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Key words: Phosphorus, source, apportionment, domestic, sewage, loads

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

28 entering UK sewage treatment works each year. In the UK, food additives are estimated to contribute
29 29% of the domestic load, automatic dishwashing detergents contribute 9% and potentially increasing,
30 domestic laundry 14% including contributions from phosphonates, but decreasing, phosphorus dosing to
31 reduce lead levels in tap water 6%, food waste disposed of down the drain 1% and personal care products
32 1%. Although UK data is presented here, it is anticipated that similar impacts would be expected for other
33 developed economies. Consideration of alternatives to all preventable sources of phosphorus from these
34 sources would therefore offer potentially significant reductions in phosphorus loads to sewage treatment
35 works and hence to the aquatic environment. Combining all source control measures and applying them
36 to their maximum extent could potentially lead to the prevention of over 22,000 tonnes-P/year entering
37 STW.

39 **Introduction**

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

54 work towards achieving good status, varied mitigation measures will need to be identified by the
55 Regulators (in consultation with stakeholders) to further reduce inputs of phosphorus to surface waters.

56

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

67

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

81 new drinking water standard for lead of 10 µg/l to be introduced in December 2013 in line with World
82 Health Organisation guidelines [7].

83
84 In order to safeguard future supplies of phosphorus as well as to make cost effective decisions regarding
85 further reductions of phosphorus discharges to surface waters, it is first necessary accurately to quantify
86 the most significant sources. In this study, a mass balance of phosphorus sources to STW from domestic
87 sources is undertaken based on work sponsored by UK Water Industry Research (UKWIR) in conjunction
88 with Scotland and Northern Ireland Forum for Environmental Research (SNIFFER) and UKTAG
89 supported by the Environment Agency and the Scottish Environmental Protection Agency (SEPA).

90
91 **Methods**
92 To generate a mass balance for the domestic loads of phosphorus to STW a number of approaches are
93 required utilising a broad dataset of statistics and assumptions. These are described in the following
94 methodology section.

96 *Phosphorus in personal care products*

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

104
105 Certain toothpastes contain phosphorus-based ingredients at low concentrations mostly, tetra sodium
106 pyrophosphate, dicalcium phosphate and pentasodium triphosphate and disodium phosphate (Table 1). In
107 most fluorinated toothpastes the active ingredient is sodium fluoride, however, in a limited number of

108 products sodium monofluorophosphate is used and an exact concentration given on the packaging. A
109 survey of the UK market identified 42 common products from 5 companies. Of the 42 products, 12
110 contained no phosphate, with the others using a range of the aforementioned phosphates. Taking account
111 of the number of products containing each of these substances and the likely percentages of the
112 compounds present in toothpaste (1.6 to 2.5 mg-P/kg, with a mean of 2.1 mg-P/kg, based on
113 concentrations provided on the packets) it was possible to estimate the phosphorus content. In the absence
114 of marketing data, it was assumed that the 42 products had equal market share and so a load was
115 calculated using the ratio of the number of products containing phosphate multiplied by the estimated
116 concentration (converted to P) and finally multiplied by an assumed usage per day (5 g toothpaste per
117 person) to derive a *per person* per day load to sewer (Table 1).

118
119 **- Table 1 here -**
120

121 To test the sensitivity of the calculated load a predicted value was generated assuming phosphate
122 concentrations in toothpastes at the highest and lowest reported concentrations.
123

124 ***Phosphorus in foods***

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

135

136

- Table 2 here -

137

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

142

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

148

149 Besides phosphorus derived from unprocessed foods, there is a significant intake of phosphorus via
150 additives in drinks and processed meats amounting to an estimated 0.59 g-P/person/day (Table 3). Adding
151 phosphorus derived from natural products, food additives and dietary supplements generates a total of
152 1.95 g-P/person/day ingested.

153

154

- Table 3 here -

155

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

159

160 *Phosphorus in detergents*

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

165
166 The use of phosphate in household detergents has reduced in recent decades [18]. In the 1990s, legislation
167 and voluntary agreements in the EU encouraged the development of alternative non-phosphate laundry
168 detergents. These phosphate free laundry products use zeolite-based detergents together with the
169 associated necessary co-builders. The detergent industry has sought to reduce or replace phosphate in
170 laundry products since alternative products are now available and already dominate the market [19], with
171 levels to be limited to a maximum of 0.4% as of 2015 [18]. Consequently, phosphorus-based laundry
172 detergents tend now to be restricted to use in some tablet formulations and in supermarket 'own-label'
173 brands. Earlier studies have shown that over the last decade the phosphate based products in laundry
174 detergent have been reducing with estimates of them only representing between 19 % [20] and 45 % [21]
175 of the market in the UK. As the ban on phosphate-based laundry cleaning products approaches, this value
176 is expected to decrease further and the most up to date estimate of 3,360 tonnes-P/year was provided by
177 the detergent industry for the Defra consultation on the phosphate ban [18]. Dividing this figure by the
178 estimated UK population connected to sewer of 59,382,016 provides an estimate of 0.155 g-P/person/day
179 [22].

180
181 The automatic dishwashing detergent market evolved separately from that of laundry detergents. It is
182 currently the view of the detergent industry that phosphate alternatives for automatic dishwashing
183 detergents are inferior and therefore require greater energy during the washing process [19]. The use of
184 phosphorus based products for automatic dishwashers is therefore very high and represents 96% of the
185 current UK market share in terms of product sold [23]. The percentage of phosphate in phosphorus based
186 domestic detergent products is around 30%, mainly in the form of sodium tripolyphosphate or tri sodium
187 phosphates [24]. A low and high estimate of automatic dishwashing phosphorus used in the UK of 3,600

188 and 4,000 tonnes-P/year has been estimated [18]. Taking an average value of 3,800 tonnes of
189 phosphorus/year and dividing by the UK population connected to sewer generates an estimate of 0.175 g-
190 P/person/day.

191
192 Phosphonates are also often found in household detergent products. The most common phosphonates
193 used as chelating agents and scale inhibitors are:

- 194 • aminotris(methylene phosphonic acid) (ATMP) – 31% P,
- 195 • 1-hydroxyethylidene diphosphonic acid (HEDP) – 28% P and
- 196 • diethylenetriamine penta(methylene phosphonic acid) (DTPMP) – 27% P

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

201
202 Based on assumptions regarding per person use of detergents (2.1 g/d automatic dishwashing detergent;
203 20.8 g/d laundry detergent), the percentage of products containing phosphonates (4% for automatic
204 dishwashers and 81% of laundry detergents), the possible phosphonate content (assumed to be 30% for all
205 detergents where phosphonates are used) and its composition (29% P), it is possible to estimate a per
206 person per day loading of phosphonates to sewer of 0.0006 g-P/person/day for automatic dishwashing
207 detergents and 0.12 g/person/day for laundry detergents (Table 4).

208
209 **- Table 4 here -**

210 211 *Water supply source of phosphorus*

212 To meet new WHO drinking water standards for lead in the UK (25 µg-Pb/l until December 2013; 10 µg-
213 Pb/l thereafter) phosphate is dosed into the main water supply. The majority of the UK's water supply is
214 now dosed with between 1 and 2 mg-TP/l as orthophosphoric acid or sodium phosphate [26]. Not all of

215 the added phosphate reacts with the lead present in the plumbing pipework and after sufficient time, an
216 equilibrium concentration at the tap is achieved (i.e. the concentration dosed will equal the concentration
217 observed at the tap) which can allow dosing concentrations to be reduced, whilst still maintaining
218 compliance with the lead standard. As a consequence residual concentrations will be discharged to sewer,
219 via the water supply. A maximum level of phosphorus at the tap allowed under the Drinking Water
220 Directive is 2.2 mg/l [26].

221
222 A recent survey of 13 water companies serving a population of 40 million reported 91% of that
223 population to be receiving phosphorus-dosed water. Average target concentrations per company ranged
224 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
225 13 companies being 0.91 mg-P/l [26]. This range is likely to reflect chemical factors influencing
226 plumbosolvency as well as background levels of phosphate in the raw water. For the source
227 apportionment exercise the average concentration was used and converted to a per person load to sewer
228 by calculating a load based on an assumption of 91% of the population receiving tapwater containing an
229 average of 0.91-mg-P/l and using 150 l/person/day, then dividing by the UK population connected to
230 sewer [26]. This generates a value of 0.13 g-P/person/day. In terms of total load to STW, however, it
231 should be noted that not just domestic water supply is dosed with phosphorus, all water supplied to a
232 catchment is actually dosed, including that supplied to offices, industry and commercial premises and so
233 the overall contribution to STW is actually higher.

234

235 ***Food waste***

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

242

243 ***Human excreta***

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

252

253 ***Total domestic contribution of phosphorus load to STW***

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

260

261 ***Source apportionment***

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

268

269 - Table 5 here -

270

271 **Results**

272

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

276

277 - Figure 1 here -

278

279 After removing half the contribution of food additives to measured urine loads to sewer (unlike earlier
280 studies where all food additive contributions were subtracted from the overall urine load – [22]), urine is
281 still the predominant source of phosphorus contributing an estimated 30% considered to be derived from
282 a 'natural diet'. Additives to food and drinks, however, are estimated to contribute a significant
283 phosphorus source from domestic inputs to sewer (29%). The total excretion rate of 1.4 g-P/person/day
284 added to the average daily requirement of 0.55 g-P/person/day adds up to a total phosphorus intake of
285 1.95 mg-P/person/day which compares well with the overall estimated dietary intake of natural diet (1.32
286 g-P/person/day), supplements (0.0625 g-P/person/day) and food additives (0.59 g-P/person/day) of 1.97
287 g-P/person/day). The closeness of the two estimates generated independently provides confidence in the
288 loads calculated and suggests that the apportionment from human sources, particularly the relatively high
289 input from food additives are of the correct order. Inputs from laundry and dishwashing detergents and
290 tap water dosing range from 6% to 14%, with food scraps and personal care products of minor
291 significance. Excluding phosphonates from the apportionment reduces the contribution of domestic
292 laundry cleaning products to 8%.

293

294

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

300

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

318

319

- Table 6 here -

320

321 **Discussion**

322

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

341

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

349 sewer. Overall, it was considered that the value generated for this project was more reliable and therefore
350 used for source apportionment purposes.

351

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

365

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

375

376 In the UK 91% of potable water is dosed with typically 1 mg-P/l to meet forthcoming drinking water
377 standards for lead which are being reduced to 10 $\mu\text{g/l}$ in December 2013. The phosphorus dosed into the
378 mains supply at water treatment works reacts with lead to form insoluble phosphate minerals and so
379 prevent the dissolution into the water supply. The method is highly effective with 99% compliance with
380 the standard [26]. Phosphorus dosing is employed owing to the cost of finding and replacing residual lead
381 pipework both external to and within properties. In the UK water companies are responsible for lead pipe
382 between the main and a property boundary, but the house owner is responsible for lead between the
383 property boundary and the tap, where samples for compliance monitoring are taken. Without phosphorus
384 dosing, to be completely effective in meeting the new lead standard, all residual lead pipe, as well as
385 potentially lead soldered joints and brass fittings would need to be replaced [26]. Estimates for one water
386 company serving a population of approximately 7 million, amounted to £890 million to replace company
387 and householder lead pipes [26]. It is therefore considered that the currently most cost effective solution is
388 to continue to dose with phosphorus. Recent advances in chemical lining technologies may, however,
389 offer a cheaper alternative to lead pipe replacement and could find more widespread use in the future
390 [26]. Assuming an average per person domestic daily use of drinking water of 150 litres, phosphorus
391 contributions from this source to sewer loads is approximately 6% of the total domestic load. Earlier
392 estimates for all tap water dosed for use by domestic, commercial, light industry and industrial use
393 (amounting to 250 l/person/day) estimated loads contributing up to 10% to STW influent loads [22].
394 Given the reported concentration of phosphorus entering STW is approximately 8.25 mg-P/l and more up
395 to date mean dosing concentrations are reported as 0.91 mg-P/l [26] then the overall contribution to STW
396 loads is likely to be closer to 11%.

397
398 Comparing the domestic load with that predicted to be entering STW suggests that they comprise 93% of
399 the total load to STW. Other potential sources of phosphorus to STW include road runoff, industrial
400 sources (e.g. chemicals, food and drink, laundrettes, metal processing) and commercial and town centre
401 activities such as bars, restaurants, offices, hospitals and car washes. However, road and roof runoff
402 contributes a significant amount of the additional flow to STW which makes up the difference between

403 the measured per person flow (250 l/day) and the domestic flow (150 l/d). Concentrations of phosphorus
404 in runoff, however, are not particularly high. For example 0.66 mg-P/l has been reported for developed
405 urban areas [40] around 10 times less than measured concentrations at STW. The load from this source is
406 therefore unlikely to be a major contribution. Industrial discharges may have high phosphorus
407 concentrations, but only contribute (generally) small flows to sewers compared with domestic discharges
408 and runoff. It has been reported elsewhere that industrial contributions only account for 6% of the load to
409 sewer, but will vary depending on the catchment [22]. The limited data therefore suggest that other
410 contributions of phosphorus from sources other than domestic are relatively minor in magnitude.

411
412 Summing all of the domestic contributions comes to a total of ca. 42,000 tonnes-P/year entering STW
413 after accounting for losses from CSOs and misconnections. The total load of phosphorus considered to be
414 derived from preventable sources (tap water dosing, food additives and waste, detergents and personal
415 care products) amounts to over 25,000 tonnes (including phosphonates), approximately 52% of the total
416 load to STW. These estimates show the potential impact of source control on reducing the phosphorus
417 load to STW should such measures be considered cost effective and can be employed to their maximum
418 extent.

419
420 To meet EU legislation most UK STW serving populations over 10,000 apply some form of phosphorus
421 reduction to meet effluent discharge limits of 1 or 2 mg-P/l. Consequently not all phosphorus entering a
422 STW is discharged in the effluent, a significant proportion is present within the sludge. Estimates (2007)
423 of the loads of phosphorus discharged into receiving waters suggest a range from 25,300 to 34,800
424 tonnes-P/year [41]. Phosphorus reduction at STW has been escalating under the WFD and so loads
425 discharged from STW are continually reducing and so possibly tending towards the lower end of the
426 estimated range reported. Overall loads of phosphorus to receiving waters and their impacts on
427 compliance with WFD standards is the subject of a follow up paper to this one.

428

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

432

433 **Conclusion**

434

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

448

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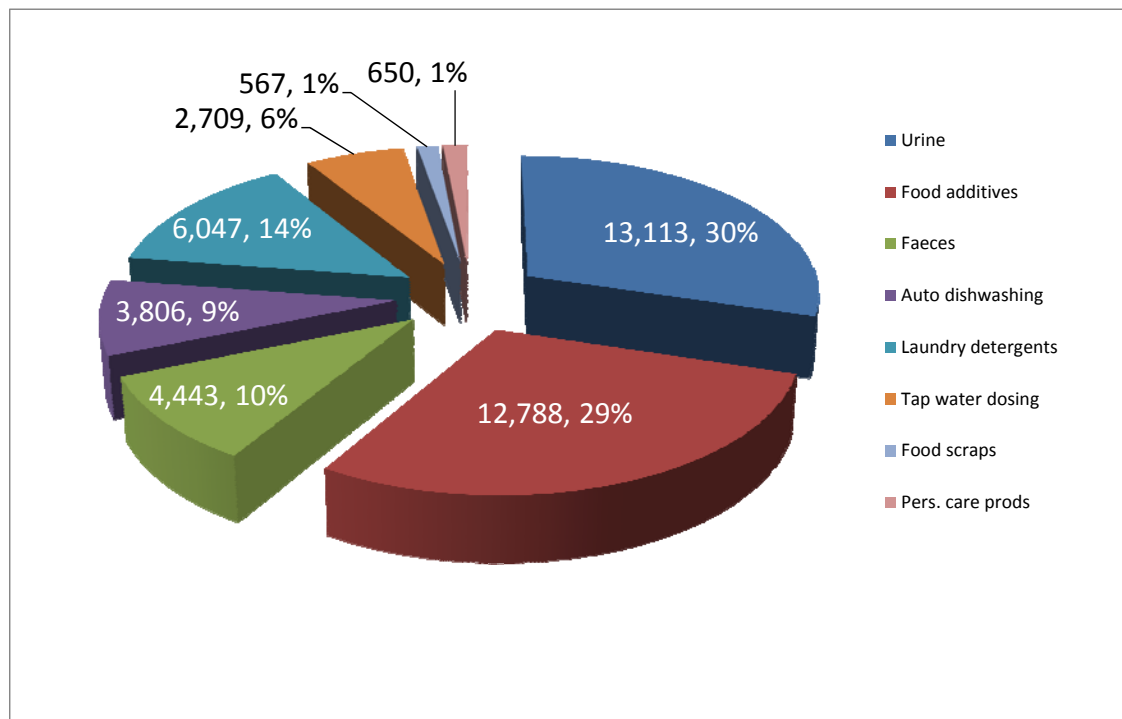
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567 **Figure 1 Tonnes-P/year discharged to sewer from domestic sources and %**
568 **contribution to total load (food additive sources have**
569 **been separated from urine and faeces loads)**

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571
572 **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

573 ^a taking account of phosphorus content in each of the chemical multiplied by the percentage of the
574 chemical in the product.

575 ^b assumes 5 g of toothpaste used per person per day, and all of phosphate containing product is released
576 to sewer.

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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
<i>of which</i>				
- Bread	110	120	0.132	10
Meat & meat products	161	200	0.322	24
Milk & cream	290	95	0.276	21
<i>of which</i>				
- 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
<i>of which</i>				
- beers & lagers	97	25	0.024	2
Soft drinks	295	15	0.044	3
Fruit	185	20	0.037	3
<i>of which</i>				
- 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
<i>of which</i>				
- 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

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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

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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
<i>Total detergent released to sewer per person per day</i>	<i>2.1 g</i>	<i>21.5 g</i>
Percentage of phosphonates [24]	4	81
Percentage of phosphonates in products [24]	2.5	2.5
<i>Amount of phosphorus discharged per person per day derived from use of phosphonates (g-P/capita/day)</i>	<i>0.0006</i>	<i>0.12</i>

591 * Standard mass of tablet. **Manufacturer data for moderately hard waters.

592 *** UK 2011 Census data.

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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

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

598 133 STW

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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%

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