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Mains water leakage: Implications for phosphorus source apportionment and policy responses in catchments

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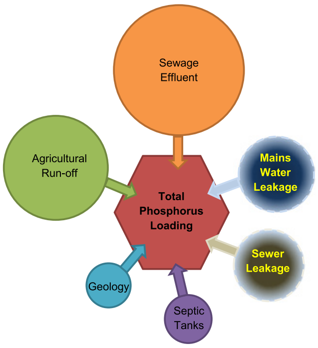
HIGHLIGHTS

- Mains water leakage of phosphate (MWL-P) dosed drinking water is currently not included in P budgets
- A new approach to estimate the spatial distribution and time-variant flux of MWL-P is demonstrated in an exemplar catchment
- Measures to reduce P from agricultural and sewage mean MWL-P could become a relatively more significant source of P
- There is a need to balance human health with ecological health
- New research is needed to better constrain the ultimate fate of MWL-P and the role of MWL-P within aquatic ecosystems

GRAPHICAL ABSTRACT



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ABSTRACT

Effective strategies to reduce phosphorus (P)-enrichment of aquatic ecosystems require accurate quantification of the absolute and relative importance of individual sources of P. In this paper, we quantify the potential significance of a source of P that has been neglected to date. Phosphate dosing of raw water supplies to reduce lead and copper concentrations in drinking water is a common practice globally. However, mains water leakage (MWL) potentially leads to a direct input of P into the environment, bypassing wastewater treatment. We develop a new approach to estimate the spatial distribution and time-variant flux of MWL-P, demonstrating this approach for a 30-year period within the exemplar of the River Thames catchment in the UK. Our analyses suggest that MWL-P could be equivalent to up to c.24% of the P load entering the River Thames from sewage treatment works and up to c.16% of the riverine P load derived from agricultural non-point sources. We consider a range of policy responses that could reduce MWL-P loads to the environment, including incorporating the environmental damage costs associated with P in setting targets for MWL reduction, alongside inclusion of MWL-P within catchment-wide P permits.

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1. Introduction

Phosphorus (P) is a vital element for all life. However, P is also the subject of an environmental paradox. One the one hand, world food security and the growing production of biofuels rely on enhanced P inputs to ecosystems, largely through the application of inorganic fertilisers and feed supplements manufactured from finite phosphorite deposits. Volatility in global markets can lead to dramatic increases in the price of P fertiliser, for example by 800% in 2008 (Cordell and White, 2011), meaning that parsimonious use and management of P resources is judicious (Cordell et al., 2009; Elser and Bennett, 2011; Elser et al., 2014; Jarvie et al., 2015). On the other hand and in parallel with increased mining and processing of phosphate rock, widespread enrichment of aquatic ecosystems with P has occurred in many parts of the globe (Carpenter, 2005). Anthropogenic inputs of P to these ecosystems have far-reaching effects, impairing water quality through stimulation of eutrophication with profound impacts on ecosystem function and health (Smith and Schindler, 2009). In turn, these ecosystem impacts can be directly linked to significant economic costs (Dodds et al., 2009; Pretty et al., 2003).

Research has attempted to quantify the absolute and relative contribution of agriculture (diffuse source) and sewage treatment work (STW) effluent (point source) to total P loadings in aquatic ecosystems (e.g. Jarvie et al., 2006; White and Hammond, 2009; Haygarth et al., 2014). Further work has considered the potential P load from other sources, including septic tank systems (e.g. Withers et al., 2012) and atmospheric deposition (Tipping et al., 2014). In response to P enrichment of aquatic ecosystems, policy and mitigation practices have predominantly targeted reductions in the export of P from agricultural land and from sources of waste water (i.e. sewage treatment works), involving changes in fertiliser, manure/slurry and other land management practices alongside the introduction of tertiary treatment technologies for P removal at sewage treatment works. However, these responses have had varying success with respect to improving water quality and reversing eutrophication within aquatic ecosystems (Hukari et al., 2016; Jarvie et al., 2013b; Lewis et al., 2011; Sharpley et al., 2015).

Here, we argue that P loads to the environment from mains water leakage (MWL) could be important in the context of eutrophication in aquatic ecosystems, but have not been sufficiently well constrained to date. Current P loads from MWL are potentially significant, especially within highly populated areas. Further, without action, the relative importance of MWL-P is likely to grow as P loads from other sources decline following the introduction of appropriate policies and mitigation practices. Therefore, the need to address MWL-P in order to protect and to restore aquatic ecosystems in the face of eutrophication is likely to increase in the future (Doody et al., 2014; Lewis et al., 2011).

Phosphate (PO_4) dosing of mains water supplies was introduced in the USA during the first half of the 20th century to prevent calcite precipitation within distribution networks (Rice and Hatch, 1939). The additional benefits associated with reduced iron corrosion from distribution pipes were quickly established (Hatch and Rice, 1940). However, widespread dosing of mains water supplies with PO_4 in the UK, parts of Europe (Flem et al., 2015) and the USA was not adopted until the 1990s, largely in response to legislative requirements to reduce lead (Pb) and copper (Cu) concentrations in drinking water due to the impacts of heavy metal exposure on human health (Edwards et al., 2009). In the USA, a standard of 50 $\mu g\ L^{-1}$ for both Pb and Cu in drinking water was originally adopted. However, since 1991 an action level of 15 $\mu g\ L^{-1}$ Pb has been introduced under the lead and copper rule (LCR). If the LCR is exceeded, appropriate action must be taken by the relevant water utility, including introduction or optimisation of PO_4-dosing. As permitted concentrations of Pb in drinking water have been reduced across Europe, for example from 25 $\mu g\ L^{-1}$ to 10 $\mu g\ L^{-1}$ in 2013 (EU Drinking Water Directive, 1998), there has been an increase in both the concentration and the spatial extent of PO_4-dosing to ensure better compliance with these more stringent standards (CIWEM, 2011; Comber et al., 2011). Current PO_4-dosing for drinking waters in the UK typically achieves final P concentrations between 700 and 1900 $\mu g\ L^{-1}$ (UKWIR, 2012) and is essentially applied nationally (95% of sources). In the U.S., more than half of water utilities use a range of PO_4-based corrosion inhibitors (Dodrill and Edwards, 1995). Where applied and optimised, PO_4 dosing of mains water represents an effective technological solution to reduce Pb and Cu concentrations in drinking water (Comber et al., 2011).

However, leakage from mains drinking water networks is a globally-significant issue, with the volume of water that leaks costing water utilities worldwide an estimated $14 billion per year (World Bank, 2006). Mains leakage from the distribution network in England and Wales is currently estimated to be 22% of treated water, equivalent to around 3200 $ML\cdot day^{-1}$, which has declined considerably since the mid-1990s when leakage peaked at just over 30% of treated water (CIWEM, 2015). Pipe failure in drinking water distribution networks is also a major concern within North America, where recent data from the USA and Canada suggest a current failure rate of 11 failures 100 $miles^{-1}$ $year^{-1}$, with highest failure rates over 5 years for cast iron (28 failures 100 $miles^{-1}$ $year^{-1}$), ductile iron (6.15 failures 100 $miles^{-1}$ $year^{-1}$) and steel (5.9 failures 100 $miles^{-1}$ $year^{-1}$) pipes (Folkman, 2012). Further, there has been a significant deterioration in the overall condition of drinking water distribution networks over the last three decades in the USA, with 68% classified as excellent in 1980, 42% in 2000 and 32% in 2010 (EPA, 2002; Folkman, 2012). A recent assessment of utility water loss in China found that the average leakage rate was approximately 18%, with 40% of water utilities suffering leakage rates >20% whilst some smaller utilities had leakage in excess of 60% (Pan et al., 2009). Although Holman et al. (2008) noted that leakage of PO_4-dosed mains water could be an important source of P, research has only recently attempted to quantify the load of P delivered to the environment from MWL. Within the UK, Gooddy et al. (2015) estimated the total P load from MWL to be approximately 1000 tonnes $year^{-1}$. Subsequently, using a more sophisticated national-scale modelling approach, Ascott et al. (2016) revised this figure to 1200 $tonnes\cdot P\cdot yr^{-1}$.

In this paper, we highlight the importance of properly accounting for MWL-P by developing an approach to quantify MWL contributions to P loads within the River Thames catchment over the past 30 years. The River Thames catchment is characterised by a high population density (~960 people km^2, Merrett, 2007) and variable mains leakage rates (between approximately 23 and 26% over the study period), and we compare estimates of MWL-P with P loads from both agricultural land and from STW effluent within the same catchment. Subsequently, we discuss how environmental policy could be adapted in the future to balance both protection of human health by minimising heavy metal exposure through drinking water and protection of aquatic ecosystems through reducing P loads derived from MWL.

2. Methods

2.1. Estimating the annual MWL-P load for 2011–2013

We estimated the annual load of MWL-P in the Thames catchment for 2011–2013 using published water company data. The Thames catchment is supplied by four water utilities: Thames Water; Affinity Water; Southeast Water; and Sutton and East Surrey Water. These companies also supply areas outside of the Thames catchment. Each water utility is divided into water resource zones (WRZs) in which the water supplied is largely self-contained in the area (Environment Agency, 2012). Within the Thames catchment, there are 10 WRZs and their boundaries coincide or very closely coincide with the topographical catchment boundary (Fig. 1). Published water company leakage rates ($ML\cdot day^{-1}$) for 2011–2013 for the WRZs were extracted from water company resource planning tables. These are publically available on water company websites (Affinity Water, 2014; Southeast Water, 2014; Sutton and East Surrey Water, 2014; Thames Water, 2014). The