 (11), 2547–2559.
Canter, L.W., Knox, R.C., 1985. Septic Tank Systems: Effect on Ground Water Quality. Lewis Publishers, Chelsea, MI.
Conn, K., Siegrist, R.L., 2009. Occurrence and Fate of Trace Organic Contaminants in Onsite Wastewater Treatment Systems and Implications for Water Quality Management. Technical Completion Report. Colorado Water Institute (http://www.cwi.colostate.edu Last accessed March 2015).
Crites, R., Tchobanoglous, G., 1998. Small and Decentralized Wastewater Management System. The McGraw-Hill, New York 0-07-289087-8.
D'Amato, V.A., Bahe, A., Bounds, T., Comstock, B., Konsler, T., Liehr, S.K., Long, S.C., Ratanaphruks, K., Rock, C.A., Sherman, K., 2008. Factors affecting the performance of primary treatment in decentralized wastewater systems. WERF, Final Report. 2008.
Dawes, L., Goonetilleke, A., 2003. An investigation into the role of site and soil characteristics in onsite sewage treatment. Environ. Geol. 44, 467–477.
Dudley, B., May, L., 2007. Estimating the Phosphorus Load to Waterbodies From Septic Tank. A Report to the Scottish Environment Protection Agency and Scottish Natural Heritage. Centre for Ecology and Hydrology ((CEH Project Number: C03273, C01352). http://nora.nerc.ac.uk/2531/2/DudleySepticTanksRep.pdf. Last accessed January 2015).
Edem, C.A., Akpan, B., Dosunmu, M.I., 2008. A comparative assessment of heavy metals and hydrocarbon accumulation in *Sphyraena afra*, *Orechromis niloticus* and *Elops lacerta* from Anantigha beach market in Calabar—Nigeria. Afr. J. Environ. Pollut. Health 6, 61–64.
Edwards, A.C., Withers, P.J.A., 2008. Transport and delivery of suspended solids, nitrogen and phosphorus from various sources to freshwaters in the UK. J. Hydrol. 350 (3-4), 144–153.
Efroymson, R.A., Jones, D.S., Gold, A.J., 2007. An ecological risk assessment framework for effects of onsite wastewater treatment systems and other localized sources of nutrients on aquatic ecosystems. Hum. Ecol. Risk. Assess. 13, 574–614.
Environment Alliance — The Environment Agency for England and Wales, the Scottish Environment Protection Agency and the Environment and Heritages Service for Northern Ireland, 2006W. Treatment and Disposal of Sewage Where no Foul Sewer is Available: PPG4. (http://a0768b4a8a31e106d8b0-50dc802554eb38a24458b98ff72d550b.r19.cf3.rackcdn.com/pmho0706bjgl-e-e.pdf Last accessed Jan 2015).
EPA, Ireland, 2000. Wastewater treatment manuals. Treatment Systems for Single Houses (ISBN: 1840950226).
FEH, 1999. Flood Estimation Handbook. Centre for Ecology and Hydrology, UK (ISBN 9781906698003).
Flint, K.P., 1987. Long-term survival of *Escherichia coli* in river water. J. Appl. Bacteriol. 63, 261–270.
Gill, L., Johnston, P., Misstear, B., O'Suilleabhain, C., 2004. An investigation into the performance of subsoils and stratified sand filters for the treatment of wastewater from on-site systems. Project 2000-MS-15-M1. Report Prepared for the Environment Protection Agency 2004.
Gross, M.A., 2005. Wastewater characterization text. In: Gross, M.A., Deal, N.E. (Eds.), University Curriculum Development for Decentralized Wastewater Management. National Decentralized Water Resources Capacity Development Project. University of Arkansas, Fayetteville, AR.
Harris, J., Humphrey, C.P., O'Driscoll, M.A., 2013. Transport of indicator microorganisms from an onsite wastewater system to adjacent stream. Univ. J. Environ. Res. Technol. 3 (3), 423–426.
Haygarth, P.M., Condron, L.M., Heathwaite, A.L., Turner, B.L., Harris, G.P., 2005. The phosphorus transfer continuum: linking source to impact with an interdisciplinary and multi-scaled approach. Sci. Total Environ. 344, 5–14.
Hudson, N., Baker, A., Reynolds, D., 2007. Fluorescence analysis of dissolved organic matter in natural, waste and polluted waters—a review. River Res. Appl. 23, 631–649.
Idaho, Department of Environmental Quality, 2012. Domestic wastewater phosphorus concentration report. (https://www.deq.idaho.gov/media/883278-phosphorus-concentration-report-0812.pdf, Last accessed May 2015).
Igbinosa, E.O., Okoh, A.I., 2009. Impact of discharge wastewater effluents on the physico-chemical qualities of a receiving watershed in a typical rural community. Int. J. Environ. Sci. Technol. 6 (2), 175–182.
Kusk, K.O., Krüger, T., Long, M., Taxvig, C., Lykkesfeldt, A.E., Frederiksen, H., Andersson, A.M., Andersen, H.R., Hansen, K.M., Nellemann, C., Bonefeld-Jørgensen, E.C., 2011. Endocrine potency of wastewater: contents of endocrine disrupting chemicals and effects measured by in vivo and in vitro assays. Environ. Toxicol. Chem. 30 (2), 413–426.
Lloyds, D.S., Koenings, J.P., LaPerriere, J.D., 2011. Effects of turbidity in fresh waters of Alaska. N. Am. J. Fish Manag. 7, 18–33.
Lowe, K.S., Tucholke, M.B., Tomaras, J.M.B., Conn, K., Hoppe, C., Drewes, J.E., McCray, J.E., Munakata-Marr, J., 2009. Influent Constituent Characteristics of the Modern Waste Stream From Single Sources. IWAP (ISBN: 978-1-84339-351-1/1-84339-351-4).
Lusk, M., Toor, G.S., Obreza, T., 2011. Onsite Sewage Treatment and Disposal Systems: Bacteria and Protozoa. University of Florida – IFAS, Gainesville, FL (http://edis.ifas.ufl.edu/pdffiles/SS/SS55200.pdf. Last accessed Jan. 2015).
Mandal, H.K., 2014. Influence of wastewater pH on turbidity. Int. J. Environ. Res. Dev. 4 (2), 105–114.
May, L., Place, C.J., George, D.G., McEvoy, J., 1996. An Assessment of the Nutrient Loadings From the Catchment to Bassenthwaite Lake (Report to the Environment Agency). Institute of Freshwater Ecology, Edinburgh.
Methods for Chemical Analysis of Water and Wastes, U.S. Environmental Protection Agency, 1983n. (EPA 600/4-79-020, 365.1).
O'Luanaigh, N.D., Gill, L.W., Misstear, B.D.R., Johnston, P.M., 2012. The attenuation of microorganisms in on-site wastewater effluent discharged into highly permeable subsoils. J. Contam. Hydrol. 142-143, 126–139.
Patterson, R.A., 2003. Temporal Variability of Septic Tank Effluent. pp. 305–312 (ISBN 009579438-1-4).
Richards, S., Paterson, E., Withers, P.J.A., Stutter, M., 2015. The contribution of household chemicals to environmental discharges via effluents: combining chemical and behavioural data. J. Environ. Manag. 150, 427–434.
Robertson, W.D., Cherry, J.A., Sudicky, E.A., 1991. Ground-water contamination from two small septic systems on sand aquifers. Ground Water 29, 82–92.
Robertson, W.D., Schiff, S.L., Ptacek, C.J., 1998. Review of phosphate mobility and persistence in 10 septic system plumes. Ground Water 36, 1000–1010.
Rowe, D.R., Abdel-Magid, I.M., 1995. Handbook of Wastewater Reclamation and Reuse (ISBN 0-87371-671-X).
Seabloom, R.W., Bounds, T.R., Loudon, T.L., 2005. Septic Tanks Text. In: Gross, M.A., Deal, N.E. (Eds.), University Curriculum Development for Decentralized Wastewater ManagementNational decentralized water resources capacity development project. University of Arkansas, Fayetteville, AR.

Sharpley, A.N., Chapra, S.C., Wedepohl, R., Sims, J.T., Daniel, T.C., Reddy, K.R., 1993. Managing agricultural phosphorus for protection of surface waters: issues and options. J. Environ. Qual. 23 (3), 437–451.

Siegrist, R.L., Lowe, K.S., Geza, M., McRay, J.E., 2012. Soil treatment units used for effluent infiltration and purification within onsite wastewater systems: science and technology highlights. International Symposium on Domestic Wastewater Treatment and Disposal Systems. Dublin, Ireland.

Standard methods for the examination of water and wastewater, 1999. Heterotrophic plate count. Part 9215C.

Toor, G.S., Lusk, M., Obreza, T., 2011. Onsite Sewage Treatment and Disposal Systems: An Overview. University of Florida – IFAS, Gainesville, FL (http://edis.ifas.ufl.edu/ss549. Last accessed May 2015).

Ward, M.H., deKok, T.M., Levallois, P., Brender, J., Gulis, G., Nolan, B.T., VanDerslice, J., 2005. Working report: drinking-water nitrate and health—recent finding and research needs. Environ. Health Perspect. 113 (11), 1607–1614.

Whelan, B.R., Titamnis, Z.V., 1982. Daily chemical variability of domestic septic-tank effluent. Water Air Soil Pollut. 17, 131–139.

Wilhelm, S.R., Schiff, S.L., Cherry, J.A., 1994. Biogeochemical evolution of domestic waste water in septic systems: 1. Conceptual model. Ground Water 32 (6), 905–916.

Withers, P.J.A., Jarvie, H.P., Stoate, C., 2011. Quantifying the impact of septic tank systems on eutrophication risk in rural headwaters. Environ. Int. 37 (3), 644–653.

Withers, P.J.A., Jordan, P., May, L., Jarvie, H.P., Deal, N.E., 2014. Do septic tank systems pose a hidden threat to water quality? Front. Ecol. Environ. 12 (2), 123–130.