

Long-term phosphorus removal in Land Treatment Systems: evaluation, experiences and opportunities

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Excessive release of phosphorus (P) from urban wastewater into water bodies is a significant environmental concern. Land treatment systems (LTS) have been used for the last 150 years as a low cost, and low energy tertiary wastewater treatment. However their P removal capacity is limited by soil adsorption capacity. Accurate P-removal lifespan prediction is needed to provide confidence in this technology and to support long-term wastewater treatment planning. This review outlines the history of LTS, describes the main P removal processes in soils and critically analyses the research methods used to date to assess long term P removal in soil. Finally, an assessment is made of the role that modelling tools can play in aiding our understanding of P processes in LTS soils and in forecasting system longevity.

KEY WORDS: phosphorus, soil, wastewater treatment, longevity, modelling

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1. INTRODUCTION

The release of excessive soluble phosphorus (P) to water bodies is a significant global environmental concern and the resultant eutrophication is one of the most common water quality problems (Smith et al. 2006; Carpenter & Bennett 2011). The consequence of eutrophication is the degradation of water resources by toxic algal blooms, excessive aquatic plant growth, oxygen depletion, death of aquatic life, and consequent loss of biodiversity. Together these water quality impacts can cause considerable loss of value of fresh water ecosystems in terms of diminished recreational value and profit reductions of the tourist sector (Carpenter & Caraco 1998) and increased water treatment costs. Pretty et al. (2003) quantified the eutrophication damage in England and Wales to be around £155 million per year.

The sources of P in surface waters vary depending on each context, and they can be classified as diffuse and point sources. The main diffuse pollution sources in the UK are natural landscapes, agricultural fields, rural and urban surfaces, waste from non-sewered populations, farm animals and, atmospheric deposition. The principal point sources are municipal and industrial effluent. The total P load to surface waters in Great Britain is estimated to be 41.6 kt/a: municipal effluent is the largest fraction with 60.7% of the P contribution, while the agricultural and industrial contributions are 28.3% and 4.6% respectively (and others 6.4%) (White and Hammond, 2002). The total phosphorus (TP) concentration in typical municipal wastewater depends on the local water consumption and it ranges from 4-25 mg/l (Henze et al. 2008). The principal sources of P in municipal wastewater in the UK are black water (66%) and grey water (34%) (White & Hammond 2002).

Since domestic wastewater is a main source of P, the EU (EU Parliament Regulation 2004) and countries such as USA, Canada or Japan, have focused their efforts during the last decades on reducing the P content in detergents (European Commission 2012). In 2010, the Detergents

Regulations in the UK (UK Parliament 2010) banned the commercialization of domestic laundry detergent that contained more than 0.4% of inorganic phosphates (Richards et al. 2015). Hence, to complement the measures to control P at source, many governments are setting strict pollutant discharge limits in their environmental policies. The European Waste Water Directive (European Commission 1991) sets discharge limits concentrations in wastewater effluents to sensitive areas at 1-2 mg/l for TP (depending on the population). However, in order to meet the standards of the receiving waters, required by the Water Framework Directive (European Commission 2000) it is expected that discharge P limits will have to be further reduced and in some cases it may be as low as 0.1 mg/l (Parliamentary Office of Science and Technology 2014).

Because of the need for efficient treatment, new technologies have been developed to enhance P removal from sewage but with the increased effectiveness their cost has risen. Thus, to meet these legal requirements, the wastewater industry faces the problem of providing efficient but low cost, low energy and low carbon wastewater treatments. Land treatment - defined by Crites et al., (2000, p. 7) as the “controlled application of water onto the land surface to achieve a specified level of treatment through natural, physical, chemical, and biological processes within the plant-soil-water matrix”- can help to overcome these challenges, however such systems have a finite capacity for P removal because of the limited adsorption capacity of the soil.

The aim of this paper is to critically review the existing knowledge and tools available for making reliable predictions about how long a Land Treatment System (LTS) can effectively perform as a tertiary treatment for wastewater without compromising the quality of the nearby environment and to identify the current knowledge gaps in long-term P removal behaviour of these systems. In order to analyse the previous studies about long term performance of LTS, the state-of-the-art is examined using the following approach: description of LTS and problems

associated with P forms in this type of natural wastewater treatment; analysis of current knowledge regarding P removal and longevity in laboratory-scale and full-scale systems; and finally, evaluation of the gaps for further research needs.

2. LAND TREATMENT SYSTEMS

Since humans established permanently in communities, LTS have been used as a way to manage wastewater (Inc. Metcalf & Eddy et al. 2003). Historical reports illustrate the use of LTS in early Greek and Chinese civilizations as an irrigation and sanitation method (Tzanakakis et al. 2007), but it was not until the second half of the 19th century when “sewage farming” (a historical term used for LTS) was used to protect public health after the cholera epidemics in England. This expansion drove the development of the basic principles of planning, operation and management of the systems. By that time, the first LTS appeared in the USA, France and Germany contributing to the development of the technology. However, their use declined as a result of the development of more intensive treatments to cope with population growth and lack of land availability (Jewell & Seabrook 1979). In the USA, the Clean Water Act (The 92nd United States Congress 1972) renewed interest in land treatments when planners realized that these systems were able to meet new discharge requirements of the National Pollutant Discharge Elimination System. Recently, interest in these systems has been renewed due to the possibilities that they offer as on-site treatments for remote areas and small communities, overcoming the high energy cost of conventional systems. In addition, they have been used as a tertiary treatment for polishing effluent from Wastewater Treatment Plants (WWTP), in some cases utilising the supply of nutrient-rich water for biomass production for economic benefit (Paranychianakis et al. 2006; Nissim et al. 2015).

During the period 1920-1970, LTS were used as a tertiary treatment in the UK to provide confidence with respect to meeting the so-called Royal Commission 20:30 biological oxygen

demand: suspended solids discharge consent standard which was widely applied at British wastewater treatment works (Gray 1989). Many of these LTS were subsequently inherited by the regional water authorities following the Water Act (1973) and remain today. Sweaney (2011) gathered data in relation to organic matter, suspended solids and ammonia removal from 20 LTS used for tertiary treatment by UK water companies and found that the systems did not have any formal design and used different applications rates and sizes (probably due to the lack of official guidance), this made it difficult to draw conclusions about any performance trend. The study however did not show results for P (Sweaney, 2011).

Compared to mechanical or chemical wastewater treatments, LTS are cheaper to operate and maintain, whilst also being less energy demanding (Sapkota et al. 2014; Tzanakakis et al. 2007). Their main constraint is that they require larger amounts of land than conventional centralised wastewater treatments, so they have largely been used in rural areas, for single household or small-scale applications, where land availability is not a problem. They have been successfully implemented for small communities (< 10 000 p.e.) in Scandinavia, the UK, Australia and USA.

Depending on the loading rate and flow path, LTS can be classified, into: slow rate (SR), overland flow (OF) and rapid infiltration (RI) systems (Smith 2006). Each achieves different performance outcomes and can/not be implemented, depending on the site characteristics and the desired level of treatment (Table1). In LTS, the main treatment mechanisms are: chemical retention and transformation, mechanical retention and biological transformation. While mechanical retention (e.g. grass filters strips) and biological transformation can treat pollutants such as solids, organic matter (OM), nitrogen and pathogenic microorganisms; adsorption and precipitation are the main processes responsible for P removal in soils (Vohla et al. 2011). These mechanisms differ from soil to soil and depend significantly on soil surface chemistry and pH.

Each type of soil is characterized by a P fixation capacity and is dependent on the number of reactive sites that can react with the phosphate. It depends on the amount and type of clay present, the soil pH and the OM content. When all the P-fixation sites are filled, the maximum phosphorus-fixing capacity of the soil is reached, thus the soil is supersaturated with P (Brady & Weil 2008). Consequently, P removal in LTS is a finite process (Drizo et al. 2002). In these situations the required level of P removal is not achieved and excess P can be released to the environment either in leachate or runoff as dissolved P.

Although longevity of the LTS is one of the key parameters to achieve cost-effective treatments, little research has been carried out regarding effects of long term wastewater application in LTS and the longevity of the system in terms of P removal (Hu et al., 2006). Three key questions regarding long-term P removal in LTS remain (Hu et al. 2005; Hu et al. 2006; Robertson 2012; Weiss et al. 2008; Moura et al. 2011; Eveborn et al. 2012; Eveborn et al. 2014): i) is the required knowledge available about how long one of these systems can immobilize P?, ii) what are the mechanisms involved and what is their relative importance? and iii) what should be the approach to estimate of the P removal capacity by LTS in the long term?

3. PHOSPHORUS REMOVAL PROCESSES IN LAND TREATMENT SYSTEMS

The main removal phosphorus mechanisms in natural treatments are vegetation uptake, microbial processes, precipitation and adsorption (Reddy et al. 1999). In overland flow systems vegetation uptake removal pathway can be significant (~20-30%) if vegetation is harvested regularly (Crites et al. 2006). Precipitation is the process in which phosphates can be removed from the soil solution when it reacts with Fe, Al, Mn (acidic soils) or Ca (basic soils) to form phosphate minerals. This process is considered to be irreversible but depends on pH, redox conditions and the concentration of the mineral ions in solutions required to precipitate

(McCray et al. 2009). Adsorption is the process of fixation (chemisorption) of PO_4 ions to soil particles. P interacts with soil particles in its exchangeable orthophosphate form, the pH drives the availability of each orthophosphoric form in the soil solution H_3PO_4 , $\text{H}_2\text{PO}_4^{-1}$, HPO_4^{-2} and PO_4^{-3} , at soil pH, PO_4^{-3} has the strongest binding capacity (MacBride 1994). Positive charged soils with Fe, Al, Ca content attract phosphate (PO_4) anions but they can also be adsorbed to the soil surface through non-electrostatic forces (Evangelou 1998). Adsorption is fast process but desorption is usually slower. It is driven by an equilibrium constant and if the concentration of PO_4 ions rise in the soil solution, the ion will adsorb to soil charged surfaces to restore the equilibrium. Adsorption is limited by the number of available sorption sites (McCray et al. 2009)

Despite the numerous studies and significant knowledge regarding all these processes, it is complicated to predict P removal performance in LTS as different environments (soil pH, soil type, temperature, etc.) will promote different processes that operate at different rates (McCray et al. 2009). Current understanding of soil P availability to plants gives us a conceptual model to help us to understand P dynamics in LTS. Syers, Johnston & Curtin, (2008) proposed that phosphorus in soil can be considered to be in one of four different pools on the basis of its availability to the plant: immediately available P in soil solution, readily available P that is adsorbed weakly at the soil surface, more strongly bound P that is less available, and finally very strongly bound P that is either of very low availability or inaccessible. High concentrations of P in soil solution due to wastewater irrigation (~ 10 mg P/l) will encourage an initial rapid phase of P sorption on high-affinity sites on the soil surface (Paranychianakis et al. 2006). The positive charges associated with soils with a high anion exchange capacity allow rapid, readily-reversible and non-specific electrostatic adsorption of anions such as phosphate. These sorption processes are pH dependent and are likely to be associated with the surfaces of Fe and Al minerals in strongly acid to neutral systems and on Ca minerals in neutral to alkaline systems

(Lindsay 1980). A slower phase of P removal is attributed to phosphorus diffusion in poorly accessible sites and/or to chemical precipitation which apportions P to the strongly-bound pool (Paranychianakis et al. 2006; Syers et al. 2008). Inorganic P compounds in soils are commonly associated with iron, aluminium, and calcium. These compounds have a high degree of variability in their solubility and stability which are influenced by pH. Those compounds with very low solubility, such as apatite ($\text{Ca}_{10}(\text{PO}_4)_6(\text{OH},\text{F},\text{Cl})_2$), would be associated with the very low availability pool.

One of the key issues related to the study of lifespan of LTS is the time dependency component in the P immobilization reaction (Paranychianakis et al. 2006; Cucarella & Renman 2009). It consists of a two-step reaction: an initial and fast sorption phase and a slower phase related to P diffusion or/and chemical precipitation. However, the secondary slow or irreversible sorption that has been widely documented in these laboratory studies was not evident in long term P monitoring in septic tanks plumes in Canada by Robertson (2008). Consequently, Robertson concluded that, secondary P attenuation processes, such as P diffusion into soil particle microsites, slow recrystallization of sorbed P to insoluble metal phosphate minerals, or slow direct precipitation could be inactive in ground water zones or too slow to be observed in the 16-year period of the study, suggesting that P can be remain mobile for decades with the consequent risk of impact to nearby rivers and lakes.

If soil characteristics change over time, P sorption capacity (PSC) may not remain constant, which has implications for LTS lifetime estimations. Changes in physical and chemical soil properties due to continuous application of wastewater have been characterized from previous studies. These changes may also affect the P sorption capacity of the soil which is often assumed to remain constant for a certain site during the lifespan of the LTS (Hu et al. 2005). Hu et al. (2006) described an increase in pH from 5.6 to 7.0 in the top 15 cm layer of the soil after more than 30 years of high pH (~8.5) wastewater application coming from a paper mill

(25%), other industries (~25%) and (~25%) from domestic wastewater in the Muskegon Wastewater Treatment facility (USA) with major soil types categorized as sands. These results are consistent with those of Richardson et al. (1988) who reported statistically significant increases ($P>0.95$) in North Carolina in three acidic mineral soils at a coastal plain swamp after municipal wastewater additions for 30 years. On the contrary, Eveborn et al. (2014) in their study of P accumulation and mobility in soil treatment systems after 8 to 11 years of domestic wastewater application in sand filter beds, revealed that the pH of the top layer was between 1-2 units lower than in reference samples. Their interpretation in this case was that the pH change was due to the chemical dissolution and consumption of reactive calcium oxide and other alkaline minerals or acidifying organic degradation processes. However, the study points out that the results in the surface layer might be also have been affected by surface regeneration works carried out during the study. Moreover, due to long-term high salt content effluent application in the Muskegon studies, exchangeable Ca concentrations increased ten fold (Zhang et al. 2007; Hu et al. 2005; Hu et al. 2006). Hu et al. (2006) suggests that the increase in the pH might have as a consequence the increase in the exchangeable Ca in the topsoil and links this with the possibility of an extension of the lifespan of the LTS. The experiments of Eveborn et al. (2014) also suggest that the increase in oxalate extractable Al and Fe could be due to weathering mechanisms provoked by acidification of the soil after the wastewater additions, which will also affect the sorption capacity of the soil.

It is clear that efficiency of P removal declines with time, with slower sorption processes approaching the equilibrium, and that a number of factors affect it (soil mineral type, amount of clay, pH, OM, anion presence or temperature). However, Drizo et al. 2002 and Hu et al. 2005 pointed out the possibility of long-term P accumulation and removal capacity regeneration. The proposed mechanism depends upon the formation of new P-retentive surface clusters through phosphate compound adsorption that act as new reactive sites for adsorption

and precipitation. Eveborn et al. 2014 also suggests that P bound to the surface in stable pools may in the long term increase the P sorption capacity of soils due to changes in pH and in oxalate-extractable metals during the wastewater application. Furthermore, Drizo et al. 2002 demonstrated that a wetland constructed using electric arc furnace slag as a filter medium got back 74% of its P retention capacity after four weeks rest and claim that other studies observed that soils had restored their P adsorption capacity after repeated wetting and drying cycles. The mechanisms involved are not well understood, but it is suggested that it is related with elevated pH after draining the material that will bring Ca, Fe and other mineral ions in supersaturation with the solution to create new sites for P adsorption/precipitation in the filter pores Bisone et al. (2016) studied behaviour of a clay soil with wastewater additions and the influence of hydraulic loading. The study focused on the evaluation of wetting and drying cycles in clay soil used for wastewater treatment and results indicated the potential to adsorb P and that saturation and desaturation cycles did not influence phosphate retention but enhanced nitrification. However, the soil saturation can lead into P desorption caused by Fe reduction and therefore intermittent loading can favour infiltration and help to avoid desorption. Therefore, LTS design and management approaches which permit resting periods could allow the use of clay soils as a longer term polishing treatment for P removal.

4. METHODS TO ASSESS PHOSPHORUS REMOVAL CAPACITY IN SOILS

The standard tests to assess P transport in soils (such as water extractable phosphate, exchangeable phosphate, sorption and desorption isotherms) are usually based on agronomic aspects of P availability for the plant and not to determine environmental risk of P loss in soils (Moura et al. 2011). Although they can be used to quantify the nature and quantity of P concentrations in the soil, a better understanding is needed to determine which of those indices are more suitable to better assess long-term P fate in LTS.

243 Hooda et al. (2000) studied the potential of different soil tests to predict P release to water of
244 different soils in the UK that had received long-term fertilization or sewage sludge: Soil Test
245 P (STP), sorption–desorption indices, the degree of saturation of P (DPS) and the amount of
246 water dissolvable-P. The study discussed that the DSP of the soils is more important than other
247 indices because soil extractable-P does not integrate the P soil characteristics, but the DSP
248 index associates P management and soil type factors helping to identify soils that are likely to
249 become diffuse sources. Moura et al. (2011) studied the effects of long-term reclaimed water
250 application on P leaching potential in rapid infiltration basins, the study concluded that
251 extractable P and P-saturation ratio are good indicators of soluble concentrations in the
252 leachates. Furthermore, Hu et al. (2005) reported that labile P distribution is not a good
253 indicator of P leaching in soil wastewater treatments since it is not correlated with TP, Fe-
254 bound P, or Ca/Mg-bound P, but, identified the need for a new index that integrates DSP and
255 Ca adsorption.

256 Traditionally, the P removal capacity of the soils has been related to the absorption-adsorption
257 P capacity. This can be determined by batch-scale experiments where the soil interacts with
258 solutions at different P concentrations until the equilibrium is reached, and translated to
259 Langmuir or Freundlich equations to represent their kinetic relationship (Kovar & Pierzynski
260 2009). However, many researchers agree that there is a lack of studies advising how to interpret
261 and use such batch experimental results to assess long term effects and life expectancy of soil
262 infiltration systems (Zhang et al. 2007; Cucarella & Renman 2009; Hu et al. 2006; Eveborn et
263 al. 2012; Drizo et al. 2002).

264 Nair et al. (1984) identified a wide range of methodologies that had been used to determine P
265 adsorption. Although diverse methodologies made the comparison among studies difficult,
266 they proposed a standard method to predict the partitioning of the dissolved inorganic P. In
267 addition, Graetz & Nair (2000) pointed out that the laboratory procedures to determine the P

adsorption had advantages; such as the possibility to separate the soil and solution or the possibility to obtain the necessary volume sample for carrying out the tests. However, they also described experimental disadvantages such as particle breakdown while shaking. The study of Hooda et al. (2000) asserts that phosphorus adsorption-desorption isotherms are useful to compare soil characteristics but their empirical nature make them unsuitable to explain mechanisms of sorption-desorption of P in soils as they do not reflect field conditions like runoff or rainfall.

The Onsite Wastewater Treatment Systems Manual from the Office of Research and Development of the U.S. Environmental Protection Agency (2002) states that the estimation of soil capacity removal can be based on sorption isotherms but it totally underestimates the capacity of P removal since they do not reflect the slow reactions that take place (the standard procedure extraction time is 24h) and declare that studies revealed that, in the long term, the capacity could be extended from standard isotherms predictions by 1.5-3 times. Similarly, Hu et al. (2006) evaluated the effects of long-term wastewater application on sorption capacity of the soil by comparing the 1-day maximum sorption capacity ($P_{\max}$) before and after long-term wastewater application. The study revealed that the 1-day $P_{\max}$ increased by ~3 times since the start of wastewater application indicating that it is possible for the soil to continuously adsorb P and therefore, difficult to get a reliable estimate of $P_{\max}$. Ádám et al. (2005) attempted to estimate the long-term P sorption capacity of filter materials. The study criticizes the use of 24-h sorption batch tests claiming that results differ from full-scale systems. To get more reliable long-term P sorption estimations they proposed a long-term experiment of a full scale horizontal constructed wetland (CW) and also concluded that batch experiments are not appropriate to measure sorption capacity materials because the experimental parameters (e.g. soil solution P concentration and water:soil ratio) are usually higher than in full-scale systems. However with full-scale constructed wetlands the extrapolation of the results are more difficult

because of the complexity of the systems due to biofilm developments or the presence of plants that can enhance the P removal but can also generate cracks or pores in the material leading to preferential flow (Ádám & Krogstad 2006).

Cucarella and Renman (2009) exhaustively and critically reviewed batch experiments used to estimate the PSC of filter materials used in on-site wastewater treatments. The study confirmed the findings of Nair et al. (1984) by certifying that different studies are not comparable because they are arbitrarily run under different experimental conditions and with different experimental parameters such as, solution-ratio during shaking, P concentrations of the soil water, contact time, agitation characteristics and temperature. As those parameters have the potential to significantly influence P processes they should be properly established in the experimental set up to reduce their influence in the PSC determination. Additionally, experiments should, as much as possible, represent real field conditions. Drizo et al. (2002) recommended to couple batch experiments with long-term column experiments for P removal efficiency studies in order to integrate the effect of soil chemical and hydrological properties.

Column experiments are frequently used to determine hydrological properties, evaluate transport models and monitor fate and mobility of pollutants in soil (Lewis & Sjöstrom 2010). However, Zhang et al. (2007) criticised previous column tests used to predict the fate of P in slow rate wastewater treatment soils. The tests used high hydraulic loading rates (up to 250 times those typically used slow rate systems) and were fed continuously, which does not correspond with typical LTS management parameters and, according to Hu et al. (2006), these column tests were not run for long enough to allow slow P precipitation. Eveborn et al. (2014) set up experimental columns to study the P removal and leaching potential of soil materials using deionized water. Results indicated that P removal in unsaturated soil depends on P loading, and that wash-out processes can take place in these systems, for example, during rain events and that dissolution of aluminium phosphates and the shift in ionic strength could be a

possible P release mechanism. Drizo et al. (2002) aimed to determine the long-term P saturation of filter materials through column experiments. The study revealed the advantages of P saturation obtained from column experiments compared to batch experiments, for example particles do not breakdown as a result of the shaking and the saturation is progressive. The study finally recommended P feeding concentration in column tests between 40-400 mg/l to reach the saturation point of filter materials in a practical timescale and experiments lasting 3-5 months to allow time for slower P retention processes to occur.

Direct mass balance calculations ($P_{\text{accumulated}} = P_{\text{inlet}} - P_{\text{outlet}}$) of long-term performance systems have also been used to assess the P removal capacity of soils although few attempts of evaluating the P removal performance of full-scale long-term sewage effluent irrigated soils have been reported. Kardos & Hook (1976) quantified the P added, removed by crops or leached over 10 years of irrigation with treated municipal wastewater. They concluded that soluble P concentrations at 120 cm depth in a clay loam soil remained close to 0.05 mg/l and, <2% of the P added was leached in 10 years without vegetation removal. The same experience in sandy loam reported 3% leaching. Hu et al. (2006) performed a 27 years mass balance of the Muskegon wastewater treatment plant (USA), reporting 99% retention of the P applied. Eveborn et al. (2012) studied the performance of four Swedish uncovered soil treatment community-scale systems aged from 14 to 22 years old. Using a mass balance approach, the treatments presented much poorer P removal (8-16%) than previous soil treatment reports. Robertson (2012) quantified the P retained in a lakeshore non-calcareous sand filter with water table fluctuations, and compared it with the estimated lifetime after 20 years of operation. Contrary to Eveborn's findings, the results showed that the filter bed had retained almost all of the P loaded with the wastewater over the two decades of operation. More recently, Dzakpasu et al. (2015) studied the long-term capacity and efficiency of a soil substrate full-scale integrated constructed wetland in Ireland, by studying the wastewater inflow, outflow and

storage of P in plants and sediments. Results revealed a 91% a total P removal, where 58% of P storage is accounted for P removal in the soil. One of the largest experiences with soil infiltration systems is situated in Bardu (Norway), where municipal wastewater from 5000 inhabitants has been pumped into glaciofluvial sand and gravel deposit infiltration basins at a mean temperature of +0.7°C. After 25 years of operation the treatment performance was 99% P removal and still it was estimated to last 12 years more (Jenssen et al. 2014). Reddy et al. (1999) identified the main difficulties when trying to assess P retention in wetlands as: failure to identify and measure inputs and outputs of P and water, use of only one form of P, comparison of synchronous flows and grabbing samples from strong variable flow or concentration. Therefore, the few attempts at quantifying the P removal efficiency of long-term full-scale experiences in natural treatments have been reported, mainly in grasslands and temperate climates, with variable results. The results comparison among studies indicates high removal variability probably due to differences in soil chemical properties, age of the system or sampling and calculation methodologies.

5. TOWARDS ESTIMATES OF LONGEVITY

There is not a clear definition regarding life expectancy or longevity of LTS (Yu 2012). In fact, there is a common misunderstanding between exhaustion of P, retention capacity of the material and longevity of the system. From the point of view of on-site treatments, longevity must be interpreted as the time when the system reaches the effluent P discharge limit (Heistad et al., 2006), which differs among countries and legislations in terms of both concentration and exceedance statistics. A number of studies have calculated longevity from a simple approach, the $P_{\max}$ sorption capacity of the soil (g of P/kg), the volume of land being used for treatment (m^3), P content of applied wastewater (g of P/PE) and the discharge rate (g P/day) (Table 2). However, the limitations discussed in previous sections highlighted how experimental

conditions in $P_{\max}$ assessment can contribute to errors in such a lifetime forecast. Cucarella & Renman (2009), Vohla et al. (2011) and Chang et al. (2014) noted these limitations and suggested that life expectancy calculations could not be entirely addressed through filter materials characteristics and that, to forecast precisely the lifespan of the system, other factors (including hydrological conditions, temperature and microbiological transformations) must be taken into consideration.

Simulation models can help to better understand the importance of bio-physico-chemical and hydraulic processes relevant to pollutant removal, while helping to further understand how design parameters affect the performance of the system and predict longevity and exhaustion of the material (Beach & McCray 2003). Recently, researchers have gone beyond the black-box, empirical models, to develop mechanistic models that consider the hydrodynamic and biodegradation process in natural treatments (García et al. 2010). They cover a wide range of biokinetic, process-dedicated, and design support models (Meyer et al. 2015). Process dedicated models represent degradation and transfer of compounds; hence they can help with understanding the fate of P and removal in LTS. These models describe P transport and sorption by soil or filter materials under different hydrological conditions and some of them predict breakthrough curves (Langergraber & Šimůnek 2012; Claveau-Mallet et al. 2014; Sinclair, Jamieson, Gordon, et al. 2014; Sinclair, Jamieson, Madani, et al. 2014; Liolios et al. 2015).

Intensive research has been produced since the late-1970's to develop models able to simulate the interaction in between the soil matrix, the water transport and P. The main aims of these models was to evaluate non-point source pollution of subsurface waters by agricultural P (Vadas et al. 2013). Many of these models have been updated through time and continuously developed. Different models have been used to accomplish the aims depending on spatial scale and resolution (watershed, field-scale), time scale (long-term, short-term), and the hydrological system (saturated flow, variable saturated flow, horizontal flow and, vertical

flow). These models can be divided into ones that use a water balance model and the ones that use numerical solution of the Richard's equation. The models based on Richard's equation are more input intensive and computationally demanding than the water balance models but they provide more accurate solutions for field scale modelling. Regarding the overview of soil phosphorus dynamics of those models. McGechan & Lewis (2002b) provided an exhaustive review of a number of field scale P dynamics models and the equations used (e.g. ANIMO (Groenendijk & Kroes 1999), GLEAMS (Leonard et al. 1986), MACRO (Jarvis & Larsbo 2012) and DAYCENT (Parton et al. 1998)), pointing out MACRO as the most complete model for soil transport processes but with more simple representations of P transformation.

Some of the most recent experiences of numerical modelling of on-site wastewater treatments and phosphorus fate predictions are related with the use of HYDRUS (J. Šimůnek, M. Šejna, H. Saito, M. Sakai 2013). HYDRUS-1D and 2D are able to simulate one and two-dimensional movement of water, heat and multiple solutes in variably-saturated media and can be coupled with different specific modules like wetland module (CW2D) to be able to run P degradation along with other processes (Langergraber & Šimůnek 2012). Recently, Langergraber (2016) reviewed process-based models applicable to subsurface flow wetlands treatment, and identified the HYDRUS Wetland Module as one of the most advanced ones because of its multi-component biokinetics-models and stated that it is powerful tool for understanding wetland processes. PHREEQC (Parkhurst & Appelo 1999) can also be coupled with HYDRUS and be used to solve complex geochemical calculations (Claveau-Mallet et al. 2014). In addition, MODFLOW (Twarakavi et al. 2008) is a 3D finite-difference groundwater model that can be also coupled and adapted with HYDRUS.

The HYDRUS-1D and 2D numerical code since version 4.0, released in 2007, is capable of simulating a large quantity of non-equilibrium flow and transport processes. They can be divided in physical non-equilibrium and chemical non equilibrium processes. The study by

417 Šimůnek & van Genuchten (2008) gave an overview of the conceptual models, and the
418 specifications of each model with the water flow equations, the solute transport equations and
419 the number of parameters needed in each. This new feature provides a wide range of
420 possibilities to simulate phosphorus transport in soils, such as dual permeability models to
421 simulate water flow in two different domains, with different flow velocities and non-
422 equilibrium chemical models. These models range from the simple one kinetic site model
423 described as a first-order rate equation to two sites models with different sorption kinetics for
424 different fractions, where one fraction is assumed to be instantaneous and the other one is
425 kinetic. Vogel et al. (2015) successfully simulated flow and transport in a two-dimensional
426 dual-permeability system with spatially variable hydraulic properties permitting to compare
427 different spatial distributions of hydraulic properties with model responses comparison.

428 Regarding P studies with HYDRUS Naseri et al (2011) compared physical modelling of silty
429 clay-loam texture columns against the numerical modelling of HYDRUS-3D, the results
430 concluded that it simulated the water flow in the columns successfully, but overestimated the
431 final sorbed PO_4 concentrations in the soil. Elmi et al. (2012) found similar over-estimation
432 results when using HYDRUS-1D to study the vertical distribution and transport processes of
433 PO_4 in soil columns. The simulation indicated that 98% of the P applied was accumulated in
434 the first 0.2 m of the column and decreased with depth. Sinclair et al. (2014a) also used
435 HYDRUS-2D to simulate different lateral flow sand filters in on-site wastewater treatments
436 after septic tanks showing poor removal rates and effluent exceeding 1 mg P/l concentration at
437 the end of the study. Morrissey et al. (2015) studied with HYDRUS-2D the impact of
438 unsewered cluster housing simulating the attenuation of contaminants through the unsaturated
439 zone revealing limited impact to groundwater quality, and used the calibrated model to simulate
440 the impact of increasing the house density with new developments. All those studies were

focused on studying transport and contamination effects but none of them introduced the time variable in the study in order to predict remaining lifetime.

Although a number of studies point out the potential for exhaustion of the P sorption capacity in treatment systems, there have only been a few attempts to forecast P longevity in soil infiltration systems. The first one is related with the Muskegon (USA) (Zhang & Dahab 2006) wastewater treatment plant which was part of the large-scale demonstration project for nutrient removal. The project aimed to evaluate long-term P performance, as it is known to be one of the most important lifespan limiting factors. The first phase of the study calculated new 1-day P_{max} after 30 years of operation and the new remaining life expectancy (RLE). The new estimations had an extension in the RLE because of the changes in soil properties after long-term wastewater application in the soil (Hu et al. 2006). The second phase of the same study consisted of column breakthrough modelling, where they re-calculated the RLE (Zhang et al. 2007). As a result, the study proposed a remaining life expectancy prediction formula:

$$RLE = t_b * F / 180 \quad (1)$$

where

t_b = the breakthrough day

180 = the irrigation days per year at the Muskegon plant

F = the correction factor for the inlet P concentration and the concentration used in the study.

The same project proposed a model based on the mass balance principle. The empirical model is able to predict the life expectancy on a yearly basis through the effects of the main operational parameters of the system (rotating crop type, hydraulic loading rate, annual precipitation, soil type, etc.). However, the interaction between the soil and the hydraulic systems are not reflected upon. Parkhurst et al. (2003) described a reactive-transport model

465 developed to simulate P in the sewage plume from treated sewage effluent to ground-
466 infiltration disposal beds at the Massachusetts Military Reservation on western Cape Cod
467 (USA). The simulations covered the discharged period (1936-1995) and the 60 following years
468 after cessation of disposal. The three-dimensional reactive-transport model used to develop the
469 base-case was PHAST (Parkhurst & Kipp 2002), model limitations were associated with
470 loading, flow systems and sorption characteristics of the aquifer uncertainties. Regardless that
471 the aim was not to study the longevity of the system because the activity of the filter beds had
472 stopped, it is a useful exercise of long-term plume migration modeling. Yu (2012) attempted a
473 one-dimensional model that aimed to provide the longevity of any point of the infiltration
474 system considering a homogeneous and isotropic soil, and constant and unsaturated flow. It
475 was aimed to estimate the longevity, the exhaustion time and sorbed P. The model proposed
476 was a contaminant solute transport model where advection, diffusion, dispersion and sorption
477 reactions were represented. The simulation indicated that the most sensitive factors for P
478 concentration in a soil column to reach critical concentration were the average pore flow
479 velocity and the P sorption capacity of the soil. The longevity estimations from the model
480 compared to the service time of the infiltration study sites were shorter Herrmann et al. (2013)
481 modelled the transport and removal of PO_4 in a reactive filter using the hydro-geochemical
482 transport code PHREEQC (Parkhurst & Appelo 2011), the study claims that in order to be used
483 to forecast performance and longevity it needs to be further tested and develop due to that it
484 does not take into consideration adsorption processes or the effect of biofilms growth in the
485 filter material. Claveau-Mallet et al. (2014) proposed a prediction tool for slag filter longevity
486 based on dissolution and precipitation kinetics. The proposed methodology was based on three
487 steps: (1) experimental batch tests methodology, (2) numerical calibration of the batch test (3)
488 numerical simulations of the filter. However the study assumed several limitations and
489 highlighting the principal one as being the assumption that the contact between the water and

the filter particles is limited, and not being affected by clogging from precipitates or particulate OM. The model needs to be calibrated before being used as a design tool and proposes to couple a hydrodynamic and geochemical code such as HYDRUS-PHREEQC to overcome those drawbacks.

6. SYNTHESIS AND CONCLUSIONS

LTS have been in use since wastewater treatments were applied to protect public health and still they have a role to play at the current wastewater industry as a low energy and low maintenance polishing step for small wastewater treatments. They are normally used before the wastewater treatment plant effluent is released to the environment to avoid environmental problems, mainly eutrophication related with excessive P concentrations.

P removal mechanisms in LTS are physical retention, sorption processes and microbial and plant uptake. Sorption is a finite process and depends on the interaction with the environment and the chemical properties of the soil (ion presence, pH, OM, clay content, etc). Thus, if this conditions change over time, mainly due to long-term wastewater irrigation, the P removal potential will also change.

It is well accepted that estimation of the P sorption capacity of soils by batch experiments has several limitations when it is used to calculate the $P_{\max}$ in the long term or when used to forecast the longevity of the system. The standard methodology is a short-term sorption analysis (24h) that underestimates the long-term removal capacity because it does not take into account the slow precipitation processes and because the experimental set up does not represent the real systems and interactions with the ecosystem. Thus, studies advise that these methods are not used for lifespan prediction but to compare materials and soils characteristics. Column experiments should be also correctly design when addressing long-term P removal

characterization and filter material saturation, mainly regarding length of the experiment and hydraulic loading in order to correctly translate results to full-scale experiences.

Regarding lifetime predictions in LTS, usually, direct mass balance approach using the $P_{\max}$ has been used, however the drawbacks previously pointed out also affect this methodology. Using modelling tools to assess the water flow, contaminant transformation and contaminant-transport processes can help to assist in the integration of all the parameters that affect the functioning of the system. However, few attempts to estimate the P longevity of LTS through models have been found and none of them has been completed and published due to several limitations and further development and research needed (uncertainties in data acquisition, empirical models, models not validated or neglecting important variables of the removal processes).

LTS's modelling challenge lies in getting useful results from batch and column experiment regarding soil P adsorption behaviour in the long term, and how to transfer those experimental results into the solute transport equation. The longevity of the LTS is one of the key parameters to achieve cost-effective treatments and if new studies are able to successfully model treatment scenarios then we will become a useful LTS management tool and provide greater confidence in the sustainable operation of these systems required by both operators and regulators.

FUNDING

This work was supported by Albion Water Ltd. and Cranfield University.

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Table 1 Comparison of Land Treatment Process Design Features. **Source:** (Smith 2006)

Feature	Slow rate (SR)	Overland flow (OF)	Rapid Infiltration (RI)
Minimum pre-treatment	Primary sedimentation	Screening	Primary sedimentation
Annual loading rate (m/yr)	0.5-6	3-20	6-125
Typical annual loading rate (m/yr)	1.5	10	30
Field area required (ha)	23-280	3.6-44	3-23
Typical weekly loading rate (cm/week)	1.9-6.5	6-40	10-240
Disposition of applied wastewater	Evaporation and percolation	Evapotranspiration surface run off, limited percolation	Mainly percolation
Application techniques	Sprinkler, surface or drip	Sprinkler or surface	Usually surface
Need of vegetation	Required	Required	Optional
Climate needs	Winter storage in cold climates	Not critical	Not critical

Table 2 Previous longevity estimations in different substrates and systems¹

Source	Substrate/type systems	Longevity (years)	Land use	Wastewater type	Soil Texture
Drizo et al. (2002)	Electric Arc Furnace (EAF) Steel slag shale	13-37	Batch experiment	Municipal wastewater	-
Dong et al. (2005)	Oyster shell	8-23	Batch experiment	-	-
Xu et al. (2006)	Furnace slag	22	Batch experiment	-	-
Hu et al. (2006)	Soil	29-49-151	Unproductive	~50% mill industry ~25% from other industries and ~25% from domestic waste- water.	Four major types of sandy soil on the site: Rubicon, Roscommon, Augers, and Granby
Heistad et al. (2006)	Filtralite®	5	Sub-surface flow CW	Domestic wastewater	-
Weiss et al. (2008)	Filtralite® Filtral P Soil	5 10 25	-	Domestic wastewater	-
Jenssen et al. (2014)	Infiltration basin	36	-	Domestic wastewater	Glaciofluvial sand and gravel deposit

¹ Different volumes, loading and wastewater characteristics assumptions for calculations



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Long-term phosphorus removal in land treatment systems: Evaluation, experiences, and opportunities

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2017-04-18

Taylor & Francis

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Seguí MD, Hess T, Sakrabani R, Tyrrel S, Long-term phosphorus removal in land treatment systems: Evaluation, experiences, and opportunities, Critical Reviews in Environmental Science and Technology, Vol. 47, Issue 5, pp. 314-334