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Domestic Source of Phosphorus to Sewage Treatment Works

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Abstract

Phosphorus is an element essential for life. Concerns regarding long term security of supply and issues related to eutrophication of surface waters once released into the aquatic environment, have led Governments considering and applying measures for reducing the use and discharge of phosphorus. Examples of source control include legislation to reduce phosphorus use in domestic detergents. This research shows that other domestic sources of phosphorus also contribute significantly to the domestic load to sewer and that overall, domestic sources dominate loads to sewage treatment works. Estimates provided here show that although the natural diet contributes 40% of the domestic phosphorus load, other potentially preventable sources contribute significantly to the estimated 44,000 tonnes of phosphorus

entering UK sewage treatment works each year. In the UK, food additives are estimated to contribute 29% of the domestic load, automatic dishwashing detergents contribute 9% and potentially increasing, domestic laundry 14% including contributions from phosphonates, but decreasing, phosphorus dosing to reduce lead levels in tap water 6%, food waste disposed of down the drain 1% and personal care products 1%. Although UK data is presented here, it is anticipated that similar impacts would be expected for other developed economies. Consideration of alternatives to all preventable sources of phosphorus from these sources would therefore offer potentially significant reductions in phosphorus loads to sewage treatment works and hence to the aquatic environment. Combining all source control measures and applying them to their maximum extent could potentially lead to the prevention of over 22,000 tonnes-P/year entering STW.

Introduction

Phosphorus is a naturally occurring element essential to life on earth, however, there are concerns regarding long term sustainability and reliability of supply [1]. Although essential for life, the release of excessive amounts of phosphorus into the aquatic environment via diffuse agricultural inputs or via sewage treatment works (STW) can lead to eutrophication, where by excessive growth of algae can lead to reductions in biodiversity or even death of fish populations in severe cases. The European Water Framework Directive (WFD, Directive 2000/60/EC) and other regulation such as the Urban Wastewater Treatment Directive (UWWTD, Directive 91/271/EEC) and the Habitats Directive (Directive 92/43/EEC) place pressure on dischargers to the aquatic environment to reduce inputs of phosphorus (P), amongst other substances. A 2006 report by the UK Technical Advisory Group (UKTAG), supported by river basin characterisation exercises which place water bodies into high, good, moderate, poor and bad categories, predicted that a large percentage of water bodies in England and a smaller number in Wales, Scotland and Northern Ireland are failing to achieve “good status” for phosphorus, as required under the WFD [2]. Data for 2008 available from the Environment Agency reports that 51% of English rivers had phosphorus concentrations considered to be ‘high’ in other words greater than 0.1 mg/l [3]. In order to work towards achieving good status, varied mitigation measures will need to be identified by the Regulators (in consultation with stakeholders) to further reduce inputs of phosphorus to surface waters.

To ensure that the measures meet their objectives without incurring disproportionate costs to industry and in particular, the water industry, it is essential to derive accurate source apportionment data, so that decisions made by the regulators provide the expected environmental benefits. Measures to reduce chemical loads discharged to surface waters include (i) source control, (ii) end-of-pipe treatment at sewage treatment works and (iii) control of agricultural runoff. The most cost effective option depends on the use patterns of the chemical (whether they are used for specific purposes only or are used broadly) and how they are released into the environment (from point sources, such as STWs, or diffuse sources, e.g. agricultural run-off). For phosphorus, inputs to the environment are numerous, but, in terms of overall loads to water bodies in the UK, are dominated by point source discharges from STW and diffuse inputs from agriculture [4].

Control of industrial discharges of phosphorus to sewer is not likely to have a substantial impact because these sources are relatively minor [5]. However, benefits may be derived by applying source control measures through the reduction or removal of phosphorus-based chemicals in domestic products and wastewater. Concern regarding eutrophication of surface waters has led to a decline in usage of phosphates in laundry products (typically with zeolite-based products) culminating with the UK government deciding to limit the weight of inorganic phosphate expressed as phosphorus in domestic laundry detergents to no more that 0.4% of the weight of the detergent. Paragraph 9 of the Detergents Regulations 2010 states that it will be prohibited to place on the market a domestic laundry detergent that fails to comply with this requirement after 1 January 2015 [6]. Phosphorus, however, is still a major constituent of automatic dishwasher detergents (often present at around 30% phosphate by weight) and is still used in the form of phosphonates (generally present as less than 5% by weight) in domestic laundry cleaning products. Phosphorus is present as a food additive in processed meats and other food products. Phosphates are also added to the water supply across most of the UK in order to ensure compliance with a new drinking water standard for lead of 10 μg/l to be introduced in December 2013 in line with World Health Organisation guidelines [7].

In order to safeguard future supplies of phosphorus as well as to make cost effective decisions regarding further reductions of phosphorus discharges to surface waters, it is first necessary accurately to quantify the most significant sources. In this study, a mass balance of phosphorus sources to STW from domestic sources is undertaken based on work sponsored by UK Water Industry Research (UKWIR) in conjunction with Scotland and Northern Ireland Forum for Environmental Research (SNIFFER) and UKTAG supported by the Environment Agency and the Scottish Environmental Protection Agency (SEPA).

Methods

To generate a mass balance for the domestic loads of phosphorus to STW a number of approaches are required utilising a broad dataset of statistics and assumptions. These are described in the following methodology section.

Phosphorus in personal care products

Phosphorus is rarely used in personal care products such as hair shampoo, conditioner, shower gel and body soap [8]. However, where added, the most common form of phosphorus found is cocamidopropyl PG-dimonium chloride phosphate [7]. Traces of this compound are also found in some hair shampoos, hand soaps, some styling gels and lotions, and hairspray. Traces of sodium diethylenetriamine pentamethylene phosphate are also used in some hair care products, although at very low concentrations. Considering that only trace amounts of phosphorus are used in these products, their contribution to the load to sewer was considered insignificant.

Certain toothpastes contain phosphorus-based ingredients at low concentrations mostly, tetra sodium pyrophosphate, dicalcium phosphate and pentasodium triphosphate and disodium phosphate (Table 1). In most fluorinated toothpastes the active ingredient is sodium fluoride, however, in a limited number of products sodium monofluorophosphate is used and an exact concentration given on the packaging. A survey of the UK market identified 42 common products from 5 companies. Of the 42 products, 12 contained no phosphate, with the others using a range of the aforementioned phosphates. Taking account of the number of products containing each of these substances and the likely percentages of the compounds present in toothpaste (1.6 to 2.5 mg-P/kg, with a mean of 2.1 mg-P/kg, based on concentrations provided on the packets) it was possible to estimate the phosphorus content. In the absence of marketing data, it was assumed that the 42 products had equal market share and so a load was calculated using the ratio of the number of products containing phosphate multiplied by the estimated concentration (converted to P) and finally multiplied by an assumed usage per day (5 g toothpaste per person) to derive a *per person* per day load to sewer (Table 1).

- Table 1 here -

To test the sensitivity of the calculated load a predicted value was generated assuming phosphate concentrations in toothpastes at the highest and lowest reported concentrations.

Phosphorus in foods

Phosphorus is very widely distributed in both plant and animal foods and is an important mineral for many essential processes in the body. In combination with calcium it is necessary for the formation of bones and teeth. Phosphorus is also involved in the metabolism of fat, carbohydrate and protein, and is essential for efficient absorption of B-group vitamins and in energy metabolism [9]. A review of the available data on the phosphorus content of a range of food and drink was conducted, along with an evaluation of a survey of annual food consumption. Table 2 presents the average consumption, average phosphorus content and estimated intake of phosphorus from that food. As the phosphorus content of a food will vary according to the processing, cooking or quality of the product, an average value was used. Results from Table 2 indicate an average phosphorus intake from food of around 1.3 g-TP/person/day of which the majority comes from cereals, dairy and meat products.

- Table 2 here -

In 2003 the National Diet and Nutrition Survey estimated the mean daily intake of phosphorus from food sources for men and women around 1.5 g and 1.1 g of phosphorus respectively [15]. Assuming a 50:50 population of males and females, an average phosphorus intake from food can be estimated around 1.3 mg-TP/person/day. This compares well with the value estimated in Table 2.

Elemental phosphorus and phosphates also occur in multi-vitamin and mineral supplements at levels between 0.0008 to 0.14 g [16]. Phosphorus intake from dietary supplements varies in the population; older people tend to have the highest consumption and younger people the lowest. An average phosphorus intake from dietary supplement can be estimated between 0.055 and 0.070 g-P/person/day (a mean of 0.0625 g-P/person/day), [16].

Besides phosphorus derived from unprocessed foods, there is a significant intake of phosphorus via additives in drinks and processed meats amounting to an estimated 0.59 g-P/person/day (Table 3). Adding phosphorus derived from natural products, food additives and dietary supplements generates a total of 1.95 g-P/person/day ingested.

- Table 3 here –

The phosphate supplements used within food products (Table 3) are a mixture of soluble and insoluble substances (when ingested) and so it was assumed that for the purposes of source apportionment, they are excreted in urine and faeces on a 50:50 basis.

Phosphorus in detergents

Phosphates (sodium tripolyphosphate – 25% P for dry detergents or sodium/potassium phosphates for liquid detergents – 19% P for trisodium phosphate) have been traditionally used in detergents as builders, binding polyvalent cations such as calcium and magnesium ions, which otherwise interfere with the surfactant's properties.

The use of phosphate in household detergents has reduced in recent decades [18]. In the 1990s, legislation and voluntary agreements in the EU encouraged the development of alternative non-phosphate laundry detergents. These phosphate free laundry products use zeolite-based detergents together with the associated necessary co-builders. The detergent industry has sought to reduce or replace phosphate in laundry products since alternative products are now available and already dominate the market [19], with levels to be limited to a maximum of 0.4% as of 2015 [18]. Consequently, phosphorus-based laundry detergents tend now to be restricted to use in some tablet formulations and in supermarket 'own-label' brands. Earlier studies have shown that over the last decade the phosphate based products in laundry detergent have been reducing with estimates of them only representing between 19 % [20] and 45 % [21] of the market in the UK. As the ban on phosphate-based laundry cleaning products approaches, this value is expected to decrease further and the most up to date estimate of 3,360 tonnes-P/year was provided by the detergent industry for the Defra consultation on the phosphate ban [18]. Dividing this figure by the estimated UK population connected to sewer of 59,382,016 provides an estimate of 0.155 g-P/person/day [22].

The automatic dishwashing detergent market evolved separately from that of laundry detergents. It is currently the view of the detergent industry that phosphate alternatives for automatic dishwashing detergents are inferior and therefore require greater energy during the washing process [19]. The use of phosphorus based products for automatic dishwashers is therefore very high and represents 96% of the current UK market share in terms of product sold [23]. The percentage of phosphate in phosphorus based domestic detergent products is around 30%, mainly in the form of sodium tripolyphosphate or tri sodium phosphates [24]. A low and high estimate of automatic dishwashing phosphorus used in the UK of 3,600 and 4,000 tonnes-P/year has been estimated [18]. Taking an average value of 3,800 tonnes of phosphorus/year and dividing by the UK population connected to sewer generates an estimate of 0.175 g-P/person/day.

Phosphonates are also often found in household detergent products. The most common phosphonates used as chelating agents and scale inhibitors are:

- aminotris(methylene phosphonic acid) (ATMP) – 31% P,
- 1-hydroxyethylidene diphosphonic acid (HEDP) – 28% P and
- diethylenetriamine penta(methylene phosphonic acid (DTPMP) – 27% P

An average P content in phosphonate detergents was therefore calculated as 29% and used for subsequent calculations. It has been reported that 81% of laundry products and 4% of dishwasher products contain phosphonates, at a typical concentration of 2.5% phosphonate by weight [24] significantly less than phosphates where present.

Based on assumptions regarding per person use of detergents (2.1 g/d automatic dishwashing detergent; 20.8 g/d laundry detergent), the percentage of products containing phosphonates (4% for automatic dishwashers and 81% of laundry detergents), the possible phosphonate content (assumed to be 30% for all detergents where phosphonates are used) and its composition (29% P), it is possible to estimate a per person per day loading of phosphonates to sewer of 0.0006 g-P/person/day for automatic dishwashing detergents and 0.12 g/person/day for laundry detergents (Table 4).

- Table 4 here -

Water supply source of phosphorus

To meet new WHO drinking water standards for lead in the UK (25 µg-Pb/l until December 2013; 10 µg-Pb/l thereafter) phosphate is dosed into the main water supply. The majority of the UK's water supply is now dosed with between 1 and 2 mg-TP/l as orthophosphoric acid or sodium phosphate [26]. Not all of the added phosphate reacts with the lead present in the plumbing pipework and after sufficient time, an equilibrium concentration at the tap is achieved (i.e. the concentration dosed will equal the concentration observed at the tap) which can allow dosing concentrations to be reduced, whilst still maintaining compliance with the lead standard. As a consequence residual concentrations will be discharged to sewer, via the water supply. A maximum level of phosphorus at the tap allowed under the Drinking Water Directive is 2.2 mg/l [26].

A recent survey of 13 water companies serving a population of 40 million reported 91% of that population to be receiving phosphorus-dosed water. Average target concentrations per company ranged by a factor of around two from ca. 0.7 mg/l phosphorus to up to 1.9 mg/l, with an average dose across all 13 companies being 0.91 mg-P/l [26]. This range is likely to reflect chemical factors influencing plumbosolvency as well as background levels of phosphate in the raw water. For the source apportionment exercise the average concentration was used and converted to a per person load to sewer by calculating a load based on an assumption of 91% of the population receiving tapwater containing an average of 0.91-mg-P/l and using 150 l/person/day, then dividing by the UK population connected to sewer [26]. This generates a value of 0.13 g-P/person/day. In terms of total load to STW, however, it should be noted that not just domestic water supply is dosed with phosphorus, all water supplied to a catchment is actually dosed, including that supplied to offices, industry and commercial premises and so the overall contribution to STW is actually higher.

Food waste

A recent Waste Resources Action Programme (WRAP) survey estimated food waste disposed to sewer for the UK and included annual figures for a range of food stuffs including carbonated drinks, milk, cereals, gravy, puddings and fruit drinks [27]. These figures were matched to phosphorus content presented in Table 2 in order to estimate tonnes of phosphorus from domestic food waste discharged to sewer. In total over a million tonnes of products were calculated to be disposed down the drain to sewer in the UK, amounting to an estimated 567 tonnes of phosphorus per year; equivalent to 0.03 g/person/day.

Human excreta

The human body requires typically 0.55 g-P/day [28], the rest is excreted in faeces or urine. The amount of phosphorus excreted by a person depends upon the diet and age of the individual. Studies have indicated that for a western population, the average amount of phosphorus in urine is in the region of 0.9 g-P/person/day and in faeces 0.5 g-P/person/day [29, 30]. In the absence of data to accurately apportion food additives between the urine and faeces, it was assumed that the phosphorus-based additives consumed as part of the daily diet were excreted in equal proportions between the urine and faeces. Earlier apportionment exercises assumed all of the additives would be excreted in the urine [22] but there was no actual basis for this assumption.

Total domestic contribution of phosphorus load to STW

In order to put domestic contribution to STW into perspective, it is necessary to estimate loads entering an STW. The key parameters for accurate estimates of phosphorus loads to STW are the volume of wastewater entering a STW per person (a sum of domestic, infiltration, runoff, commercial and industrial flows) and the mean concentration of phosphorus in crude sewage. Based on a per person volume to STW of 250 l/person/day and a reported influent phosphorus concentration of 8.25 mg-P/l [22] it is possible to calculate a per person contribution to STW of 2.3 g-P/person/day.

Source apportionment

Table 5 presents the data used for calculating loads to sewer. By combining estimates of per person phosphorus load discharged to sewer from domestic households with the population served by mains sewerage, loads of phosphorus to sewer on a tonnes/year basis can be generated. Furthermore, based on information regarding estimates of total per person flow to STW and measured concentrations, a total load to STW can also be calculated. This allows domestic loads to be put into perspective regarding their significance of the overall load being received for treatment at the STW.

- Table 5 here -

Results

Faeces and urine combined (including the contribution of food additives) contribute 69% of the overall load to sewer from domestic sources; with contributions from the 'natural' diet of 40% of the domestic load (Figure 1).

- Figure 1 here -

After removing half the contribution of food additives to measured urine loads to sewer (unlike earlier studies where all food additive contributions were subtracted from the overall urine load – [22]), urine is still the predominant source of phosphorus contributing an estimated 30% considered to be derived from a 'natural diet'. Additives to food and drinks, however, are estimated to contribute a significant phosphorus source from domestic inputs to sewer (29%). The total excretion rate of 1.4 g-P/person/day added to the average daily requirement of 0.55 g-P/person/day adds up to a total phosphorus intake of 1.95 mg-P/person/day which compares well with the overall estimated dietary intake of natural diet (1.32 g-P/person/day), supplements (0.0625 g-P/person/day) and food additives (0.59 g-P/person/day) of 1.97 g-P/person/day). The closeness of the two estimates generated independently provides confidence in the loads calculated and suggests that the apportionment from human sources, particularly the relatively high input from food additives are of the correct order. Inputs from laundry and dishwashing detergents and tap water dosing range from 6% to 14%, with food scraps and personal care products of minor significance. Excluding phosphonates from the apportionment reduces the contribution of domestic laundry cleaning products to 8%.

For toothpastes, classified as 'personal care products', loads to sewer from domestic sources were considered to be extremely low (approximately 1.5 % of total domestic load to sewer) compared with other inputs dominated by human sources. A sensitivity test assuming all phosphate-containing products had phosphorus concentrations at the lowest and highest concentration generated a load between 0.009 and 0.05 mg-P/person/day (equivalent to between 0.4% and 2.4% of the overall load).

Loads for each source may be calculated and percentage contribution derived (Table 5). In addition, by estimating total loads entering STW based on multiplying measured influent concentrations (8.25 mg-P/l) by total population connected to the sewer and estimate per person flow to UK STW (150 l/person/day) it is possible to determine the significance of the domestic load. Table 6 shows that approximately 44,000 tonnes of phosphorus are discharged to sewer each year from domestic sources. Compared with estimates of total loads to sewer, domestic sources are estimated to contribute the entirety of the input. However, it should be noted that a proportion of the phosphorus discharged to sewer will be lost via combined sewer overflows (CSOs) which discharge directly to surface water when storm events lead to rainfall volumes entering combined sewerage systems exceeding its capacity. Recent source apportionment modelling for the UK (unpublished data) suggests that as much as ~85 tonnes-P/year may be lost to surface water from domestic sources. A further loss from the sewerage system is as a result of misconnections, where wastewater is inadvertently plumbed into surface water drains. A value of 5% of the load has been previously estimated as the possible load lost via misconnections [18], although it was acknowledged that no reliable data exists. Using these figures reduces the domestic load to STW to approximately 42,000 tonnes-P/year equivalent to 93% of the total load estimated to enter STW. These estimates suggest that inputs from surface water runoff, industrial and commercial (town centre) sources are not significant. This prediction is considered further in the discussion below.

- Table 6 here -

Discussion

From a phosphorus management point of view a number of key observations may be made based on the results presented above. Firstly, for regulators it appears that inputs via food additives ingested then excreted is a potentially significant domestic source of phosphorus to STW. Although the HMSO report was published in 1993, more recent data from around the world corroborates the fact that the dietary intake of phosphorus via additives is significant. Uribarri and Calvo [33] report that additives present in restructured meat (e.g. chicken nuggets and hot dogs) processed and spreadable cheeses, 'instant' puddings and sauces could elevate phosphorus sources in the diet to 0.47 g-P/day, but depending on the diet could increase intake by as much as 1.0 g-P/day. It needs to be noted that diets vary considerably between countries, with America sitting at an extreme end of the spectrum of natural to processed food diet; however, similar findings have been published in Spain [34] and Brazil [35]. There are no recent reports for dietary intake of phosphorus in the UK, but as the UK tends towards a US-style dietary regime dominated by processed foods, phosphorus intake from food additives cannot be expected to decrease in the near future. Control of the use of phosphorus-based additives in foods could therefore offer an important policy option for the reduction of phosphorus loads entering STW. The phosphorus is added to foods primarily for aesthetic and preservation reasons, to maintain 'juiciness', as an emulsion stabiliser, in cure colour development and extend shelf life or in colas where it is used as an acidity regulator. In many cases, a move away from processed foods or use of alternatives would reduce phosphorus from this source.

Food disposed to sewer is estimated to total 567 tonnes/year, amounting to only 1.3% of the total domestic load, although, it is largely avoidable. There are no other UK data to support these estimates; the only available data for phosphorus discharged in food waste to sewer specifically are over 10 years old at the very least and for non-UK locations. These put estimates between 0.1 and 0.4 g/person/day [36-38] compared with 0.03 g/person/day calculated for this source apportionment exercise. However, it may be considered that this older data may be out of date and not necessarily relevant to the UK situation as, unlike the UK, some countries use food disposal units which encourage the disposal of food waste to sewer. Overall, it was considered that the value generated for this project was more reliable and therefore used for source apportionment purposes.

The contribution of phosphorus from household detergents is a dynamic variable owing to the agreed restriction on phosphorus in laundry cleaning products in the UK as of 2015, where phosphorus content (as phosphates) will be limited to a maximum 0.4% by weight. This combined with a voluntary move towards phosphate-free, zeolite-based alternatives in laundry detergents over the past two decades has seen the contribution of this source to phosphorus loads to sewer decrease significantly. However, the 'phosphate free' detergents do contain a small proportion of phosphonates (typically 2.5% by weight in the detergent product) which contain phosphorus (typically 29% P) in a form considered to have less impact on the aquatic environment owing to its likely accumulation in sludge rather than discharge into water via effluents [24]. Consequently, contributions of phosphorus to domestic loads from this source will not decrease to zero. A current estimate of 0.12 g-P/person/day corresponds to an approximate 7% contribution of domestic phosphorus loads to sewer from domestic laundry detergents, assuming 81% of laundry detergents contain phosphonates [25]. Assuming a 100% usage would increase loads to 0.15 g-P/person/day and the overall contribution to phosphorus loads to sewer to 8%.

Automatic dishwashing detergents are estimated to contribute 8.7% of the phosphorus load to sewer from domestic sources but that figure is expected to rise over time as the market is currently dominated by phosphorus-based detergents (96% of the market) and the ownership of dishwashers is continuing to rise in the UK, from the currently estimated rate of 40% household ownership at the moment [22]. There is the potential for a doubling of the contribution from this source as the market comes to maturity in the future. Many other countries in Europe and elsewhere have already put restrictions on phosphorus-based automatic dishwasher detergents and so there are already precedents for switching to alternatives, although there are concerns from the phosphate industry that alternative products are inferior in their effectiveness [39].

In the UK 91% of potable water is dosed with typically 1 mg-P/l to meet forthcoming drinking water standards for lead which are being reduced to 10 µg/l in December 2013. The phosphorus dosed into the mains supply at water treatment works reacts with lead to form insoluble phosphate minerals and so prevent the dissolution into the water supply. The method is highly effective with 99% compliance with the standard [26]. Phosphorus dosing is employed owing to the cost of finding and replacing residual lead pipework both external to and within properties. In the UK water companies are responsible for lead pipe between the main and a property boundary, but the house owner is responsible for lead between the property boundary and the tap, where samples for compliance monitoring are taken. Without phosphorus dosing, to be completely effective in meeting the new lead standard, all residual lead pipe, as well as potentially lead soldered joints and brass fittings would need to be replaced [26]. Estimates for one water company serving a population of approximately 7 million, amounted to £890 million to replace company and householder lead pipes [26]. It is therefore considered that the currently most cost effective solution is to continue to dose with phosphorus. Recent advances in chemical lining technologies may, however, offer a cheaper alternative to lead pipe replacement and could find more widespread use in the future [26]. Assuming an average per person domestic daily use of drinking water of 150 litres, phosphorus contributions from this source to sewer loads is approximately 6% of the total domestic load. Earlier estimates for all tap water dosed for use by domestic, commercial, light industry and industrial use (amounting to 250 l/person/day) estimated loads contributing up to 10% to STW influent loads [22]. Given the reported concentration of phosphorus entering STW is approximately 8.25 mg-P/l and more up to date mean dosing concentrations are reported as 0.91 mg-P/l [26] then the overall contribution to STW loads is likely to be closer to 11%.

Comparing the domestic load with that predicted to be entering STW suggests that they comprise 93% of the total load to STW. Other potential sources of phosphorus to STW include road runoff, industrial sources (e.g. chemicals, food and drink, laundrettes, metal processing) and commercial and town centre activities such as bars, restaurants, offices, hospitals and car washes. However, road and roof runoff contributes a significant amount of the additional flow to STW which makes up the difference between the measured per person flow (250 l/day) and the domestic flow (150 l/d). Concentrations of phosphorus in runoff, however, are not particularly high. For example 0.66 mg-P/l has been reported for developed urban areas [40] around 10 times less than measured concentrations at STW. The load from this source is therefore unlikely to be a major contribution. Industrial discharges may have high phosphorus concentrations, but only contribute (generally) small flows to sewers compared with domestic discharges and runoff. It has been reported elsewhere that industrial contributions only account for 6% of the load to sewer, but will vary depending on the catchment [22]. The limited data therefore suggest that other contributions of phosphorus from sources other than domestic are relatively minor in magnitude.

Summing all of the domestic contributions comes to a total of ca. 42,000 tonnes-P/year entering STW after accounting for losses from CSOs and misconnections. The total load of phosphorus considered to be derived from preventable sources (tap water dosing, food additives and waste, detergents and personal care products) amounts to over 25,000 tonnes (including phosphonates), approximately 52% of the total load to STW. These estimates show the potential impact of source control on reducing the phosphorus load to STW should such measures be considered cost effective and can be employed to their maximum extent.

To meet EU legislation most UK STW serving populations over 10,000 apply some form of phosphorus reduction to meet effluent discharge limits of 1 or 2 mg-P/l. Consequently not all phosphorus entering a STW is discharged in the effluent, a significant proportion is present within the sludge. Estimates (2007) of the loads of phosphorus discharged into receiving waters suggest a range from 25,300 to 34,800 tonnes-P/year [41]. Phosphorus reduction at STW has been escalating under the WFD and so loads discharged from STW are continually reducing and so possibly tending towards the lower end of the estimated range reported. Overall loads of phosphorus to receiving waters and their impacts on compliance with WFD standards is the subject of a follow up paper to this one.

By comparison, it has been reported that almost 12,000 tonne-P/year are discharged to surface waters from agriculture [41]. Overall it is evident that source control has the potential to substantially reduce the loads of phosphorus to STW and thence to receiving waters.

Conclusion

As part of a balanced phosphorus management plan to reduce discharges to the environment which seeks the most cost effective measures to meet WFD water quality requirements and conserve reserves of an essential element, source control options will need to be considered in concert with end-of-pipe STW treatment and reductions in diffuse agricultural discharges. The data presented here suggests significant reductions in phosphorus loads to STW may be achieved by seeking alternatives to, or reductions in the use of phosphorus in automatic dishwashing detergents, dosing of tap water and in food additives. Complete elimination of phosphorus from these sources to sewer could provide up to around a 50% decrease in loads to sewer from domestic sources. The effectiveness of source control has been demonstrated in the UK (and other countries) via restrictions on the use of phosphorus in laundry detergents and many other countries have extended controls to phosphorus-based automatic dishwashing detergents. It is therefore recommended that in light of long term phosphorus management, both in terms of sustainability of supply and reducing environmental impacts, further source control options should be considered as part of WFD programmes of measures.

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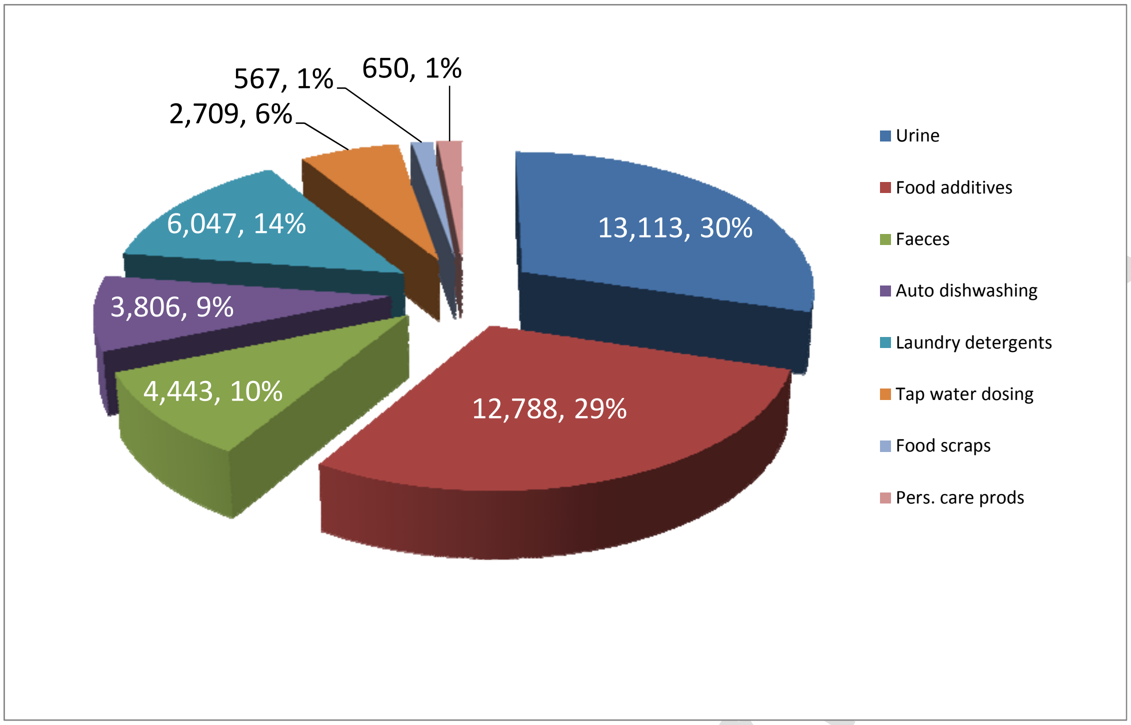

Figure 1 Tonnes-P/year discharged to sewer from domestic sources and % contribution to total load (food additive sources have been separated from urine and faeces loads)

Table 1 Phosphorus in toothpaste contribution to loads to sewer

Substance	No. of products containing phosphates	Approximate % in product	Average P content (mg-P/g)[a]	g-P/person/day[b]
Phosphate-free	12			
Sodium Monofluorophosphate	9		1.98	0.0022
Dicalcium Phosphate Dihydrate	4	2.5	4.5	0.0021
Tetrasodium Pyrophosphate	7	3	14	0.012
Disodium Pyrophosphate	2	2	5.6	0.0013
Trisodium Phosphate	3	1.5	8.5	0.0030
Penta Sodium Triphosphate	5	1	2.5	0.0015
Total	**42**			**0.022**

[a] taking account of phosphorus content in each of the chemical multiplied by the percentage of the chemical in the product.
[b] assumes 5 g of toothpaste used per person per day, and all of phosphate containing product is released to sewer.

Table 2 **Source of phosphorus in the average British diet (excluding additives)**

	Average consumption (g/d) [9]	P content (mg/100g) [10, 11, 12]	P intake (g/d)	% of daily intake
Cereals	252	130	0.328	**25**
of which				
- Bread	*110*	*120*	*0.132*	*10*
Meat & meat products	161	200	0.322	**24**
Milk & cream	290	95	0.276	**21**
of which				
- whole milk	*68*	*93*	*0.063*	*5*
- semi-skimmed milk	*134*	*94*	*0.126*	*9*
- skimmed milk	*30*	*94*	*0.028*	*2*
- yogurt	*28*	*98*	*0.028*	*2*
Cheese	20	500	0.100	**8**
Potatoes (fresh & processed)	131	60	0.079	**6**
Fish	26	215	0.056	**4**
Alcoholic drinks	191	25	0.048	**4**
of which				
- beers & lagers	*97*	*25*	*0.024*	*2*
Soft drinks	295	15	0.044	**3**
Fruit	185	20	0.037	**3**
of which				
- Fresh apples	*26*	*10*	*0.003*	*0*
- Pure fruit juices	*50*	*17*	*0.009*	*1*
Vegetables excluding potatoes	26	30	0.008	**1**
Confectionery	20	90	0.018	**1**
Eggs	0.23	210	0	**0**
Fats	26	0	0	**0**
of which				
- Butter	*5*	*0*	*0*	*0*
Beverages	26	10	0.003	**0**
Sugar & preserves	18	0	0	**0**
Ice cream, desserts & cakes	4	100	0.004	**0**
Total P intake from food			**1.32**	**g-P/capita/d**
Total P intake from food & dietary supplements [13]			**1.38 – 1.39**	**g-P/capita/d**

Table 3 **Phosphorus additive intake via diet Data from [17] and there in**

Additive Name	Number	Dietary intake (g-P/person/d)
Sodium and potassium diphosphates	E450a	0.26
Calcium orthophosphates	E341	0.15

Sodium and potassium triphosphates	E450b	0.06
Sodium orthophosphates	E339	0.03
Ammonium phosphatides	E442	0.03
Sodium and potassium polyphosphates	E450c	0.03
Orthophosphoric acid	E338	0.022
Potassium orthophosphates	E340	0.008
Sodium aluminium phosphate basic	E541	0.001
Riboflavin 5’-phosphate	E101	0.00005
Edible bone phosphate	E542	0.0002
Inosine 5- (disodium phosphate)	E631	0.0001
Guanosine 5- (disodium phosphate)	E627	Trace
Total		**0.59**

Table 4 Use of phosphonate based detergents in households in the UK and estimated levels of phosphorus released to sewer.

	Dishwashers	Laundry
Weight of detergent used	20 g*	88 g**
Number of washes per day per household [25]	0.7	0.6
% of population using dishwashers/washing machines [24]	36	100
Average household occupancy***	2.36	2.36
Total detergent released to sewer per person per day	*2.1 g*	*21.5 g*
Percentage of phosphonates [24]	4	81
Percentage of phosphonates in products [24]	2.5	2.5
Amount of phosphorus discharged per person per day derived from use of phosphonates (g-P/capita/day)	***0.0006***	***0.12***

* Standard mass of tablet. **Manufacturer data for moderately hard waters. *** UK 2011 Census data.

Table 5 Data used for calculating phosphorus loads to sewer

General	Data	Units
UK population*	61,791,900	
UK connected population [31]	59,382,016	
Assumed average flow to WwTW per capita per day [22]	250	l/capita/day
Domestic water use [32]	150	l/capita/day
Occupancy*	2.36	
Measured influent P concentration [22]	8.25 +/- 0.9**	mg-P/l

* UK 2011 Census data. ** 95th percentile confidence limits on average measured total phosphorus at 133 STW

Table 6 Estimation of domestic phosphorus load to UK STW

Phosphate discharges	P type	Per capita discharge to sewer (g-P/capita/day)	Annual load to sewer (tonnes-P/yr)
Food additives		0.59	12,788
Faeces		0.21	4,443
Urine		0.61	13,113
Washing machines	Phosphates	0.155	3,360
	Phosphonates	0.12	2,688
Auto dishwasher	Phosphates	0.175	3,793
	Phosphonates	0.0006	13
P dosing of tap water		0.125	2,709
Food scraps		0.10	567
Personal care products		0.022	477
Total domestic load to sewer		**2.03**	**43,951**
Potential loss from mis-connections			2,449
Possible loss via CSOs			85
Estimate of domestic load to STW			41,678
Total measured load to STW		mean	44,714
Domestic sources as % of total load			93%