Urban surface water pollution problems arising from misconnections

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Abstract

The impacts of misconnections on the organic and nutrient loadings to surface waters are assessed using specific household appliance data for two urban sub-catchments located in the London metropolitan region and the city of Swansea. Potential loadings of biochemical oxygen demand (BOD), soluble reactive phosphorus (PO_4-P) and ammoniacal nitrogen (NH_4-N) due to misconnections are calculated for three different scenarios based on the measured daily flows from specific appliances and either measured daily pollutant concentrations or average pollutant concentrations for relevant greywater and black water sources obtained from an extensive review of the literature. Downstream receiving water concentrations, together with the associated uncertainties, are predicted from derived misconnection discharge concentrations and compared to existing freshwater standards for comparable river types. Consideration of dilution ratios indicates that these would need to be of the order of 50-100:1 to maintain high water quality with respect to BOD and NH_4-N following typical misconnection discharges but only poor quality for PO_4-P is likely to be achievable. The main pollutant loading contributions to misconnections arise from toilets (NH_4-N and BOD), kitchen sinks (BOD and PO_4-P) washing machines (PO_4-P and BOD) and, to a lesser extent, dishwashers (PO_4-P). By completely eliminating toilet misconnections and ensuring misconnections from all other appliances do not exceed 2%, the potential pollution problems due to BOD and NH_4-N discharges would be alleviated but this would not be the case for PO_4-P. In the event of a treatment option being preferred to solve the misconnection problem, it is shown that for an area the size of metropolitan Greater London, a sewage treatment plant with a Population Equivalent value approaching 900000 would be required to efficiently remove BOD and NH_4-N to safely dischargeable levels but such a plant is unlikely to have the capacity to deal satisfactorily with incoming PO_4-P loads from misconnections.

Keywords

Misconnections; stormwater sewers; urban surface waters; pollutant (BOD, PO_4-P, NH_4-N) loadings); remediation schemes

1. Introduction

Surface water misconnections occur when sewage or wastewater, arising from household appliances such as toilets and washing machines, are incorrectly connected. Such misconnections have become a significant water management issue in the UK (Environment Agency, 2013a), with the national environmental regulatory agency estimating that as many as one in five properties may have misconnections discharging wastewater effluent directly to receiving waters via separate sewer systems (Environment Agency, 2007). National estimates of the total numbers of properties in the UK possessing offending misconnections vary between 130,000 and 1.25 M (Royal Haskoning, 2010; Dolata *et al*., 2013; Ellis and Butler, 2015) and the illicit wastewater discharges from misconnected properties can directly impact on receiving water quality potentially prejudicing the achievement of relevant environmental quality standards (EQSs). Total numbers of officially recorded pollution incidents attributed to misconnections only amount to about 250 per year (Environment Agency, 2012), but pressure analysis of water bodies in England and Wales failing Water Framework Directive (WFD) “good status” during 2012 showed that the urban and associated transport sectors were directly responsible for a total of nearly 1500 failures. Excess concentrations of phosphate, ammonia and BOD were identified as the source of 29%, 9% and 4% respectively of these urban diffuse pollution failures (Environment Agency, 2013a). It is therefore highly likely that misconnections can exert a detrimental impact on urban receiving water quality although the scale and severity of such impacts remains to be adequately quantified (Ellis and Butler, 2015). The development of effective river basin management plans (RBMPs) under the statutory requirement of the EU WFD (CEC, 2002) depends on adequate quantification of such illicit urban diffuse pollution inputs and their potential impacts on receiving water quality (Ellis and Mitchell, 2006).

There is only limited field evidence to clearly link the long term chronic attribution and impacts of household wastewater misconnections on receiving water pollutant loadings and environmental quality standards. Modelling therefore becomes an essential approach in both quantifying the specific sources affecting daily discharges from domestic premises (particularly the potential contribution of individual domestic appliances), and in exploring their potential receiving water impacts (Environment Agency, 2013b). Generic source apportionment modelling of urban wet weather discharges on a catchment scale have been developed (Crabtree *et al*., 2009; Crabtree *et al*., 2010) based on Monte Carlo simulations to predict receiving water responses to such effluent inputs. However, there has been very little quantified consideration of attributions for specific wastewater sources associated with separate surface water (stormwater) systems. Wastewater flows have been traditionally measured in terms of per capita consumption and concentrations, but such average-based determinations can be misleading given the diversity and complexity of domestic water usage as reflected in differing technological and socio-demographic household water practices (Pullinger *et al*., 2013). Despite continued national regulatory insistence that UK water companies develop their forward water management planning based on per capita water use, there have been increasing arguments for a more detailed analysis of usage micro-components to explore and explain the inherent variability contained within the “average” data (Makki *et al*., 2011; Parker and Wilby, 2012).

This paper attempts to identify the potential effect of misconnections on the organic and nutrient loadings to urban surface waters through the disaggregated quantification of BOD, ammonia (NH_4-N) and phosphate (PO_4-P) loads discharged from various domestic sources and appliances. Specific household micro-component data drawn from surveyed urban catchments in London and Swansea (South Wales) are used to provide detailed calculations of misconnection loadings and dilution ratios and as a basis for extrapolation to wider catchment situations. The adopted approach is based on simple, well recognised generic volume-concentration and mass balance determinations rather than on any more complex, blackbox process-based procedures. Despite the simplicity of the applied methodological approach, it is acknowledged that the basis for the derivation is data-rich and the robustness of the procedure is an essential consequence of the density of information acquired by the micro-component analysis. The described approach has not been previously attempted and in this respect it represents an innovative procedure which would support planning-level strategies for better management of urban drainage discharges and future improvement of in-stream urban water quality. The novelty of the proposed method is in its simplicity and capability for ready field verification through a rapid low-cost, screening-level application which permits the work-up of draft risk assessment and catchment management plans for heavily modified waterbodies (HMWBs) in urbanised areas and as a basis for further priority study.

2. Methodology and Study Sites

The application of a simple volume-concentration approach for determining pollutant loads from urban discharges has been widely used (Marsalek, 1991; Ellis and Viavattene, 2014). Such procedures have been tested by various workers against annual load estimates derived from deterministic multi-parameter hydrologic methods and have been found to either match or even outperform the more complex modelling algorithms (Van Buren *et al*., 1997). The functionality of complex operational modelling can be confounded by definitions of boundary conditions as well as process dynamics and kinetics which often make them difficult to calibrate and unwieldy to implement and collect reliable real-time data. Such complex research-type models are better suited to process-knowledge improvement rather than simplified management tools (Wainwright and Mulligan, 2003).

The available volume and concentration data for domestic appliance discharges is not usually expressed as event mean concentrations (EMCs) but either as specific unique (one-off) values or sample averages. Whilst individual appliance volumes and pollutant concentrations should not be inherently random in nature, catchment greywater outputs can be expected to be influenced by culture, life style, dietary and other personal factors. Thus the extension of international appliance volume-concentration data to geographically differing urban locations needs to be applied with caution.

2.1. Appliance Pollutant Loading to Surface Waters

Abel (2008) proposed a formula to calculate the misconnection daily domestic appliance BOD loading (kg day^{-1}) to receiving waters and a similar relationship also applies to other pollutants such as phosphate and ammonia. The formula considers the pollutant loading as a function of the total population served in the catchment (P_{tot}), the number of occupants per property or dwelling (N_p), the total number of properties investigated (N_{prop}), the number of each type of individual appliances misconnected (N_{apmis}) and the appliance loadings (kg capita day^{-1}; A_l). In the case of BOD the equation is:

$$BOD = [P_{tot} / N_p] \times [N_{apmis} / N_{prop}] \times A_l \times N_p \qquad \text{Eq.1}$$

But P_{tot} / N_p = the number of properties (N_{prop}) and so this equation simplifies to:

$$BOD = N_{apmis} \times A_l \times N_p \qquad \text{Eq.2}$$

2.2. Pollutant Concentration Downstream of a Misconnection Discharge

Assuming efficient mixing, a basic mass balance approach can be applied to determine the pollutant concentration downstream of a dry weather misconnection discharge from a separate sewer outfall. In the case of BOD, this can be represented by:

$$(BOD_1 \times Q_1) + (BOD_x \times Q_x) = (BOD_2 \times Q_2) \qquad \text{Eq.3}$$

Where BOD_1 = upstream BOD concentration (mg L^{-1})
BOD_x = misconnection flow BOD concentration (mg L^{-1})
BOD_2 = downstream BOD concentration (mg L^{-1})
Q_1 = upstream flow rate (L s^{-1})
Q_x = flow rate due to misconnections (L s^{-1})
Q_2 = downstream flow rate (L s^{-1})

If the dilution ratio = n and the misconnection flow rate (Q_x) is set to 1, the mass balance equation becomes:

$$(n + 1)\, BOD_2 = n\, BOD_1 + BOD_x \qquad \text{Eq.4}$$

This basic equation can be applied to the outfall point of the misconnection discharge to a receiving water assuming that there are no other inputs to the surface sewer system such as infiltration baseflow, cross-connections, septic tank or landfill seepage etc. The mixing concentrations within the receiving water can be determined for differing levels of the dilution ratio (n) and varying ambient receiving water concentrations and the results compared with threshold freshwater standards as a basis for assessing potential compliance with receiving water standards. Table 1 shows percentile BOD, NH_4-N and reactive phosphorus standards which have been set for the achievement of good ecological potential (GEP) as specified under the EU WFD for differing types of receiving water (Defra, 2014). Types 3, 5 and 7 refer to lowland rivers having high alkalinity (>50 mg L^{-1} $CaCO_3$) typical of urban rivers in the metropolitan Midlands and SE England regions. The majority of HMWBs in UK urban areas are designated as either Type 5 or Type 7.

Table 1. Freshwater standards according to river type (Defra, 2014).

	BOD (99%ile; mg L^{-1})		NH_4-N (99%ile; mg L^{-1})		Reactive Phosphorus (95%ile; µg L^{-1})	
	Types 1,2,4,6	Types 3, 5, 7	Types 1,2,4,6	Types 3, 5, 7	Lowland (Low alkalinity)	Lowland (High alkalinity)
High	7	9	0.5	0.7	26	50
Good	9	11	0.7	1.5	52	91
Moderate	14	14	1.8	2.6	140	215
Poor	16	19	2.6	6.0	918	1098

2.3.Study Sites

The developed methodology has been applied to surface water misconnection discharges from two urban sites located in the London metropolitan region and the city of Swansea in South Wales (Figure S1) and which have contrasting climate and receiving water characteristics. The 9065 ha Ching Brook catchment is located in the suburban fringe of NE London and receives an annual rainfall of just below 600 mm. The area consists of predominantly low to medium density housing built prior to 1930 with terraced and detached dwellings set in tree-lined streets. The Ching, a tributary of the River Lee, is classified as being of "poor" ecological and chemical status and subject to both extreme event flooding and pollution resulting from suspected household misconnections (Environment Agency, 2013c). 2D modelling for the 1:100 year, 6 hour duration storm event predicts a peak flow rate of 22 m^3 s^-

[1] producing a total volume of 0.81M m^3 of which 20% would spill out of channel over the adjoining flood plain (PBA, 2009). In 2009, Thames Water introduced a drainage initiative to survey a 100 ha sub-catchment having 2068 properties in the lower reaches of the Ching Brook which was characterised by persistent poor water quality resulting in its designation as a heavily modified water body (HMWB) under the WFD. Sampled dry weather surface water outfalls have indicated that BOD, NH_4-N and PO_4-P concentrations can vary between 9.8 and 275.6 mg L^{-1}, 0.04 and 6.55 mg L^{-1} and 0.85 and 1.4 mg L^{-1} respectively. (Environment Agency, 2010). The primary purpose of the Thames Water investigation was to identify the distribution, extent and source of pollution contributions from the separately sewered housing sub-catchment to the receiving water (Dunk *et al*., 2012).

The 2000 ha River Clyne catchment lies in the westernmost suburbs of the city of Swansea, South Wales and discharges into Swansea Bay at Blackpill (or "black stream"). The annual average rainfall is approximately 1000 mm. The spring-fed, 8 km long stream drains via a steep-sided channel through a historic 20th century industrial landscape with the densely built-up ribbon terraces of Dunvant representing a mix of Victorian and 1960s brownfield housing estates. The receiving water is contaminated by acid mine water drainage and associated elevated heavy metal concentrations, especially iron compounds, with upstream PO_4-P concentrations varying between 0.01 and 0.2 mg L^{-1} (Mestre, 2009). The river status is classified as being of "poor" to "moderate" chemical and ecological quality. Persistent bathing beach failures adjacent to the Blackpill discharge into the bay prompted the Swansea city authorities and Welsh Water to undertake, during 2011/12, a joint investigation of 936 properties on the Dunvant estate to determine potential contamination sources of surface water outfalls to the receiving water (King *et al.*, 2014).

Measurements of individual appliance discharges and concentrations were taken at each property identified from the field surveys as possessing a misconnection (see Section 3) although in the case of the Swansea Clyne catchment only appliance discharge was monitored. The concentrations of the measured parameters (BOD and PO4-P) for effluents from appliances in the Ching Brook catchment are discussed in Section 4. In addition, final discharge outfall rates from the surveyed catchment to the main receiving waters were monitored.

3. Domestic Appliance Misconnections and Outputs

The drainage surveys undertaken in the urbanised Chingford and Dunvant sub-catchments of the Ching Brook and River Clyne commenced by detection of polluted surface water outfalls (PSWOs) to the receiving streams followed by sewer tracer backtracking to offending laterals and individual contaminated household discharges. Details of the marker pollutants and other indicators used to identify the presence and sources of illicit greywater and black water substances in the surface water sewers are fully described elsewhere (Ellis and Butler, 2015). The general misconnection distribution pattern is similar for both urban catchments with approximately half being associated with washing machines and kitchen sinks; together with hand basins and dishwashers, these four appliances account for 70% to 80% of all misconnections. These results confirm the findings of previous studies where appliance outputs were expressed as proportional to instantaneous discharge (Butler *et al*., 1995).

3.1. Appliance Water Consumption

Over the past decade there have been a number of studies which have measured the daily water consumption of domestic appliances and Table 2 summarises reported international per capita daily usage data. It is assumed that the consumption rates represent discharges over the full operational cycle of the appliance, but the geographic variability in the data is nevertheless quite considerable although the UK studies are more compatible. The variability can be at least partly explained by whether the appliance (e.g. hand basin, kitchen sink, bath etc.) is operated on a "fill-and-empty" or "run-to-waste" mode (Friedler *et al*., 2013).

Table 2. Water consumption rates associated with domestic appliances

Water Production (L capita^{-1} day^{-1})						
	Shower Bath	Toilets	Washing Machine	Dish washer	Hand Basin	Kitchen Sink
France						
CIEAU (2012)[1]	49	25	25	12		
Eau de Paris (2012)[2]	46.8	24	14.4	-		
SEDIF (2013)[3]	57 – 78	30 – 40	18 – 24	15 – 20		
Greece						
Antonopoulou et al (2013)	33.9 ±33.2 21.9 (median)	59.4±29.6 54 (median)	21.3±19.9 14.6 (median)	6.6±7.2 4.1 (median)	8.6±7.2 4.1 (median)	12.2±14.3 7.5 (median)
Israel						
Penn et al (2012)	39.2	37.7	16.6	-	26.6	26.6
Friedler (2004)	20 (shower) 20 (bath)		13	5	15	25
Oman						
Jamrah et al (2008)	64 – 85	37.7	18 – 30	-	18 – 30	38 – 51
USA						
Mayer et al (1999)	47 – 55	35 – 73	45 – 64	4	-	-
International Literature						
Friedler (2004)[4]	12 – 20 (shower) 16 (bath)		17 – 60	2 – 6	8 – 13	13 – 19
UK						
POST (2000) Anglia Region	5.9 (shower) 19.5 (bath)	39.4	24.2	0.2	-	29.2
Ellis & Butler (2015) Thames Region	22 (shower) 36 (bath)	56.1	12	6	-	24

[1]www.cieau.com; [2]www.eaudeparis.fr; [3]www.sedif.com; [4]compilation of literature data

3.2. Appliance Flow Quality

Table 3 summarises reported international data for individual appliance (other than toilet) concentrations for BOD, NH_4-N and PO_4-P and demonstrates the variability which is influenced by supply characteristics, household life style, behaviour and hygiene, differing appliance chemicals etc. Clearly composition and concentration vary not only in terms of geographic location but also in time due to diurnal and seasonal changes in water usage patterns which affect the pollutant characteristics (Eriksson *et al.*, 2002). Despite the data variability, it can be seen that both BOD and PO_4-P concentrations are an order of magnitude or more greater than the receiving water standards shown in Table 1 indicating the potential problems associated with discharging untreated effluents from these sources.

	Shower/Bath			Washing Machine			Dishwasher			Hand Basin			Kitchen Sink		
	BOD	NH_4-N	PO_4-P	BOD	NH_4-N	PO_4-P	BOD	NH_4-N	PO_4-P	BOD	NH_4-N	PO_4-P	BOD	NH_4-N	PO_4-P
Greece															
Antonopoulou et al (2013)		8.4±12.6 4.5(Median)	0.4±0.6 0.2 (Median)								2.6±2.9 1.2(Median)	0.7±0.9 0.3(Median)		4±4.8 1.2 (Median)	0.4±0.4 0.3(Median)
Israel															
Friedler (2004)	424±219 (Shower) 173±218 (Bath)	1.2±0.83 (Shower) 0.89±1.49 (Bath)	10±13.7 (Shower) 4.6±5.3 (Bath)	462	4.9	169	699	5.4	537	205±43	0.39±0.29	15±13.8	890 ±480	0.8±0.81	22±27
Oman															
Jamrah et al (2008)	380	242		296						100					
USA															
Laak (1974)	192		0.94	282	11.3	171				236	1.15	48.8	676	5.44	12.7
Siegrist et al (1976)	170	2	1	380	0.7	15	1040	4.5	32				1460	6	31
Rose et al (1991)		0.11-0.37			0.1-3.47										
Australia															
Boyjoo et al (2013)	23-300			48-472											
Christove-Boal et al (1998)		<0.1-15		48-290	<0.1-1.9										
International Literature															
Friedler (2004)		1.2(Shower) 1.1(Bath)		280-470	0-11	4-170	390	4.5	32	33-236	0.3-1.2	13-49	530-1450	8	13-31
Li et al (2009)	50-300	7-505		48-472											
Eriksson et al (2002)	170			48-472											
Almeida et al (1999)		1.2(Shower) 1.1(Bath)	19.2 (Shower) 5.3 (Bath)		2	21					0.3	13.3		0.3	26
UK															
Ellis & Butler (2015)	22 (Shower) 38(Bath)		14 (Shower) 101 (Bath)	41		35	31		44				44		28
Jefferson et al (2004)	146±55 (shower) 129±57 (Bath)		0.3±0.1 (Shower) 0.4±0.4 (Bath)							155±49		0.4±0.3			
Surendran & Wheatley (1998)	216	1.56	1.63	472	10.7	101				252	0.53	45.5	536	4.6	15.6

Table 3. Daily pollutant concentrations (mg L^{-1}) in the effluents produced by domestic appliances (other than toilets)

4. Results and Discussion

The methodological approach given above has been applied to misconnection data obtained for the two described sub-catchments. In each case it has been assumed that there is an average of 2.48 inhabitants occupying each property (ONS, 2014) and three working scenarios are developed. Two of these scenarios refer to the Ching sub-catchment and the other to the Clyne sub-catchment as identified below:

Scenario A: applies to the Ching sub-catchment using the measured daily pollutant concentrations (BOD and PO_4-P) in the effluents (mg L^{-1}) from specific appliances (see Table 4) and the measured daily flows (L cap^{-1}) from each of the appliances for the homes surveyed (see Table 5).
Scenario B: applies to the Ching sub-catchment using the measured daily flows (L cap^{-1}) from specific appliances for the homes surveyed in this catchment (see Table 5) and derived mean daily pollutant concentrations (BOD, PO_4-P and NH_4-N) in the effluent (mg L^{-1}) from each of the appliances as reported in the literature (see Table 4 for greywater values and Box 1 for black water [toilet] values). The Ryan-Joiner test for normality has been applied to the data to confirm that the mean values presented in Table 4 provide a realistic estimate of the central tendency of the data given in Table 3.
Scenario C: follows the same approach as for Scenario B but applies to the Clyne sub-catchment; the measured daily flows (L cap^{-1}) from specific appliances for the homes surveyed in this catchment are shown in Table 6.

Table 4, Mean daily greywater concentrations in effluents produced by domestic appliances either measured directly (for Ching sub-catchment) or derived from the international literature database (contained in Table 3).

		Shower	Washing Machine	Dishwasher	Kitchen Sink	Hand Basin
BOD (mg L^{-1})	Measured value	30	41	31	44	38
	Literature mean value	181 ±114	336 ±145	710 ±325	773 ±205	181 ±60
PO_4-P (mg L^{-1})	Measured value	14	35	44	28	101
	Literature mean value	4.8 ±7.3	94.0 ±68.1	200.3 ±291.6	18.4 ±2.1	15.6 ±19.8
NH_4-N (mg L^{-1})	Literature mean value	2.5 ±3.0	5.2 ±4.7	5.0 ±0.6	3.5 ±2.5	1.0 ±0.9

4.1. Appliance Discharges Due to Misconnections

The daily volumetric outflows from individual appliances have been calculated as illustrated by the following example for shower data in respect of the Ching sub-catchment. Measured daily water volumes due to shower usage of 22 L cap^{-1} (Table 5) equate to daily household water volumes of 54.6 L (22 x 2.48) and daily volumes produced by the 2068 homes in the sub-catchment of 112830.1 L (Table 5). Given that 4.7% of showers have been estimated to be misconnected, the daily contributory misconnection volumes due to shower usage will be 5303.0 L (Table 5). Similar calculations for the other contributing appliances provide the total daily volumes due to misconnections shown in Table 5. The corresponding values for the Clyne sub-catchment are given in Table 6.

Box 1. Determination of pollutant concentrations in black water derived from toilets

Daily toilet flush volumes:
Waterwise (2016) identifies the flush volumes associated with dual flush toilets as being 4 L (low flush) and 6 L (high flush) with the traditional single flush systems using 13 L. For the Chingford catchment, it has been assumed that 30% of the homes surveyed are fitted with dual flush toilets and that the 'high flush' option will be selected for faeces flushing with the 'low flush' option being used for urine flushing. On the basis that each person performs a faeces flush once a day and urine flushing four times a day, the daily flush volume for faeces averaged over the catchment would be

$$(6 \times 0.3) + (13 \times 0.7) = 10.9 \text{ L cap}^{-1}$$

and the daily flush volume for urine would be:

$$(4 \times 4 \times 0.3) + (4 \times 13 \times 0.7) = 41.2 \text{ L cap}^{-1}$$

giving a total daily flush volume of 52.1 L cap^{-1}
This value is similar to those determined for the Ching and Clyne sub-catchments of 56.1 L cap^{-1} day^{-1} and 50.5 L cap^{-1} day^{-1} for toilet flushing.
BOD concentration in toilet flush water:
For the Ching sub-catchment, Ellis and Butler (2015) report a daily concentration of 120 mg L^{-1}.
Alternatively, Butler *et al.* (2013) quote average BOD loadings in urine and faeces of 5.8 g cap^{-1} day^{-1} and 12 g cap^{-1} day^{-1} producing a total organic loading due to BOD of 17.8 g cap^{-1} day^{-1}. Given a daily toilet flush volume of 52.1 L cap^{-1}, this equates to a daily BOD concentration discharged from domestic premises due to toilet flushing of 341.7 mg L^{-1}
PO_4-P concentration in toilet flush water:
For the Ching sub-catchment, Ellis and Butler (2015) report a daily concentration of 26 mg L^{-1}.
Alternatively, Tervahaute (2014) reports PO_4-P loadings in urine and faeces of 0.3 g cap^{-1} day^{-1} and 0.2 g cap^{-1} day^{-1} producing a total orthophosphate loading of 0.5 g cap^{-1} day^{-1}. Given a daily toilet flush volume of 52.1 L cap^{-1}, this equates to a daily PO_4-P concentration discharged from domestic premises due to toilet flushing of 9.6 mg L^{-1}
NH_4-N concentration in toilet flush water:
de Graaff et al. (2010) report average combined NH_4-N loadings due to urine and faeces in the black water influent to a UASB reactor of 6.82 g cap^{-1} day^{-1}. Given a daily toilet flush volume of 52.1 L cap^{-1}, this equates to a daily NH_4-N concentration discharged from domestic premises due to toilet flushing of 130.9 mg L^{-1}.

Table 5. Contributing volumes due to appliance misconnections in the Ching sub-catchment.

	Measured daily volume for individual use (L cap^{-1} day^{-1})	Daily Volume (L)	% Misconnection	Daily Discharge Volume Due to Misconnection (L)
Shower	22	112830.1	4.7	5303.0
Toilet	56.1	287716.7	4.1	11796.4
Washing machine	12	61543.7	25.7	15816.7
Dishwasher	6	30771.8	11.7	3600.3
Kitchen sink	24	123087.4	22.5	27694.7
Hand basin	10	51286.4	8.6	4410.6
TOTAL	130.1	667236.1		68621.7

Table 6. Contributing volumes due to appliance misconnections in the Clyne sub-catchment.

	Measured daily volume for individual use (L cap^{-1} day^{-1})	Daily Volume (L)	% Misconnection	Daily Discharge Volume Due to Misconnection (L)
Shower	7.6	17641.7	8.4	1481.9
Toilet	50.5	117224.6	3.2	3751.2
Washing machine	23.5	54550.1	31.6	17237.9
Dishwasher	2	4642.6	2.1	97.5
Kitchen sink	21.6	50139.6	21	10529.3
Hand basin	11.8	27391.1	15.8	4327.8
TOTAL	117	271589.8		37425.5

4.2. Appliance Pollutant Outflows Due to Misconnections

4.2.1. Pollutant loadings

The calculation of the daily pollutant loadings arising from shower usage is demonstrated below using BOD data relevant to Scenario B of the Ching sub-catchment. A mean daily BOD concentration in shower water of 181 mg L^{-1} is predicted by a review of literature data (Table 4) and at a daily water flow of 22 L cap^{-1} (Table 5) this equates to a daily BOD loading due to shower usage of 3.98 g cap^{-1}. Therefore the daily BOD loading due to shower usage for each household would be 3.98 x 2.48 = 9.88 g which increases to 20.4 kg for the 2068 homes in the sub-catchment (Table 7). Given that 4.7% of showers have been estimated to be misconnected, the daily contributory BOD loadings due to misconnected showers in the Ching sub-catchment will be 0.96 kg (Table 7). Similar calculations for the other contributing appliances enable the total daily BOD loadings both prior to and after misconnections to be calculated for the Ching sub-catchment as shown in Table 7. The daily BOD loadings for Scenario A (48.7 kg) and Scenario B (265.8 kg) equate to values of 9.5 g cap^{-1} and 51.8 g cap^{-1}, respectively. The latter value is consistent with that of 60 g cap^{-1} for average daily BOD production (British Water, 2009) and gives confidence in the reliability of the Scenario B data. Table 7 also lists the calculated PO_4-P and NH_4-N loadings arising from appliance misconnections according to Scenario B and the BOD and PO_4-P loadings arising from appliance misconnections according to Scenario A. The results for BOD, PO_4-P and NH_4-N loadings for the Clyne sub-catchment (Scenario C) are reported in Table 8 indicating an average daily BOD production of 46.8 g cap^{-1}.

4.2.2. Pollutant discharge concentrations

For each scenario the discharged pollutant concentrations due to misconnections is obtained from the total pollutant loading (Tables 7 and 8) and the total volume entering the receiving stream (Tables 5 and 6). The predicted concentrations are shown in Table 9 together with estimated downstream pollutant concentrations using Equation 4 and based on a dilution ratio of 8:1. The upstream pollutant concentrations have been taken as 2 mg L^{-1} for BOD, 0.8 mg

Table 7. Contributing loadings due to appliance misconnections in the Ching sub-catchment (Scenarios A and B).

		Shower	Toilet	Washing Machine	Dishwasher	Kitchen Sink	Hand Basin	Totals
Scenario A	BOD daily loadings (kg) BOD loadings due to misconnections (kg)	3.4 0.16	34.5 1.42	2.5 0.65	0.95 0.11	5.4 1.22	1.9 0.17	48.7 3.72
Scenario B	BOD daily loadings (kg) BOD loadings due to misconnections (kg)	20.4 0.96	98.4 4.03	20.7 5.31	21.8 2.56	95.1 21.4	9.3 0.80	265.8 35.1
Scenario A	PO_4-P daily loadings (g) PO_4-P loadings Due to Misconnections (g)	1579.6 74.2	7480.6 306.7	2154.0 553.6	1354.0 158.4	3446.4 775.4	5180.0 445.4	21194.6 2313.9
Scenario B	PO_4-P daily loadings (g) PO_4-P Loadings due to misconnections (g)	535.9 25.2	2762.1 113.2	5785.1 1486.8	6154.4 720.1	2264.8 509.6	800.1 68.8	18302.4 2923.7
Scenario B	NH_4-N daily loadings (g) NH_4-N loadings due to misconnections (g)	277.6 13.0	37690.9 1545.3	321.3 82.6	152.3 17.8	429.6 96.7	52.8 4.54	38924.4 1760.0

Table 8. Contributing loadings due to appliance misconnections in the Clyne sub-catchment (Scenario C).

		Shower	Toilet	Washing Machine	Dishwasher	Kitchen Sink	Hand Basin	Totals
Scenario C	BOD daily loadings (kg) BOD loadings due to misconnections (kg)	3.2 0.27	40.1 1.28	18.33 5.79	3.3 0.07	38.8 8.14	4.96 0.78	108.6 16.3
Scenario C	PO_4-P daily loadings (g) PO_4-P loadings due to Misconnections (g)	83.8 0.007	1125.4 36.0	5127.7 1620.4	928.5 19.5	922.6 193.7	427.3 67.5	8615.2 1944.2
Scenario C	NH_4-N daily loadings (g) NH_4-N loadings due to misconnections (g)	43.4 0.004	15356.4 491.4	284.8 90.0	23.0 0.001	175.0 36.7	28.2 0.005	15910.8 626.7

L^{-1} for PO_4-P and 0.5 mg L^{-1} for NH_4-N. Snook and Whitehead (2004) and Edmonds-Brown and Faulkner (1995) report background PO_4-P and NH_4-N concentrations of 0.8 mg L^{-1} and 0.5 mg L^{-1} for rivers in the Lower Lee catchment where the Ching Brook is located and the characteristics of the urban lowland rivers are not dissimilar to the River Clyne.

The different scenarios predict similar misconnection discharge concentrations for PO_4-P and NH_4-N and hence similar downstream river concentrations. However, in the case of BOD, these values are seriously under-predicted for Scenario A in comparison to Scenarios B and C. This can be explained by the low BOD concentrations, often by an order of magnitude, reported for the greywater discharges from the appliances in the Ching sub-catchment compared to the corresponding average values derived from international data (Table 4) and which have been used in Scenarios B and C.

Table 9. Predicted downstream pollutant concentrations (mg L^{-1}) due to misconnection discharges.

Pollutant	Sub-catchment/scenario	Calculated mean concentration in misconnection discharge	Predicted downstream concentration
BOD	Ching/Scenario A	54.2	7.8
	Ching/Scenario B	511.1	58.6
	Clyne/Scenario C	436.5	50.3
PO_4-P	Ching/Scenario A	33.7	4.5
	Ching/Scenario B	42.6	5.5
	Clyne/Scenario C	51.9	6.5
NH_4-N	Ching/Scenario B	25.7	3.3
	Clyne/Scenario C	16.7	2.3

Defra (2014) recommends that BOD should not exceed 99 percentile concentrations of 9, 11, 14 and 19 mg L^{-1} to respectively maintain high, good, moderate or poor quality waters in a lowland river with a high alkalinity (Table 1). The dilution ratios to achieve these requirements based on a discharge containing the highest calculated BOD levels for the Ching and Clyne sub-catchments of 511.1 mg L^{-1} and 436.5 mg L^{-1} and an upstream BOD concentration of 2 mg L^{-1} would be 61-72, 47-56, 35-41 and 22-29 respectively. Therefore, based on a calculated misconnection discharge volume for the Ching sub-catchment of 68621 L day^{-1}, the upstream flows would need to be 57 L s^{-1} (0.057 m^3 s^{-1}), 45 L s^{-1} (0.045 m^3 s^{-1}), 33 L s^{-1} (0.033 m^3 s^{-1}) or 23 L s^{-1} (0.023 $m^3 s^{-1}$). Snook and Whitehead (2004) report dry weather flows in tributaries of the R Lea varying between 0.14 m^3 s^{-1} and 0.53 m^3 s^{-1} and therefore the level of dilution required to achieve high quality waters with respect to BOD is feasible. However, under low flow conditions this may be more difficult to achieve and it is possible that only moderate or poor quality waters may be obtainable if BOD discharges due to misconnections are not either totally or partially eliminated.

The different scenarios yield predictions of between 4.5 and 6.5 mg L^{-1} for the PO_4-P river concentrations downstream of a misconnection discharge assuming dilution at a rate of 8:1 (Table 9). These are all in excess of the 95 percentile soluble reactive phosphorus levels of 0.05 mg L^{-1}, 0.091 mg L^{-1}, 0.215 mg L^{-1} or 1.098 mg L^{-1} which should not be exceeded to maintain high, good, moderate or poor quality waters in a lowland river with alkalinity in excess of 50 mg L^{-1} (as $CaCO_3$) (Defra, 2014). Given an upstream PO_4-P concentration of 0.8 mg L^{-1} for the Ching catchment, the only receiving water quality achievable with respect to this pollutant would be within the poor category and to reach the cut-off concentration for this category (Table 1) would require dilution of the misconnection discharges in ratios of between 109:1 (for Scenario A) and 139:1 (for Scenario B). Therefore there is clearly a need to reduce the background phosphate levels in urban lowland rivers and additionally to eliminate phosphate discharges due to misconnections in order to improve the water quality status with respect to PO_4-P. For the Clyne sub-catchment, it has been reported that background PO_4-P concentrations vary between 0.01 and 0.2 mg L^{-1} (Mestre, 2009). For the highest of these values, only the moderate and poor categories are attainable and would require dilutions ratios of 3446:1 and 52:1 respectively, and only the moderate water quality can be expected. On the other hand, for a background PO_4-P concentration of 0.01 mg L^{-1}, high water quality would be theoretically possible but, in practice, only moderate quality (dilution ratio of 252:1) or poor quality (dilution ratio of 47:1) would appear to be feasible.

Concentrations of NH_4-N in misconnection discharges from the Ching and Clyne sub-catchments are predicted to be 25.7 mg l^{-1} and 16.7 mg L^{-1}, respectively (Table 9). Snook and Whitehead (2004) and Edmonds-Brown and Faulkner (1995) report background NH_4-N concentrations for rivers in the Lower Lee catchment of the order of 0.5 mg L^{-1}. Therefore, based on an upstream NH_4-N concentration of 0.5 mg l^{-1} and a dilution ratio of 8:1, the resulting NH_4-N concentration in the receiving water due to a discharge containing 25.7 mg L^{-1} would be 3.3 mg l^{-1}. Assuming the same background NH_4-N concentration for the Clyne sub-catchment, the downstream concentration would be 2.3 mg L^{-1} (Table 9). Defra (2014) recommends that NH_4-N should not exceed 99 percentile levels of 0.7, 1.5, 2.6 and 6.0 mg L^{-1} to maintain high, good, moderate or poor quality waters in a lowland river with a high alkalinity. Given an upstream NH_4-N concentration of 0.5 mg L^{-1}, all of these water quality standards are achievable and would require dilution ratios of 4, 11, 24, or 125 (for the Ching sub-catchment) and dilution ratios of 2, 7, 15 or 83 (for the Clyne sub-catchment) to achieve the poor, moderate, good or high water quality conditions. The ranges of upstream flows to achieve these conditions would be 5 to 99 L s^{-1} (for the Ching sub-catchment) and 0.9 to 35 L s^{-1} (for the Clyne catchment). Based on the dry weather flows of between 0.14 m^3 s^{-1} and 0.53 m^3 s^{-1} in tributaries of the R Lee reported by Snook and Whitehead (2004), the highest quality downstream water is attainable in the Ching sub-catchment but this could be jeopardised by the misconnection discharges in times of low background flows.

4.2.3. Identifying appropriate remedial actions

The contributions made to BOD, PO_4-P and NH_4-N loadings due to the different appliances, both at source (e.g. A app) and as a result of misconnection discharges (e.g. A misc) for all scenarios are shown in Figure 1. Scenarios B and C represent the worst outcomes for receiving water quality in terms of pollutant discharges due to misconnections and will be considered in more detail. Although the main source contributions of BOD are from toilets (37-38%) and kitchen sinks (36%), when the percentages of appliances misconnected is accounted for it is the kitchen sink contribution which predominates reaching 61% for Scenario B and 50% for Scenario C. Due to their high percentage misconnection rates (26-32%) washing machines also pose a problem regarding illicit BOD discharges.

In the case of PO_4-P, showers and hand basins consistently make negligible contributions at both the source and misconnection level for scenarios B and C. Washing machines are clearly important contributors to PO_4-P loadings and this effect is magnified in the misconnection discharges reaching over 80% for Scenario C. Kitchen sinks provide relevant inputs in both scenarios with dishwashers (24.6%) being a significant contributor to potential discharges for Scenario B. The picture for NH_4-N is clear cut with toilets being consistently the predominant source of this pollutant and contributing between 78% and 88% of the total load discharge through misconnections. The only other appliances contributing to NH_4-N discharges are washing machines (14%) in Scenario C.

To reduce the impacts of the three considered pollutants on receiving waters due to misconnections, the appliances which need to be targeted are toilets, kitchen sinks and washing machines with dishwashers also of concern regarding PO_4-P loadings. For Scenarios B and C, it is washing machines (25.7-31.6%) and kitchen sinks (21.0-22.5%) which demonstrate the highest misconnection rates and therefore provide the greatest scope for remediation. Three different remediation schemes are proposed as identified below. The

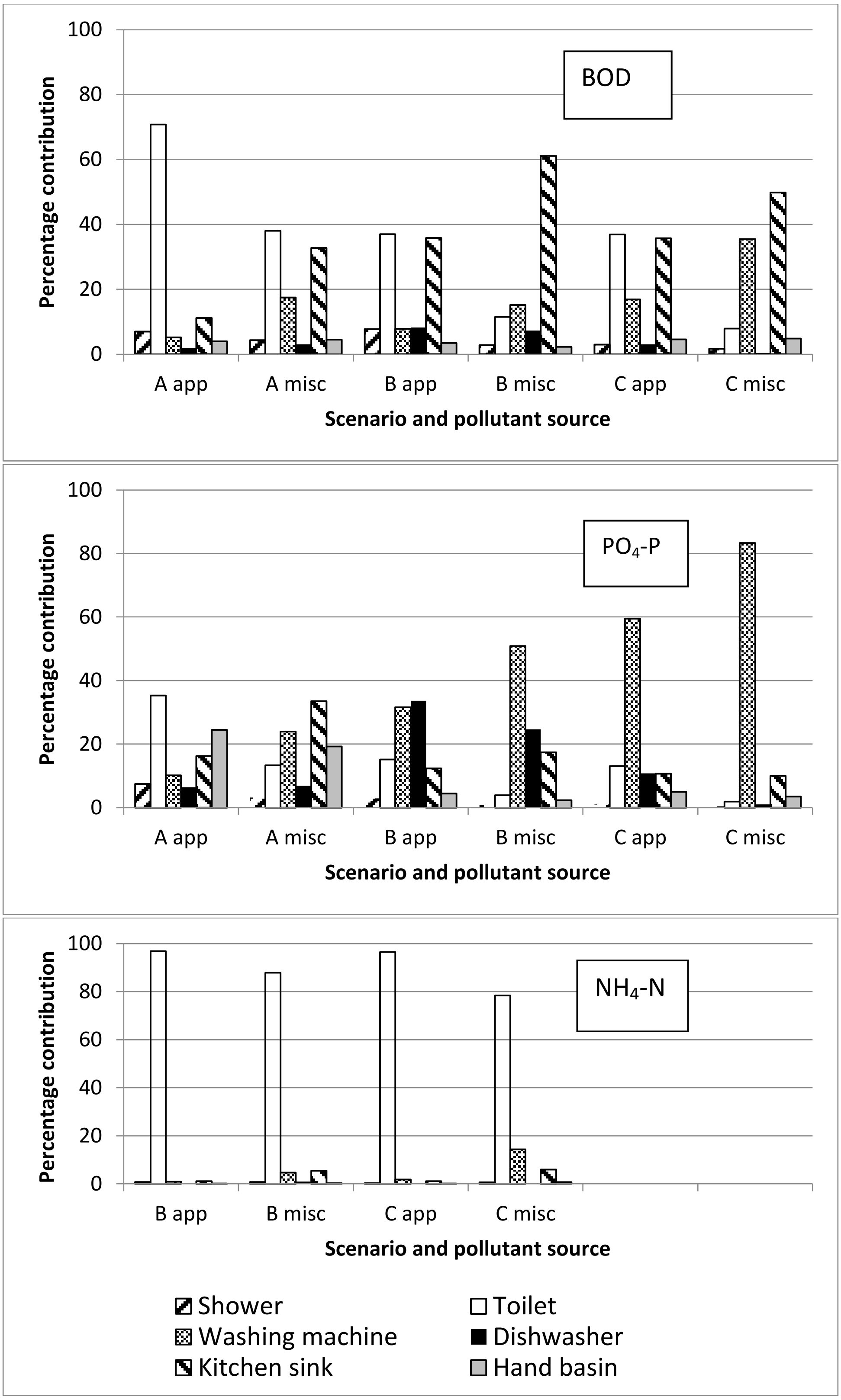

Figure 1. Percentage contributions to appliance and misconnection pollutant loadings

objective of remediation scheme 1 is to assess the impact of targeting the serious misconnection problems associated with washing machines and kitchen sinks by reducing both to 5%. Although toilet misconnections are below 5% for both sub-catchments, they contribute substantially to the NH_4-N loadings and to a lesser extent to BOD loadings and hence remediation scheme 2, in which the toilet misconnections are completely removed, has been proposed. Remediation scheme 3 additionally considers the reduction of misconnections from all other appliances to 2% and represents a realistic goal given the current problems which are being encountered with misconnections in urban areas.

The criteria associated with the three different remediation schemes are summarised below:

- Remediation 1: percentage misconnections associated with washing machines and kitchen sinks both reduced to 5%
- Remediation 2: as for remediation 1 with toilet misconnections completely removed
- Remediation 3: no toilet misconnections and misconnections from all other appliances reduced to 2%

4.2.4 Impact of remedial actions on misconnection pollutant loads

The impacts of carrying out the three different remediation schemes with respect to pollutant loads in the sub-catchment misconnection discharges are identified in Figure 2. Consistent profiles are observed for Scenarios B and C. Following the initial large BOD reductions achieved by Remediation 1, there are progressive increases in removal to over 90% for Remediation 3. The same remediations are also most effective at reducing the misconnection emissions of PO_4-P but with less discrimination between remediations 1 and 2 where toilet misconnections have been eliminated. In contrast, remediations 1 and 3 have limited impact on NH_4-N loadings and it is the elimination of toilet misconnections (remediation 2) which is the critical controlling factor.

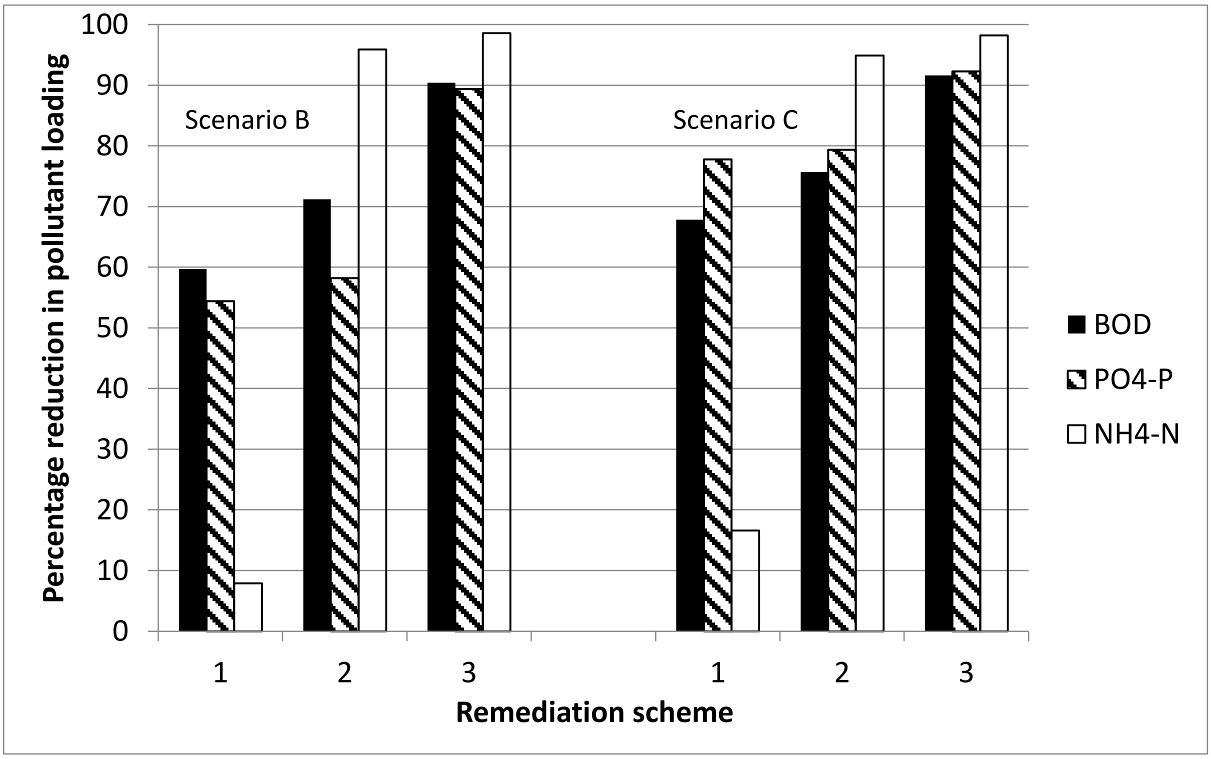

Figure 2. Pollutant load reductions resulting from the application of different remediation schemes for Scenarios B and C.

4.2.5 Assessment of uncertainty and impact of remedial actions on water quality

To enable a realistic assessment of the pollutant concentrations in the misconnection discharges and hence to predict downstream concentrations it is important to derive the uncertainty associated with these parameters. The origins of the main sources of uncertainty are within the pollutant concentrations in the effluents deriving from each type of misconnected appliance and within the effluent volumes arising from the misconnected appliance. To broaden the applicability of the concentrations used in this study, pollutant concentrations determined from extensive published datasets have been utilised in Scenarios B and C. The resulting values provide a realistic overall assessment of the pollutant concentrations in the effluents from different appliances. The variability associated with these values arises from differences in climate, dietary and lifestyle characteristics and therefore is not considered appropriate to be included at the local level associated with this study.

The most important factor influencing the uncertainty associated with the results at a local scale is the variability in the effluent volumes from the different appliances in each sub-catchment. For individual appliances these will be subject to advances in technology (e.g. the advent of low flush toilets; progressive installation of power showers; introduction of energy saving programmes for washing machines) and variations in consumer behaviour (e.g. appliance usage on a daily basis). Misconnected volumes represent a key driver for the predicted downstream pollutant concentrations due to their influence on dilution characteristics. By conducting a thorough survey of the data available for the effluent volumes produced by individual appliances, the variabilities shown in Table 10 have been established.

Table 10. Variabilities in effluent volumes (l cap^{-1} d^{-1}) arising from individual appliances for Scenarios B and C.

	Scenario B	Scenario C
Shower	22.0±7.9	7.6±2.7
Toilet	56.1±2.1	50.5±1.9
Washing machine	12.0±3.5	23.5±6.9
Dishwasher	6.0±0.1	2.0±0.03
Kitchen sink	24.0±2.8	21.6±2.5
Hand basin	10.0±1.2	11.8±1.4

The variabilities in effluent volumes have been used to calculate the uncertainties in pollutant concentrations in misconnection discharges and predicted pollution concentrations in receiving waters and the results are presented in Table 11 for Scenarios B and C. Although the maximum uncertainty in the calculated values is of the order of 25%, it is generally lower than this, providing confidence that the determined concentrations are realistic and can be confidently compared with published data, where this exists. In general, the remediation schemes do not greatly influence the pollutant concentrations in the misconnection discharges as both pollutant load and effluent volume are simultaneously reduced. In some instances there are increases in concentrations for BOD and PO_4-P and only remediation 2 clearly has a beneficial impact on NH_4-N concentrations due to the elimination of toilet sources. However, although there is often no decrease in pollutant concentration the pollutant loads arising from misconnections are decreased as shown in Figure 2. Consequently, there will be an increased dilution following discharge to a receiving stream compared to the 8:1 dilution assumed for the misconnection discharge not subjected to remediation. The progressive lowering of predicted receiving stream concentrations as the different remediation schemes are imposed is clearly shown in Table 11.

Table 11. Comparisons (with uncertainties) of the impacts deriving from the application of different appliance remediation strategies to Scenarios B and C.

		Scenario B		Scenario C	
		Concentration in misconnection discharge (mg L^{-1})	Concentration in receiving water (mg L^{-1})	Concentration in misconnection discharge (mg L^{-1})	Concentration in receiving water (mg L^{-1})
BOD	No remediation	511.1±105.4	58.6±11.7	436.5±116.2	50.3±12.9
	Remediation 1	411.7±70.7	26.1±4.2	353.1±73.7	18.6±3.5
	Remediation 2	448.2±123.4	19.6±4.9	356.8±92.1	14.7±3.3
	Remediation 3	441.0±114.2	8.0±1.6	444.0±117.1	6.5±1.2
PO_4-P	No remediation	42.6±10.2	5.5±1.1	51.9±5.7	6.5±0.6
	Remediation 1	38.7±10.4	3.0±0.6	29.1±7.6	2.1±0.4
	Remediation 2	54.0±11.3	2.9±0.5	35.6±10.6	2.0±0.4
	Remediation 3	40.9±10.6	1.4±0.1	48.5±14.8	1.3±0.2
NH_4-N	No remediation	25.7±4.3	3.3±0.5	16.7±3.6	2.3±0.4
	Remediation 1	47.1±6.7	3.2±0.4	35.1±5.6	2.1±0.3
	Remediation 2	3.2±0.8	0.61±0.03	2.8±0.8	0.59±0.03
	Remediation 3	3.3±0.9	0.54±0.01	3.6±1.0	0.53±0.01

Remediation schemes are shown to be essential if BOD levels are to approach the required river quality objectives and only remediation scheme 3 has the capability of achieving the high river water quality for both scenarios when compared to the 99 percentile standards for lowland rivers with high alkalinity (see Table 1). Remediation scheme 3 is also most effective at reducing the predicted receiving water concentrations of PO_4-P but these fail to comply with the water quality standards and only poor quality is achievable mainly due to the high background PO_4-P concentration (0.8 mg L^{-1}) which has been applied. Remediation 1 has little impact on NH_4-N concentrations as it is the elimination of toilet misconnections (Remediations 2 and 3) which is the critical controlling factor. The receiving water concentrations, and low associated variabilities, following reductions in misconnections arising from both these remediations result in predicted high water qualities for NH_4-N when compared to the standards for lowland rivers (Table 1).

4.3. Extrapolation to Catchment Scale

Few attempts have been made to estimate the wider catchment scale impact of pollutant loadings on urban receiving waters based on the extrapolation of site-based household misconnection data. Table 7 identifies the total daily pollutant loadings predicted to arise under different scenarios from misconnected appliances associated with 2068 houses in the 100 ha Ching sub-catchment. The average household BOD misconnection loading based on Scenario B criteria (using international concentration data) would be 17.0 g day^{-1}. Upscaling this site-based value to the 3.27M households (ONS, 2014) within the 1572 km^2 Greater London metropolitan area would indicate a total daily BOD loading to urban receiving waters of 55590 kg day^{-1}. This is comparable with the daily BOD load (52630 kg) arriving at Deephams STW, a large treatment works in NE London serving a population approaching 1 million. Converted to Population Equivalent (PE) values (using 1 PE = 60 g BOD cap^{-1}) the predicted value of 925024 for the misconnections arising from the Greater London metropolitan area equates to that for Deephams STW (877167). The similarity of both the BOD loadings and the PE values indicate that, based on the not unreasonable assumption (Dunk *et al*., 2008) that the misconnection distributions found in the Ching sub-catchment prevail across the wider metropolitan area, the equivalent of at least one major treatment works would be required to fully minimise the organic loading arising from misconnections deriving from an area with similar size and population density to that of Greater London. For this conurbation, a commonly quoted figure for average household misconnection rates is 3% (Dunk *et al*., 2008; Ellis and Butler, 2015). Combining this with the commonly accepted 60 g cap^{-1} average daily household BOD production (British Water, 2009), produces a total daily BOD load for the Greater London area of 14597 kg day^{-1}, which is considerably lower than the predicted value (55590 kg day^{-1}) based on site survey upscaling. The use of average per capita and misconnection data can therefore result in a significant under-estimation of potential receiving water loadings from illicit surface water discharges.

The scale of the treatment facilities required is emphasised by the data available for daily PO_4-P loadings which for misconnections over an area the size of Greater London are predicted to be far in excess (4623 kg day^{-1} for an extrapolated Scenario B situation) compared to those typically received by Deephams STW (1131 kg day^{-1}; assuming that PO_4-P constitutes 70% of TP in raw sewage). Therefore to eliminate the potential PO_4-P problems arising from misconnections would require a state-of-the-art treatment works employing phosphate stripping techniques. This is not the case for NH_4-N loadings as a treatment works of an equivalent size to Deephams (incoming NH_4-N loading 6805 kg day^{-1}) employing activated sludge would be expected to possess over double the capacity needed to deal with the daily NH_4-N loads (2783 kg) expected to arise from misconnections in an area similar to Greater London. Similarly, there would not be a problem with the incoming volume capacity which at a predicted value for misconnections of >110000 m^3 day^{-1} is less than half that of a large sewage treatment works such as Deephams (>280000 m^3 day^{-1}).

4.4 Limitations of this study and recommendations for future work

Evidence derived from two field studies has been used to assess the impacts of household wastewater misconnections on receiving water pollutant loadings and environmental quality standards. Ideally, more extensive databases are required covering a range of sub-catchments to provide greater confidence in the analysed data and to support the ability to up-scale the results to larger catchments and eventually to a national scale. A greater breadth of completed surveys should enable identification of regional variations for in-stream loadings arising from differences in appliance implementation and consumer behaviour/usage characteristics in order to contribute to the provision of a more representative picture at national level. Catchment size is a critical parameter with limitations imposed by economic and logistical factors needing to be balanced by the necessity to eliminate bias which may result from non-standard individual household behaviours. It is considered that surveys involving sub-catchments containing between 1000 and 2000 households provides a realistic compromise.

The monitoring requirements within a selected sub-catchment need to be carefully matched to the data needed to apply the described methodological approach. The only measured pollutant concentrations were for BOD and PO_4-P in the greywater deriving from appliance emissions in the Ching Brook sub-catchment. Ideally, such measurements should be available for all considered pollutants from both sub-catchments and should be extended to include the analysis of black water deriving from toilets. Given the limited availability of measured pollutant concentrations it has been necessary to source toilet flush values from available published data and greywater concentrations from international literature data. Both these approaches result in realistic pollutant loading and concentration predictions but confirmation through site monitoring would be beneficial. It would also be desirable to have an on-site measurement of the receiving water flows at the misconnection discharge outfall to enable a more accurate calculation of the dilution ratios and to support a more sophisticated modelling procedure to compare with the simple but practical approach described. Similarly, direct measurements of the upstream receiving water pollutant levels would assist in more accurate interpretations of the downstream concentrations after surface water sewer inputs and thus allow more precise interpretations of the impacts of reducing upstream pollutant sources. This is particularly important in the case of PO_4-P where there is a need for further definition and impact of urban and rural diffuse sources and mitigation strategies for phosphate levels in urban rivers.

In the described methodological approach, only the contributions of misconnections to the dry weather flows to surface water sewers have been considered. In practice, supplementary flows relating to groundwater baseflows, mains leakage, land drainage sources (e.g. golf courses, rail track discharges), septic tank/landfill plumes, cross-connections etc. may exist and further work needs to be done to discriminate these from misconnections. Groundwater infiltration (and rainfall inflow) into a sewer pipe is generally considered to be of the order of 10% of the dry weather flow and being clean water this would effectively dilute the pollutant concentration due to misconnections. Estimates of the impacts of such infiltrations could be deduced using the described methodological approach and integrated into the determination of the uncertainty associated with the predicted downstream receiving water pollutant concentrations. The currently estimated uncertainties in these values would be most strongly influenced following the instigation of remediation practices due to a greater impact on the effluent volumes arising due to misconnections. To overcome these uncertainties there is a need to conduct in-stream water quality and ecological status surveys for both acute (individual storm events) and chronic (long term accumulative) conditions to experimentally confirm the predicted influence of misconnection remediation strategies.

5. Conclusions

Illicit household discharges to surface water sewer systems present a ubiquitous problem for urban receiving water quality and one which will not be readily resolved as it requires considerable organisational, manpower and financial resources. The discharged organic and nutrient loads from such misconnections even under least-impact conditions are likely to prejudice receiving water standards and require substantial dilutions in the order of 50-100:1 to conform to ecological criteria. Even at these elevated dilution ratios, PO_4-P is only expected to achieve a poor quality status in the receiving water confirming this pollutant as a major reason for urban diffuse pollution failures. Remediation options for specific offending source appliances would need to reduce their discharge loads by values approaching 98% to achieve appropriate water quality conditions although this would still be insufficient to address the pollution problems posed by PO_4-P for which the major sources are kitchen sinks, washing machines and dishwashers. Adopting a treatment option would require a large treatment works with a population equivalent value of 900000 to effectively minimise the pollution loads arising from the misconnections associated with an urban population equivalent to that of Greater London but specialist phosphate removal facilities would need to be installed to achieve PO_4-P compliance. The micro-component approach to water usage and household misconnection loadings emphasises the need for targeted measures based on the identification and quantification of specific diffuse pollution measures to in-stream urban quality objectives.

The innovative methodological approach outlined in the paper is simple and rapid to apply as well as being readily understandable and provides a robust procedure for the quantification of surface water misconnections loadings to urban receiving waters. It further offers a baseline for the extrapolated quantification of large catchment-scale loads utilising evidence-based surveys of domestic micro-component occurrence and operation. This micro-component approach allows small (but detailed) sub-catchment data to be used for screening purposes in the initial strategic policy decisions on risk assessment for urban diffuse discharges.

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