Estimating the leakage contribution of phosphate dosed drinking water to environmental phosphorus pollution at the national-scale

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Abstract

Understanding sources of phosphorus (P) to the environment is critical for the management of freshwater and marine ecosystems. Phosphate is added at water treatment works for a variety of reasons: to reduce pipe corrosion, to lower dissolved lead and copper concentrations at customer's taps and to reduce the formation of iron and manganese precipitates which can lead to deterioration in the aesthetic quality of water. However, the spatial distribution of leakage into the environment of phosphate added to mains water for plumbosolvency control has not been quantified to date. Using water company leakage rates, leak susceptibility and road network mapping, we quantify the total flux of P from leaking water mains in England and Wales at a 1 km grid scale. This is validated against reported leaks for the UKs largest water utility. For 2014, we estimate the total flux of P from leaking mains to the environment to be c. 1.2 kt P/yr. Spatially, P flux is concentrated in urban areas where pipe density is highest, with major cities acting as a significant source of P (e.g. London into the Thames, with potentially 30% of total flux). The model suggests the majority (69%) of the P flux is likely to be to surface water. This is due to leakage susceptibility being a function of soil corrosivity and shrink-swell behaviour which are both controlled by presence of low-permeability clays. The location of major cities such as London close to the coast results in a potentially significant flux of P from mains leakage to estuarine environments. The contribution of leakage of phosphate dosed mains water should be considered in future source apportionment and ecosystem management. The methodology presented is generic and can be applied in other countries where phosphate dosing is undertaken or used prior to dosing during investment planning.

Keywords

Phosphate, Water mains leakage, Nutrient budgets, Pipe corrosion, Plumbosolvency, Eutrophication

1 Introduction

The role of phosphorus (P) fluxes in freshwater and estuarine zone eutrophication is well established (Vollenweider, 1968). Phosphorus limitation of primary production has been observed to be equally strong across freshwater, terrestrial and marine ecosystems (Elser et al., 2007). The consequences of eutrophication are significant with harmful algal blooms resulting in fish kills (Anderson et al., 2002) and disease in animals (Main et al., 1977) and humans (Falconer (1989); Funari and Testai (2008)). As a result, legislation in Europe under the Water Framework Directive (European Union, 2000) and USA (United States Environmental Protection Agency, 1972) has been introduced to control P inputs to rivers. Riverine P loadings are considered to be dominated by point source inputs from sewage treatment works (STW) (78% in Great Britain, White and Hammond (2009)), with diffuse agricultural sources also being significant (13%, White and Hammond (2009)). Since 1990, there has been significant reduction in riverine P fluxes in Europe due to the introduction of tertiary P removal at STWs (Foy, 2007). From 1974 to 2012, the estimated fluvial flux of P has declined to less than 50% of 1974 values (Worrall et al., 2015). Further improvements in discharges are anticipated through new standards for P discharges needed for the Water Framework Directive (Bowes et al., 2010).

Whilst excess P has been demonstrated to have deleterious environmental impacts, P also has direct human health benefits through plumbosolvency reduction. Lead piping is a significant source of lead contamination in drinking water (Edwards et al. (2009); Moore (1977)). Consumption of lead has been associated with increased risk of heart disease, strokes (Pocock et al., 1988) and reduced cognitive development in children (Bellinger et al., 1987). Dosing of mains water with phosphate inhibits the release of lead in piping through formation of lead phosphate precipitates. Dosing has also been shown to reduce both cuprosolvency (Comber et al., 2011) and the formation of iron and manganese precipitates which can lead to a deterioration in the aesthetic quality of drinking water (Kohl and Medlar, 2006). In the UK it is estimated that >95% of supplies are dosed with phosphate

(CIWEM, 2011). In the USA, over half of supplies are dosed with phosphate and this continues to increase (Dodrill and Edwards (1995); Edwards et al. (1999)). Typical tap water dosing P concentrations range between 700 to 1900 µg/l (UK Water Industry Research Ltd, 2012). These concentrations are more than an order of magnitude higher than limits for good ecological status in freshwater environments (28 – 63 µg/l; UK Technical Advisory Group (2012)). Comber et al. (2011) showed that as P concentrations were increased in a water company area from 400 to 1000 µg/l P between 2000 and 2006, lead concentrations fell from 4.5 to 1.5 µg/l. The increases in mains water P concentrations and corresponding decreases in lead in the UK are predominantly a result of the introduction of the EU Drinking Water Directive (European Commision, 1998) and subsequent revisions which prescribed limits of 50, 25 and 10 µg/l for lead in drinking water in 1998, 2003 and 2013 respectively. In 2011, 99.8% of random tap water samples in England and Wales complied with the 25 µg/l standard and 99.0% were below the future 10 µg/l standard (CIWEM, 2011). Similar legislation has also been implemented in the USA and Canada (Hayes, 2010).

It is estimated that the input of P from dosing represents around 6% of the P input into sewage treatment works (Comber et al., 2013a). However, a significant proportion of water pumped into supply is also lost due to leakage. Globally, the cost of water lost to leakage and unbilled consumption is estimated conservatively to be $14 billion per year (World Bank, 2006). In England and Wales, national scale leakage rates are reported as 25% to 27% (Gooddy et al., 2015). With the spatial extent of dosing and the concentrations used, leakage could be a significant source of P to the environment (Holman et al., 2008). Gooddy et al. (2015) made a first estimate of this source to be c. 1000 tonnes of P per year, but the spatial distribution of this flux has not been estimated to date. In order to further understand the role of this flux, it is critical that a simple method is available to estimate the spatial distribution of P leakage from water mains. In this study, we hypothesise that this distribution at the national scale is controlled primarily by the density and condition of the water mains network and by soil and environmental factors controlling pipe stress and corrosion. We use a generic modelling approach validated using reported water company leakage data to make the first spatially distributed national scale estimation of the flux of P from mains leakage.

2 Materials and Methods

2.1 Study area and national-scale assessment of P flux

We quantified the P flux from water mains for England and Wales. This region was chosen due to the extensive phosphate dosing of mains water (CIWEM, 2011) and good leakage data availability. An initial national scale assessment of the flux of P from water mains leakage was made building on the first estimate of Gooddy et al. (2015). Water company target leakage rates for 2014/15 were obtained from a national dataset collated by OFWAT (2011). UK Water Industry Research Ltd (2012) reported a range of dosing concentrations in England and Wales of 700 – 1900 µg P/l, with a dosing extent of 90 – 100%. Hayes (2010) showed that old in-situ pipes may take up to 2 - 3 years to reach equilibrium with the phosphate dose. Once at equilibrium, the concentration at the tap is the same the concentration used to dose the water (Comber et al., 2013a). Given that extensive dosing has occurred in England and Wales for over 10 years (UK Water Industry Research Ltd, 2012), it is assumed that concentrations of P do not change significantly within the distribution network and that an average concentration of 1000 µg P/l occurs throughout the network. The impact of variability in dosing concentrations and extents as reported by UK Water Industry Research Ltd (2012) was evaluated when considering spatial variability and uncertainty in the flux of P from water mains leakage (section 3.4). On the basis of these assumptions, the national-scale flux of P (PF_{nat}, kt P/year) from leakage can be calculated as:

$$PF_{nat} = \sum L_{WC}.P_{WC}.\frac{365}{10^6}$$

Where L_{WC} (million litres per day (Ml)/day) and P_{WC} (1000 µg P/l) are the leakage rates and phosphate dosing concentrations respectively for an individual water company *WC*. In this national-scale approach, fluxes are derived on an annual basis. It should be noted that there is likely to be some retardation of the P through sorption to soils and sediments. The degree of attenuation through sorption is highly dependent on the sediments penetrated and the proximity to a water body. As such, we are providing a potential maximum flux to the environment and the flux values presented are for comparative purposes with other sources. In addition to dosing with orthophosphoric acid, the pH of mains water is regularly increased through chemical manipulation to reduce pipe corrosion (Dodrill and Edwards, 1994). Consequently, the pH of mains water is high relative to wastewater (Robertson et al., 1998), with 90% of European tap waters above pH 7 (Banks et al., 2015). Consequently conditions are much less favourable for P adsorption to clays and iron oxy-hydroxides (Gustafsson et al., 2012). While it is acknowledged that P may be retarded in the soil and unsaturated zone, an assessment of the sorption potential of sediments is beyond the scope of this present study.

2.2 Spatially distributed P flux modelling

The spatial distribution of the P flux from water mains leakage was estimated at a 1 km grid scale for England and Wales using a GIS modelling approach as detailed in Figure 2. A 1 km grid scale was used to ensure short model run times and this is in line with other national-scale nutrient models (e.g SEPARATE (Zhang et al., 2014a)). We use a simple methodology that can be rapidly applied where suitable soil, geology, road network and river basin mapping is available.

2.2.1 Leakage susceptibility mapping

The total flux of P from water mains leakage was derived by first mapping leakage susceptibility and the road network. The physical processes leading to pipe failure are highly complex and not fully understood (Rajani and Kleiner, 2001). As a first approximation, it was conceptualised that water mains leakage was predominantly controlled by: (i) soil environmental factors, (ii) the age of the pipe, (iii) the pipe material, (iv) internal water pressure and (v) external overburden pressure. At the national scale, consideration of pipe material, ages and pressure effects is highly challenging due to the heterogeneous nature of the water distribution network. Consequently it was assumed that at this scale, only soil environmental factors such as soil corrosivity, compressibility and shrink-swell properties would control the distribution of leakage (Farewell et al., 2012). The importance of pipe age and material was considered during model validation (section 2.2.5). National risk mapping datasets for soil corrosivity, compressibility and shrink-swell (British Geological Survey (2010); British Geological Survey (2011)) were used to identify areas where soil properties would be likely to cause leaks and bursts. The risk mapping identifies 3 risk classes for corrosivity and 5 classes for shrink-swell and compressibility, as detailed in Table 1. It was assumed that leakage could only occur from areas underlain by soils which would fall into one of the following classes, which we consider to be areas of high leakage susceptibility (Figure 2):

- Shrink-swell and compressibility - Class D and E (where there is significant or very significant potential for compressibility and high or very high plasticity ground conditions (British Geological Survey, 2010))
- Corrosivity – Class 3 (where ground conditions are likely to cause corrosion to iron (British Geological Survey, 2011))

These areas represent parts of the study area where ground conditions are most likely to cause water mains leakage. It is acknowledged that there is some subjectivity in these classifications, and this is considered when undertaking model validation (section 2.2.5).

Shrink-swell/Compressibility Class	Ground Conditions		Corrosivity class	Ground Conditions
	Shrink-swell	Compressible deposits		
A	Predominantly non-plastic.	No indicators for compressible deposits identified.	1	Ground conditions beneath topsoil are unlikely to cause corrosion to iron.
B	Predominantly low plasticity.	Very slight potential for compressible deposits to be present.		
C	Predominantly medium plasticity.	Slight possibility of compressibility problems.	2	Ground conditions beneath topsoil may cause corrosion to iron.
D	Predominantly high plasticity.	Significant potential for compressibility problems.	3	Ground conditions beneath topsoil are likely to cause corrosion to iron.
E	Predominantly very high plasticity.	Very significant potential for compressibility problems.		

Table 1 Risk classes for shrink swell, compressible and corrosive ground conditions, as defined by British Geological Survey (2010) and British Geological Survey (2011).

2.2.2 Water mains network density mapping

In the study area potable water is supplied by a range of different water utilities, which privately own water mains data. This is also the case in a number of other countries such as USA and Germany, where supplies are provided by a large number of municipal utilities (Deloitte, 2014). The localised and fragmented nature of these supply systems means that direct mapping of water mains at the national scale is challenging and costly. We therefore adopted a simplified approach which can be used at the national scale elsewhere by assuming the road network could act as surrogate for the water mains network. Water mains are typically designed to deliver water for public and industrial consumption and consequently the road network is highly likely to reflect the water mains network at the national scale. The validity of this approach is illustrated in Figure 1 and S1. Figure 1 shows the road network and the road and water mains network density (m/1 km grid cell) for an English town. Water mains network data are not publically available. There is a strong, near-linear relationship (R^2 = 0.86, gradient = 0.82) between road and water main network density for this area. Figure S1 shows the same approach for the city of Vancouver, Canada, where water mains network mapping data are made public. In this area, the relationship between water mains and the road network is strong and very close to linear (R^2 = 0.88, gradient = 0.96). The stronger relationship in Vancouver reflects the modern co-incidental development of roads and water mains in the city. It is likely that in England, the longer historical development of the water and road network from the Victorian era to present results in a marginally weaker relationship between the current road network and water mains. The road network for England and Wales provided as a component of the Ordnance Survey Meridian 2 dataset (Ordnance Survey, 2015) was used in this study (Figure 2). This approach can also be applied to other solutes present in the mains distribution network e.g. trihalomethanes and nitrate.

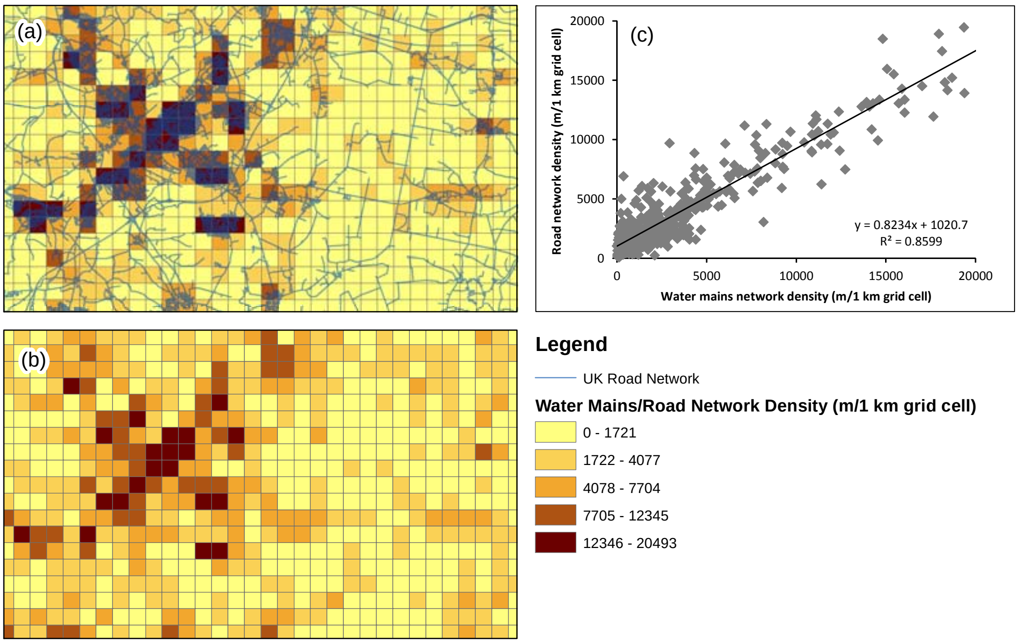

Figure 1 (a) The road network and road network density, (b) the water mains network density and (c) the relationship between road network and water mains network density for an English town. Contains Ordnance Survey data © Crown copyright and database right 2010.

2.2.3 Estimation of gridded P flux from water mains leakage

Within the areas of high leakage susceptibility, as defined above, we assume the leakage rate in a 1 km grid cell is proportional to the ratio of length of roads within the grid cell relative to the total length of roads within a water company area. This assumption is likely to be reasonable because the greater the length of roads within an area, the greater the number of water mains. Moreover, areas of high road density are also likely to have significantly more road users and consequently more frequent heavy loads on the pipes. The pressure induced by vehicles on a road has been shown to be linearly related to the pressure on a buried pipe surface (Moser and Folkman, 2001) which can contribute to pipe failure (Rajani and Kleiner, 2001). Consequently, a greater number of vehicles on the same section of water main will induce greater stress on the pipe and thus be more likely to fail and leak. On the basis of the susceptibility mapping classes identified above and the road network mapping, the leakage rate for a 1 km grid cell, L (Ml/day or kg P/day, assuming dosing at 1000 µg P/l) can be calculated as follows:

$$L = \frac{R}{R_{WC}}.L_{WC}.P_{WC}$$

Where R (m) is length of roads within a 1 km grid cell and R_{WC} (m) is the total length of roads within both a water company area and the high susceptibility area. In simple terms, the methodology distributes the total reported water company leakage L_{WC} within areas of high leakage susceptibility as defined by the risk mapping classes above. The distribution is weighted based on the density of the road (and consequently the pipe) network.

2.2.4 Surface water, groundwater and basin transport

The 1 km gridded P flux derived from the modelling approach described above was routed through surface water, groundwater and basins (Figure 2). Hydrogeological mapping at the 1:625,000 scale by the British Geological Survey (2014) was used as a basis to divide the flux of P between groundwater and surface water. It was assumed that leakage in areas underlain by moderate and high productivity bedrock aquifers (yields > 1 L/s) would flow to groundwater and leakage underlain by low productivity aquifers and rocks with no groundwater would flow to surface water. It was further assumed that over the time-step of 1 year, the vast majority of the P flux from leakage contributing to surface water flows would be likely to be exported from soils into rivers and estuaries (Worrall et al., 2014). Consequently, fluxes of P from leakage to surface waters were aggregated using the Environment Agency's Water Framework Directive River Basin Districts as shown in Figure 3(a) (Environment Agency, 2012). These represent the major river basin areas of England and Wales and have been previously used for phosphorus source apportionment at the national scale (White and Hammond, 2009).

2.2.5 Model validation

As discussed in section 2.2.1, the modelling approach adopted does not directly consider the age and material of water mains due the heterogeneity in these properties at the national scale. The selection of risk classes in the shrink-swell, compressibility and corrosivity mapping used to define areas of high leakage susceptibility is also likely to be somewhat subjective. To validate this approach, we compared the location of reported leaks with the high leakage susceptibility areas and areas where the pipe network is likely to be particularly old and made of corrodible materials such as cast and ductile iron. We hypothesized that whilst a significant number of leaks would occur under areas of legacy corrodible pipework, there would also be a large amount of leakage from the more modern distribution network. No national scale dataset for legacy corrodible piping is available. Consequently, historical urban and suburban land use data from the 1930s (the Dudley Stamp Land

Utilisation Survey, Environment Agency (2015)) and 1990 (Landcover 1990 mapping, Centre for Ecology and Hydrology (2015)) were used as a surrogate for these areas, as shown in Figure 2. Reported leaks for Thames Water were extracted from the Thames Water Live website (Thames Water, 2015) on 1st June 2015. Thames Water is the UK's largest water utility (Thames Water, 2013) and its supply area covers a range of landuse classes and geologies. Extraction of leaks reported in the summer is beneficial as this is likely to reduce sampling bias associated with freeze-thaw leaks in winter and mis-reporting of any surface runoff or groundwater discharge as leakage. Each of the reported leaks was compared against the high leakage susceptibility and the historical urban/suburban landuse mapping to determine how many leaks were located within each map class. The percentage of reported leaks within each unit was used to determine whether a significant component of leakage could be derived from land which is not underlain by areas where pipes are likely to be old and made of cast iron.

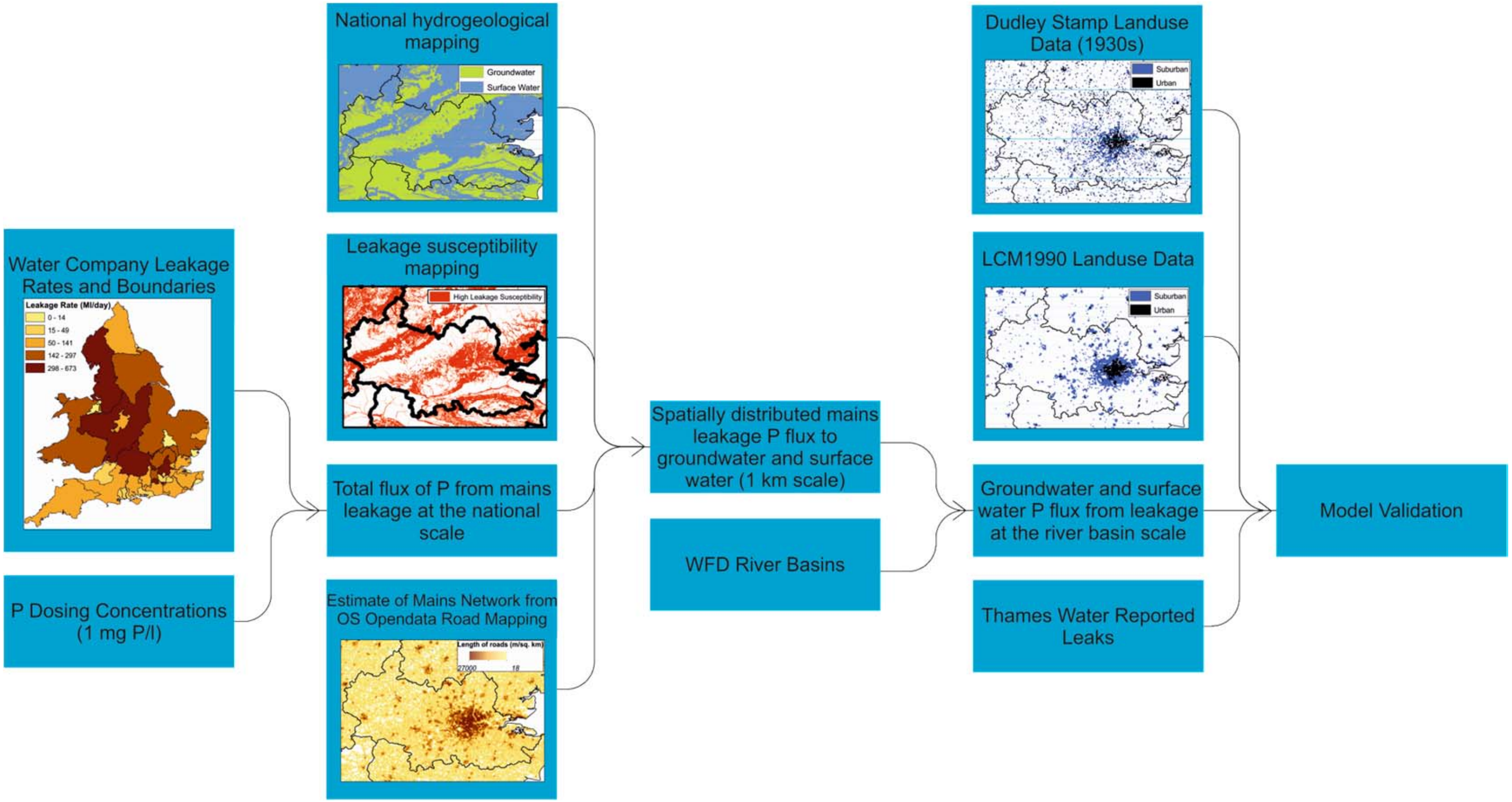

Figure 2 Methodology used to derive spatially distributed P flux in England and Wales. Based upon 1:625,000 scale digital hydrogeological mapping, British Geological Survey © NERC. Contains Ordnance Survey data © Crown copyright and database right 2010. Contains Environment Agency owned data. Contains public sector information licensed under the Open Government Licence v2.0. LCM1990 data owned by NERC - Centre for Ecology & Hydrology © Database Right/Copyright NERC - (CEH).

3 Results and Discussion

3.1 Flux of P from mains leakage in England and Wales at the national scale

The total leakage target for England and Wales for 2014/15 reported by OFWAT (2011) was 3245 Ml/day. We estimate the leakage P flux to be approximately 1.2 kt P/year. This is 20% higher than that previously reported by Gooddy et al. (2015).

3.2 Spatial distribution of P flux from mains leakage

Figure 3(b) shows the spatial distribution of P flux as estimated by the modelling approached detailed in section 2.2. At the national scale, it can be observed that leakage occurs on bedrock types whose mineralogies favour pore water chemistries that are particularly aggressive to iron piping such as the London Clay. Bedrock types which are considered to produce less aggressive porewaters or do not exhibit significant shrink-swell or compressibility properties such as the Chalk outcrop show no leakage. Within the areas of high leakage susceptibility, leakage appears to be concentrated in urban areas. Cities such as London and Kingston-upon-Hull appear to be significant local hotspots of P from water mains leakage.

The split between groundwater and surface water as defined by national hydrogeological mapping resulted in 69% of the P flux being routed to surface waters and 31% to groundwater. The predominance of surface water in this estimate is a result of the geological controls on water mains leakage. The areas of high leakage susceptibility are frequently low permeability deposits such as clays, and consequently leakage in these areas is likely to be to surface waters. The location of P flux hotspots in cities near to coastlines may result in a significant amount of the P input being discharged into estuarine environments such as the Thames and Humber estuaries.

Figure 4 shows the P flux for England and Wales aggregated to the Environment Agency's River Basin Districts and split into groundwater and surface water. This is also shown in numerical form in Table 2. The contribution of surface water P flux in the Thames basin is substantial. This is the result of the high leakage rate, the extensive coverage of high susceptibility London Clay and the extensive historic water mains network under London. In total, the Thames basin contributes 30% of the national flux of P from mains leakage. The Humber, Northwestern and Severn basins contribute 19%, 12% and 11% respectively, with all other basins < 10%. The relative contribution of groundwater and surface water to the total flux of P varies between basins. The Severn, Thames, South West and Anglian basins are dominated by surface water due to the extensive low permeability bedrocks present, with the remaining basins having a significant groundwater component.

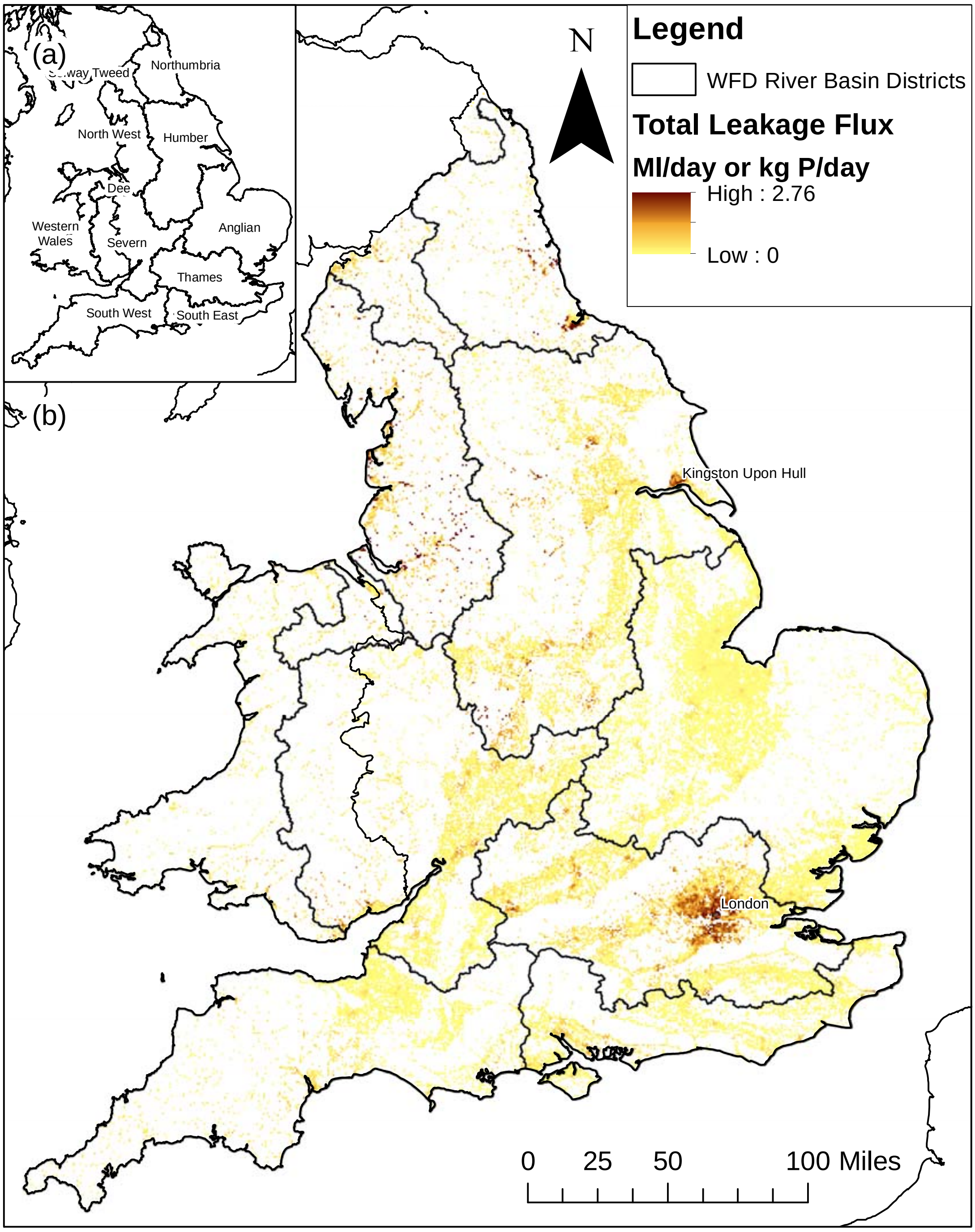

Figure 3 (a) Environment Agency River Basin Districts and (b) Modelled spatial distribution of P flux from mains leakage in England and Wales. Areas in white are estimated to have low susceptibility to water mains leakage and have not been considered in the model. Contains public sector information licensed under the Open Government Licence v2.0.

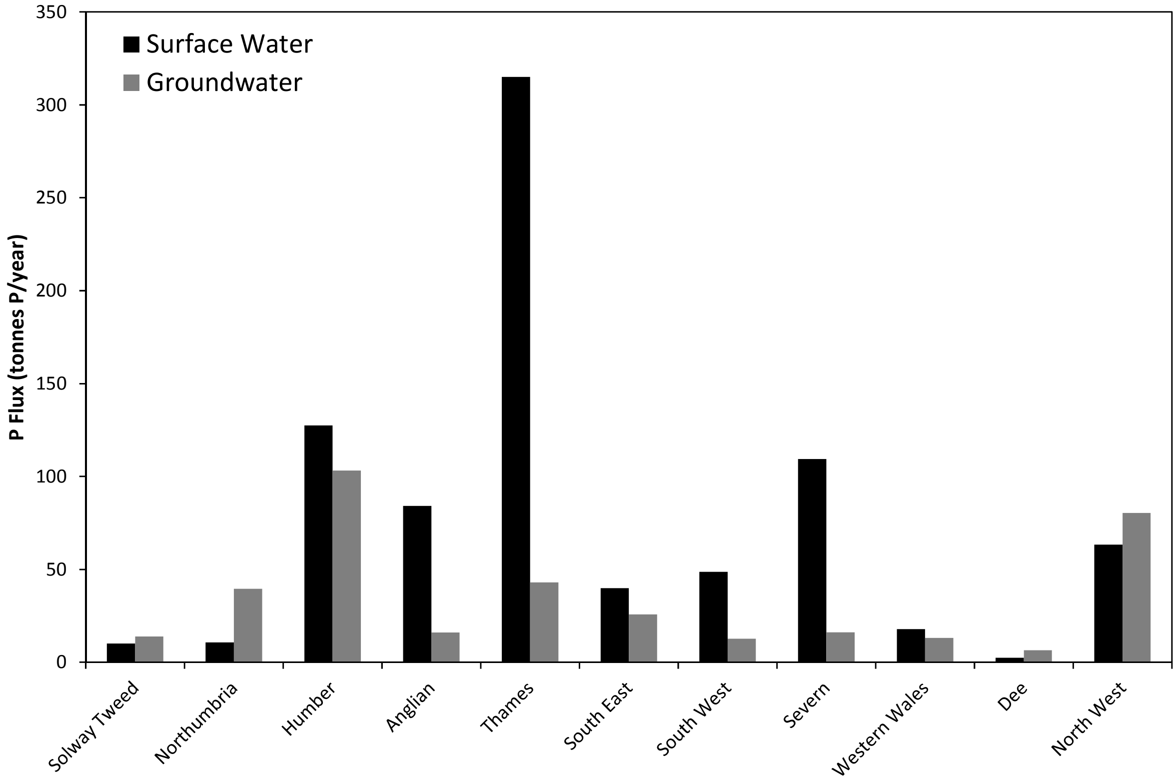

Figure 4 Fluxes of P from mains leakage to groundwater and surface water aggregated to river basin districts. Contains public sector information licensed under the Open Government Licence v2.0.

River Basin District	Estimated P flux (t P/yr)			Percentage Contribution (%)		
	Groundwater	Surface Water	Total	Groundwater	Surface Water	Total
Solway Tweed	14.0	10.1	24.1	3.8	1.2	2.0
Northumbria	39.6	10.7	50.3	10.7	1.3	4.2
Humber	103.3	127.4	230.7	27.9	15.4	19.2
Anglian	16.1	84.2	100.3	4.3	10.2	8.4
Thames	43.0	315.1	358.1	11.6	38.0	29.8
South East	25.8	39.9	65.7	7.0	4.8	5.5
South West	12.7	48.6	61.3	3.4	5.9	5.1
Severn	16.2	109.5	125.6	4.4	13.2	10.5
Western Wales	13.1	17.8	31.0	3.5	2.2	2.6
Dee	6.5	2.5	8.9	1.7	0.3	0.7
North West	80.4	63.3	143.7	21.7	7.6	12.0
Total	370.4	829.2	1199.7	100.0	100.0	100.0

Table 2 Fluxes of P from mains leakage to groundwater and surface water aggregated to river basins districts, expressed as actual fluxes (t P/yr) and as percentage contributions to the national P flux (%)

3.3 Validation and evaluation of P flux model

As discussed in section 3.3, it is critical that areas used in the leakage susceptibility mapping are validated against observed data. Figure 5 (a) shows the percentage of reported Thames Water leaks that are situated on: (i) areas of high leakage susceptibility, (ii) areas of high leakage susceptibility and within the urban and suburban categories of the 1930s landuse mapping (Figure 2) and (iii) areas of high leakage susceptibility and within the urban and suburban categories of the 1990 landuse mapping (Figure 2). A 500 m buffer has been applied to the landuse mapping to allow for the 1 km grid used. There are significantly more leaks just within high susceptibility areas (> 90%) than within areas of historical urban/suburban landuse in the 1930s and 1990s landuse data (28 and 33% respectively). This indicates that as hypothesized in section 2.2.5, water mains leakage outside of areas of legacy corrodible pipework is significant. Consequently, this suggests that use of the high susceptibility areas alone for derivation of a spatially distributed P flux is likely to be valid. At the national scale this is also likely to be the case. Figure 5 (b) shows the total aggregated P flux for each river basin district derived from using the leakage susceptibility mapping alone against P flux derived by restricting this mapping to areas underlain by historical (1930s, Environment Agency (2015)) urban and suburban landuse. This basin scale aggregation removes any local scale variability in the modelled P flux associated with different land use classes. There is a very strong correlation between the fluxes derived by using the two different approaches (R^2 = 0.9954) and the relationship is close to linear (slope = 1.0418). Therefore, when considering fluxes at the basin scale, the process of aggregation results in very similar P flux estimates using both methods. This gives some confidence in the modelling approach at the national scale.

The approach developed in this study has the advantage of only requiring national scale datasets which are generally readily available. However, the method uses a number of assumptions and also has limitations which require consideration when reviewing model outputs. The results imply that leakage is continuous across all areas of high leakage susceptibility. In reality, leakage occurs at discrete point sources. However, at the national scale, the approach is useful for identifying potential leakage hotspots. Further modelling considering the actual pipe network, age and type of mains and pressure effects would likely be required to evaluate the role of P from mains leakage at the local scale.

It should also be noted that there may be some sampling bias present in the reported leak data used in model validation. There are likely to be more reported leaks in cities due to greater populations in these areas. Leakage reports are also likely to be more common in areas of low permeability such as the London Clay. In these areas, leakage is likely to be present at the surface due to limited infiltration capacity relative to areas underlain by permeable bedrocks where leakage may not be visible. At the local scale, additional validation may be required using field data both for leaks and for P, including source fingerprinting using phosphate-oxygen isotopes (Gooddy et al., 2015). Comparison with the privately owned National Water Mains Failure Database (UK Water Industry Research Ltd, 2008) would also provide additional validation but is out of the scope of this study.

The modelling undertaken has considered the flux of P over a 1 year timescale. However, there is likely to be significant seasonality in this flux. Leakage rates are considered to be higher during winter due to bursts associated with freeze-thaw and shrink-swell in soils (UK Water Industry Research Ltd, 2007). Consequently, the flux of P from mains leakage is likely to be more significant in winter. The transport of P from leakage to surface waters is likely to show some seasonality, with greatest transport in winter associated with rainfall events washing soil P into rivers (Withers and Haygarth, 2007). As a result of these factors, it seems likely that the flux of P from mains leakage to the environment will be event driven, following a two stage process: (i) A cold weather period causing freeze thaw and shrink swell processes to increase leaks and bursts, (ii) Heavy rainfall washing P from leakage into rivers and groundwater. Modelling these highly temporally and spatially variable processes at the national scale is likely to be a significant challenge but these processes should be considered in local scale studies.

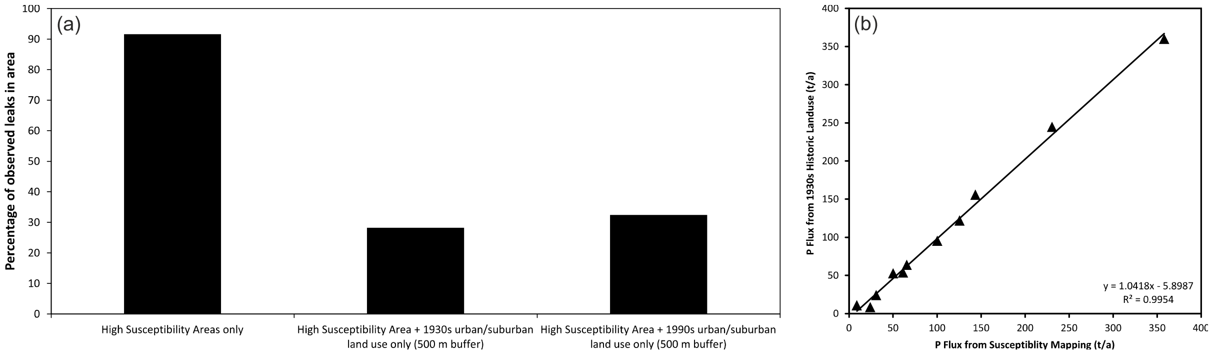

Figure 5 (a) Percentage of leaks reported in June 2015 in: high susceptibility areas only (first column), high susceptibility areas of historic urban/suburban land use in 1930 (second column), and high susceptibility areas of historic urban/suburban landuse in 1990 (third column). (b) The relationship between the aggregated WFD basin-scale P fluxes derived from just using susceptibility mapping only and using historic landuse data.

3.4 Spatial variability and uncertainty in estimation of P flux from water mains leakage

There are likely to be a number of uncertainties associated with the estimation of the P flux from water mains leakage both at the national and local scale. As noted by UK Water Industry Research Ltd (2012), there is a range in the concentrations used in dosing (700 – 1900 µg/l) and in the extent of dosing (90 - 100% across England and Wales). At the low end, assuming 90% dosing at 700 µg P/l results in a flux of 0.86 kt P/yr. Conversely, assuming 100% dosing at 1900 µg P/l results in a flux of 2.28 kt P/yr. It should also be noted, that the location of hotspots close to estuaries is likely to result in relatively short travel times and consequently relatively less potential for attenuation in comparison to inland discharges further away from receptors (Robertson et al., 1998). Furthermore, this study also does not consider sewer leakage, which can contribute to environmental P loading in urban areas (Misstear and Bishop (1997); Lerner (2002); Rueedi et al. (2009)). Some leakage may drain into the sewer network and will be treated at sewage treatment works. Nevertheless, the flux of P from mains leakage appears to have been overlooked in previous source apportionment studies (White and Hammond (2009); Zhang et al. (2014b); Comber et al. (2013b)). In these approaches, the flux is likely to have been apportioned to agricultural runoff and STW discharges. Consequently, the impact of any future reductions in P discharge concentrations from STWs or changes in agricultural practice will be tempered by a continued flux of P from mains leakage. This should be taken into consideration when undertaking future P studies.

The significance of the flux of P into the environment from mains leakage is likely to be spatially variable. Whilst the significance at the basin scale of P flux from mains leakage is the subject of further work, Figure 4 illustrates that areas such as the Thames basin appear to have significant leakage P contributions. It should be noted that at this regional scale the flux is predominantly controlled by the overall water company leakage rates rather than the spatially distributed modelling. The boundaries for the two major water companies in the Thames basin (Thames Water and Affinity Water) are almost entirely within the Thames River Basin District. Consequently, the modelling approach used to distribute the leakage rate does not affect the total flux at the basin scale.

The conceptually simple approach developed in this study can be beneficial for countries which are considering phosphate dosing in current investment plans. For example, in a 25 year water services plan, Irish Water in the Republic of Ireland are recommending the use of phosphate dosing in the development of a Lead Compliance Strategy (Irish Water, 2015). In England and Wales, future leakage rates are not estimated to drop significantly further, with a decrease of 115 Ml/day or 3.5% of the current total leakage rate predicted until 2020 (based on performance commitments and leakage rates detailed by OFWAT (2014) and OFWAT (2011) respectively). With the introduction of the 10 µg/l lead standard in 2013 (European Commision, 1998) and no currently economically viable alternatives to phosphate dosing (UK Water Industry Research Ltd, 2012), it seems likely that the flux of P from mains leakage will remain relatively constant. With decreasing P loadings from STWs due to tertiary treatment (Bowes et al., 2010), and improved agricultural practice (Withers et al. (2000); (Foy (2007))), the relative contribution of P from mains leakage is likely to increase in the future, with important implications for managing environment P concentrations and improving the status of aquatic ecosystems.

4 Conclusions

This study has quantified the spatial distribution of the flux of P from water mains leakage at the national scale for the first time. We conclude that:

- The flux of P from mains leakage is estimated to be c. 1.2 kt P/yr for England and Wales. The relative contribution of leakage to environmental P budgets is likely to increase and should be taken into consideration in source apportionment tools and in future freshwater and marine ecosystem management.
- The flux is dominated by potential leakage into surface waters (69%) due to the high susceptibility of low permeability deposits such as the London Clay.
- Cities are significant potential sources of P from leakage due to the high density of water mains, with London and the Thames basin contributing 30% of the total leakage P flux for England and Wales.
- The location of these cities close to the coast may result in a significant flux of P to estuarine environments such as the Thames and Humber estuaries. Shorter travel times also reduce the potential for attenuation.
- The methodology presented here is generic, easy to apply and can be validated against observed leakage data.

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7 Supplementary Information

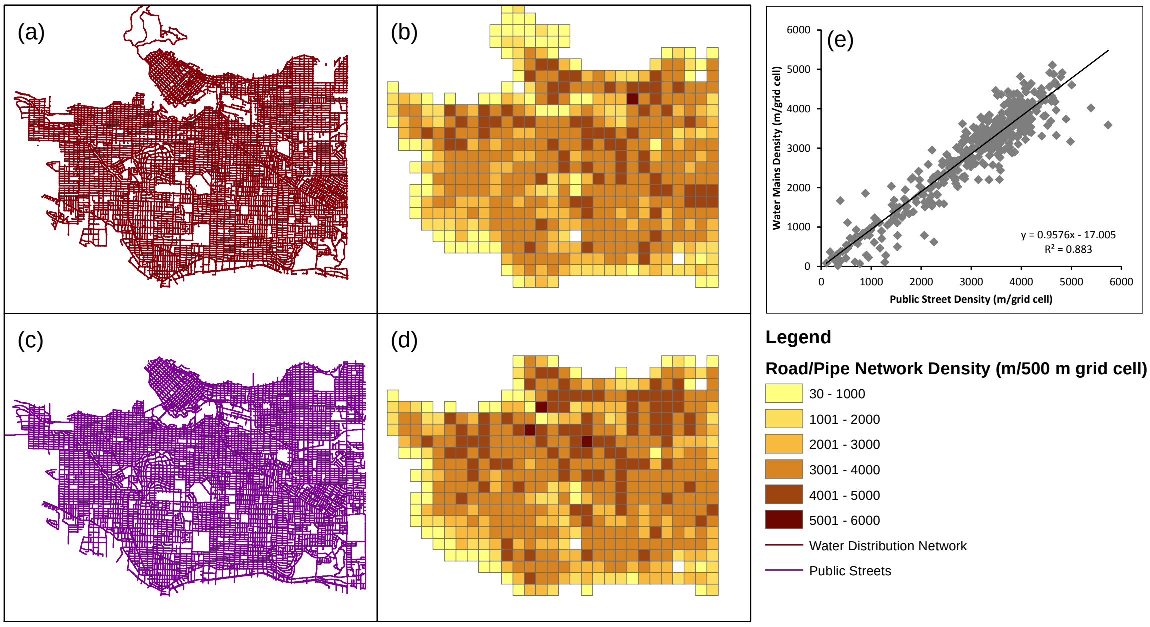

Figure S1 (a) The road network, (b) the road network density, (c) the water mains network, (d) the water mains network density and (e) the relationship between road network and water mains network density for Vancouver, Canada. Contains information licensed under the Open Government Licence – Vancouver.