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Research article



# Phosphorus removal in surface flow treatment wetlands for domestic wastewater treatment: Global experiences, opportunities, and challenges

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ABSTRACT

Treatment Wetlands (TWs) are widely used for the treatment of domestic wastewater, with an increasing emphasis on provision of multiple co-benefits. However, concerns remain regarding achieving stringent phosphorus (P) discharge limits, system robustness and resilience, and associated guidance on system design and operation. Typically, where P removal is intended with a passive TW, surface flow (SF) systems are the chosen design type. This study analysed long-term monitoring datasets (2–30 years) from 85 full-scale SF TWs (25 $m^2$ to 487 ha) treating domestic sewage with the influent load ranging from 2.17 to 54,779 $m^3$/d, including secondary treatment, tertiary treatment, and combined sewer overflows treatment. The results showed median percentage removals of total P (TP) and orthophosphate (Ortho P) of 28% and 31%, respectively. Additionally, median areal mass removal rates were 5.13 and 2.87 $gP/m^2$/yr, respectively. For tertiary SF TWs without targeted upstream P removal, 80% of the 44 systems achieved ≤3 mg/L annual average effluent total P. Tertiary SF TWs with targeted upstream P removal demonstrated high robustness, delivering stable effluent TP < 0.35 mg/L. Seasonality in removal achieved was absent from 85% of sites, with 95% of all systems demonstrating stable annual average effluent TP concentrations for up to a 30-year period. Only two out of 32 systems showed a significant increase in effluent TP concentration after the initial year and remained stable thereafter. The impact of different liner types on water infiltration, cost, and carbon footprint were analysed to quantify the impact of these commonly cited barriers to implementation of SF TW for P removal. The use of PVC enclosed between geotextile gave the lowest additional cost and carbon footprint associated with lining SF TWs. Whilst the P-k-C* model is considered the best practice for sizing SF TWs to achieve design pollutant reductions, it should be used with caution with further studies needed to more comprehensively understand the key design parameters and relationships that determine P removal performance in order to reliably predict effluent quality.

## 1. Introduction

Sewage treatment plants (STP) are recognised as one of the primary sources of phosphorus (P) in the aquatic environment along with farming (Sengupta et al., 2015). Increasing environmental pressures have promoted global regulators to adopt more stringent STP effluent concentration standards, as a point source of pollution that can deliver quantifiable benefits. In the EU and America, total phosphorus (TP) levels below 1 mg/L have become the norm in some STPs (Oleszkiewicz and Barnard, 2006), and in sensitives areas, the maximum allowable TP concentration in discharged wastewater can be as low as 0.25 mg/L (Preisner et al., 2020).

Treatment wetlands (TWs) have emerged as a promising nature-based solution for capturing P from wastewater (Castellar et al., 2019). Whilst all TWs can deliver co-benefits, free water surface wetlands or surface flow (SF) wetlands offer the greatest potential for enhanced biodiversity, stormflow attenuation, and greenhouse gas mitigation through carbon sequestration (Langergraber et al., 2020; WWAP, 2018). The original use of SF TWs for treating combined sewage treatment plant effluent and surface water dates back to 1923 in the USA (Fetter et al., 1977). A recent economic valuation study in Southern Ontario wetlands emphasised that their four SF TWs could provide a value of $4.69K per ha per year in sediment and phosphorus filtration services alone while safeguarding the drinking water source (Aziz and

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Van Cappellen, 2021). To support widespread adoption of SF TWs for P removal and co-benefit delivery, evidence-based information on design, operation and maintenance, long-term system performance, system robustness, and the trade-offs associated with construction materials need to be synthetised and made available for designers and stakeholders worldwide.

Current literature reviews have indicated the interest in P removal in TWs (Dell'Osbel et al., 2020; Zhi and Ji, 2012) without reporting specific P removal levels for the different types of TWs. When rates are summarised, they include results from short-term laboratory-scale studies (Land et al., 2016) or with mixed sources of influent water types and loads, including industrial wastewaters and agricultural runoff (Kadlec, 2016; Hickey et al., 2018). A recent analysis of 37 large-scale wetlands for P removal reported median P concentration reductions of 71%, equating to a load reduction of 0.77 $gP/m^2/yr$, and a first order rate coefficient of 12.5 m/yr (Kadlec, 2016). Whilst this has informed the latest design guidance on SF TWs (Kadlec, 2019), it is recognised the characteristics of the influent water (e.g., domestic, agricultural, industrial) can significantly impact on observed system performance, with a paucity of information on designing SF TWs for P removal in small STPs.

The present study aims to provide a comprehensive evidence base on the use of SF TWs for P removal in STPs to establish a best practice guide and identify areas for future focus. To deliver this, a dataset was compiled out of existing long-term monitoring datasets of full-scale SF TWs for domestic wastewater treatment through a combination of a systematic literature survey and raw datasets provided by practitioners and researchers. The final datasets from 85 systems worldwide were separated into four treatment scenarios, including i) secondary treatment applications, ii) tertiary treatment with targeted upstream P removal (either chemical or biological), iii) tertiary treatment without targeted upstream P removal, and iv) combined sewer overflows (CSO)/storm overflows (SO) treatment. The treatment performance in terms of total P (TP) and orthophosphate (Ortho P) were evaluated to determine the achievable effluent P concentrations. Further analysis was conducted to investigate the start-up performance, long-term stability, seasonal variances, and system robustness. The datasets were used to fit the P-k-C* SF TW design model (Kadlec, 2019) to evaluate its ability to predict performance under target scenarios. Two workshops and interviews with national and international experts were conducted to identify common practice, evidence gaps, and make recommendations regarding the system intensification approach, optimal strategies of sampling, operation, and maintenance.

## 2. Materials and methods

### 2.1. Dataset collection and workshops

#### 2.1.1. Literature data collection

The systematic bibliographic analysis was conducted in the Science Citation Index Expanded (SCI-EXPANDED) database from the Web of Science (Fig. S1, supplementary material). Firstly, the terms 'constructed wetland' or 'constructed wetlands' or 'engineered wetland' or 'engineered wetlands' or 'artificial wetland' or 'artificial wetlands' or 'man-made wetland' or 'man-made wetlands' or 'treatment wetland' or 'treatment wetlands' or 'reed bed' or 'red beds' or 'wetland' or 'wetlands' were used to compile a bibliography of papers until 2021 related to the research topic. A total of 56,808 publications resulted from the screening, and only research articles published in the English language were selected. Then, the terms 'free water' or 'surface flow' or 'integrated constructed wetland' or 'ICW' were used to refine the results. Out of 12,457 papers related to SF TWs, 1886 remained after refining results for P removal. Furthermore, each of these papers was manually reviewed and the lab/mesocosms-scale studies were excluded, which resulted in a final count of 31 papers related to the target scenarios of applied SF TWs for P removal in domestic wastewater treatment. All corresponding authors were then contacted to request systems' information and raw performance data.

#### 2.1.2. Practitioners' data collection and workshop

Additional datasets ranging between 2 and 30 years of operation were obtained from specialist practitioners located in the UK, Italy, Australia, and the USA. Four water utilities from the UK and Ireland that had implemented SF TWs for sewage treatment also contributed their system data to this study. To capture unpublished data, a survey was distributed to request datasets and experience through the Constructed Wetland Association, the Society of Wetland Scientists, and the International Water Association Specialist Group on Wetland Systems for Water Pollution Control. Four international TW designers shared their datasets or contacted their clients to obtain system data. Additionally, to extract practical information and learnings that are typically left out of research publications, two virtual workshops were held via the Zoom platform with 12 experts from around the world. The workshop provided an opportunity to openly discuss design guidance and identify risks associated with SF TW for P capture applications.

### 2.2. Dataset analysis

#### 2.2.1. System definition and assessment of phosphorus removal performance

The systems were classed as secondary treatment if they were placed immediately after septic tanks or primary settling tanks for sewage treatment. Wetlands specifically designed for combined sewer overflow (CSO) or storm overflow (CO) treatment typically integrated grey infrastructure or other wetland types, such as vertical flow, horizontal, and aerated systems. Tertiary treatment SF TWs were identified as those receiving effluent from a secondary (biological) treatment process, including trickling filters and activated sludge plants. Further classifications were conducted based on the presence or absence of targeted upstream P removal approaches, including chemical dosing or enhanced biological P removal processes.

Several applied SF TWs were composed of multiple wetland cells arranged in series and/or parallel. The monitoring may have been conducted in a single cell or the entire system. In this study, the cells from an individual stream that received independent original influent, not the effluent from other cells, and had separated monitoring data were considered to be an individual SF system (Kadlec, 2016).

The most widely accepted regulatory practice worldwide is to consent STPs based on the annual average P effluent concentration. Therefore, the annual average effluent concentrations of both TP and Ortho-P for each system were calculated for comparison where available. For the systems with sufficient data, the concentration reduction percentage in % and the mass/load removal rate for TP and Ortho-P were calculated based on the following equations.

$$CR = (C_i - C_o) / C_i \times 100 \quad (1)$$

$$PLR = q_i C_i - q_o C_o \quad (2)$$

Where CR: concentration reduction (%); $C_i$ and $C_o$: annual average inlet or outlet P concentration (mg/L), respectively; PLR: P load reduction ($gP/m^2/yr$); $q_i$ and $q_o$: average annual inlet and outlet hydraulic loading (m/yr), respectively.

When $q_o$ was unavailable and the systems were lined, it was assumed that $q_i = q_o$. For systems with information of inlet and outlet P concentrations and design population equivalents but without the flow rate, the estimated P load reduction (Eq. (1)) was calculated solely based on the inlet hydraulic loading at average flow, defined as 1.2 times the STP's dry weather flow ($q_i = 1.2$ DWF).

Based on literature and designer's input at the workshops, the P-k-C* model was identified as the most commonly used tool for sizing wetlands and predicting their performance (Kadlec and Wallace, 2008). To

evaluate the targeted systems in this study, data were used to fit the P-k-C* model (Equation (3)). Due to data availability, the modelling calculations were only applied to individual systems from the tertiary treatment SF TWs scenarios. The values of P and C* were 4 apparent TIS and 0.006 mg/L, respectively, while temperature adjustment was not applied to the rate constant $k$ (m/yr) calculation in this study.

$$\frac{C_o - C^*}{C_I - C^*} = \left(1 + \frac{k}{Pq}\right)^{-P} \quad (3)$$

where $C_i$ and $C_o$: inlet and outlet P concentration (mg/L), respectively, C*: background P concentration (mg/L); k: apparent rate coefficient (m/yr); q: inlet hydraulic loading (m/yr); P: number of tanks in series.

#### 2.2.2. System robustness evaluation

To evaluate the robustness of individual systems, datasets with more than 30 data points for outlet P concentrations were used to simulate a five-parameter model following the method of Hartshorn et al. (2015) for evaluating drinking water treatment plants. In this context, robustness is defined as how well a system's performance (e.g. effluent P concentration) can cope with changes, such as variations in influent water quality or changing operational conditions. The effluent P concentrations from each system were assigned into 100 ranges or 'bins', and the occurrence of effluent P values falling within each bin was calculated and converted into a histogram. The occurrence was then converted to a cumulative frequency percentage of the maximum P concentration to normalize the data. Using a MasterPlex® 2010 (Miraibio, San Bruno, CA, USA), the percentage cumulative frequency and the phosphorus bin data were plotted, and a five-parameter logistic curve (5 PL) was fitted to the data (Equation (4)). The coefficient of determination ($r^2$) and root mean square error (RMSE) were calculated to evaluate the correlation and fit of the 5 PL curves, with the gradient of the steep part of the curve serving as an indicator of overall ICW robustness.

$$y = a + \frac{d}{\left(1 + \left(\frac{x}{c}\right)^b\right)^e} \quad (4)$$

Where a is the minimum asymptote, b is the gradient of the steep part of the curve, c is the value at the inflection point, d is the maximum asymptote, e is an asymmetry factor, y is the cumulative probability and x is the effluent P concentration.

#### 2.2.3. Impacts of liner on the water balance, cost and carbon footprint

The water balance of SF systems with artificial liners was calculated for three example sites in the UK with Eq. (5):

$$Q_{in} + Pr^*A + G^*A = Q_{out} + ET^*A + I^*A \quad (5)$$

where $Q_{in}$ is the average daily inflow to the system in each month ($m^3$/d), Pr is the average daily precipitation rate per month (m/d), A is total surface area of the wetland ($m^2$), G is the groundwater recharge or ingress (m/d), $Q_{out}$ is the daily outflow to system ($m^3$/d), ET is the evapotranspiration rate (m/d), I is the infiltration rate (m/d). For lined systems, I and G become zero. Note: the inputs from groundwater recharge were not typically identified in the datasets. Therefore, for unlined systems the value for water loss represents the net water volume discharged onto the subsurface.

Theoretical evapotranspiration (*ET*) values were calculated using the Hargreaves-Samani method (Hargreaves and Samani, 1982) based on the temperature recorded from nearby weather stations and extra-terrestrial radiation based on the sites' latitudes (Eq. (6)).

$$ET = 0.0023 * (T_{mean} + 17.18) * (T_{max} - T_{min})^{0.5} * 0.408R_a \quad (6)$$

where ET is the evapotranspiration potential (mm/month), $T_{mean}$, $T_{max}$, $T_{min}$ are the mean, maximum, and minimum air temperatures in °C, $R_a$ is the extraterrestrial radiation (MJ/$m^2$/month), 0.408 is a conversion factor for the commonly reported $R_a$ in MJ/$m^2$/month to mm/month, and 0.0023 is the original coefficient of the Hargreaves-Samani equation.

The relative change in effluent flow against influent flow (CEF, %) was calculated with Eq. (7).

$$\text{CEF}\ (\%) = \frac{Q_{out} - (Q_{in} + Pr * A)}{Q_{in} + P * A} \quad (7)$$

The costs associated with lining of the SF TW were obtained by extracting the capital costs from two unlined systems built in the UK for sewage applications that have been published in the literature (Cooper et al., 2020). The expected cost of different liner materials was added by a practitioner. To estimate the embedded carbon in the liner materials, the same two systems were used as examples, and carbon estimates were obtained by consulting the Infrastructure Carbon Estimator (ICE) database v3.0 (John, 2019). The ICE database provides carbon footprint values in terms of $kgCO_{2eq}$/kg material. The typical thickness for wetland applications of each of the liner materials was obtained from the practitioner, and their density was used to calculate the $kgCO_{2eq}/m^2$.

### 2.3. Statistical analysis

The statistical analyses were performed using the statistical analysis software PAST v.4.03. Prior to statistical analysis, the data were checked for normality and homogeneity of variance. Nonparametric test methods were used for the analysis if the variables were not normally distributed. Therefore, one-way analysis of variance followed by Tukey's Honestly Significant Difference test or Kruskal-Wallis test followed by Dunn's post hoc test were used to identify significant differences in effluent P concentrations from different SF TWs ($p < 0.05$).

## 3. Results and discussion

### 3.1. Global implementation of SF TWs for sewage treatment

A total of 85 SF TWs (Fig. 1a) were examined in this study (Table S1), with the majority being situated in North America (31), and Europe (33). The number of datasets collected from this study significantly surpassed the reported cases (4–19) from previous studies (Table S2). The size of the SF systems varies from 25 $m^2$ to 482 ha (2.17–54,779 $m^3$/d), with 59% of the systems ranging in size from 0.1 to 10 ha (Fig. 1b). The smallest system is the Peradeniya system (Table S1) from Sri Lanka, which covers an area of 25 $m^2$ and was constructed to treat domestic wastewater from a student hostel (Jinadasa et al., 2008). Of the five SF TWs that are over 100 ha, all are located in the USA (Dahl et al., 1998; Kadlec, 2009; Keller and Walker, 2004; USEPA, 1993; Wang et al., 2006). The largest system (SF12-34 in Table S1) with a surface area of 482 ha, is located in the USA and began operating in 1987 by the City of Orlando (Wang et al., 2006).

The Houghton Lake wetland system represents the earliest system with extensive P data, with recorded data spanning over 30 years from 1978 to 2007 (Kadlec, 2009). While the construction (or refurbishment) date of 16 systems is unknown (Fig. 1c), consultations with practitioners and data mining from public websites suggest that nine systems likely started between 2000 and 2010, and the remaining systems were built between 2011 and 2020. These data indicated that SF TW implementation has steadily increased since 2000. For P removal, a SF TW with extensive P data in the UK was constructed in 2000 (SF3-1 in Table S1) albeit to treat domestic wastewater from a visitor centre rather than specifically target P. The first SF TW fed from a STP in England was the River Mun system, built in 2014, with significant interest in the UK water industry triggered from the benefit quantification and funding model used by Anglian Water in the Ingoldisthorpe integrated constructed wetland (ICW; Cooper et al., 2020). By 2022, Anglian Water proposed building 26 new SF TWs to protect rivers and chalk stream

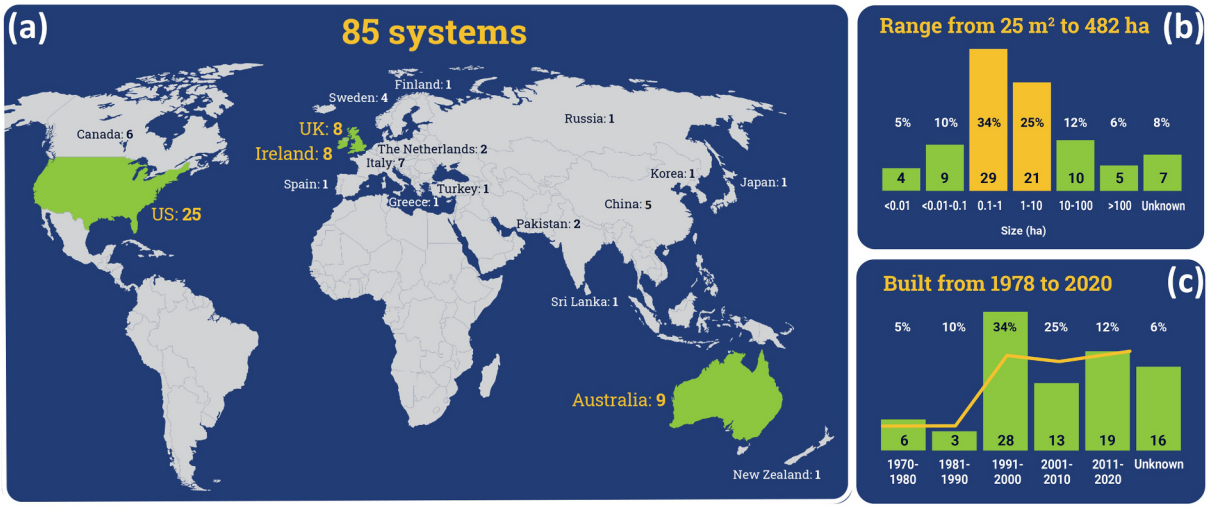



**Fig. 1.** Surface flow wetlands employed for sewage treatment from different countries or territories worldwide (a), and the distribution of system sizes (b) and ages (c).

habitats across the East of England (News, 2022) and Natural England had developed a framework for implementation of SF TWs in nutrient neutrality schemes (Natural England, 2022).

Of the collected datasets, 59 systems have the outlet P concentration measured for at least two years, and 26 systems from published literature only have informative data (e.g., average inlet and outlet P concentration). The collected systems fall into four target scenarios of tertiary treatment (with or without targeted upstream P removal), secondary treatment, and treatment of combined sewer overflow (CSO) or storm overflows (SO) (Table 1). Tertiary application of SF TWs is by far the most common use in sewage treatment worldwide. The most robust and complete datasets are available in North America and Australia, where systems typically serve medium and large STPs (10,000 to 400,000 P.E.). Secondary treatment SF TWs are less common, with many lacking information on start-up effluent concentrations and flow rates. Additionally, consents in many locations are based on Ortho P or no consent, making TP data unavailable.

### 3.2. Phosphorus removal performance

The median TP load reduction (areal mass removal) in the aggregated dataset for all SF TWs for sewage treatment was 5.13 gP/m$^2$/yr, which is similar to the reported value of 6 gP/m$^2$/yr (Kadlec and Wallace, 2008). The median Ortho P load reduction was 2.87 gP/m$^2$/yr which is lower than the TP removal indicating that multiple forms of phosphorus are being removed. The median removal percentages of TP and Ortho P for all systems, without distinguishing the target scenarios, were 28% and 31%, respectively (Table S3). The levels include much lower removal percentages than the 41%–71% previously reported (Kadlec, 2016; Land et al., 2016) and reflects the broader inclusion of sites such as ones primarily designed for N removal and/or ecosystem services.

**Table 1**
The total number of surface flow constructed wetlands per target scenario in this study.

| Scenario | Number of systems | Size (ha) | Start or upgrade year |
|---|---|---|---|
| Tertiary sewage treatment (without targeted upstream P removal) | 52 | 0.0088–354 | 1978–2020 |
| Tertiary sewage treatment (with targeted upstream P removal) | 21 | 0.23–482 | 1987–2020 |
| Secondary sewage treatment | 9 | 0.0025–3.6 | 1999–2012 |
| Treatment of combined sewer overflow (CSO)/Storm overflows (SO) | 3 | 0.45–9.3 | 2006–2018 |

#### 3.2.1. Tertiary treatment SF TWs

For the 52 tertiary systems without targeted P removal, the annual average influent concentrations of TP and Ortho P were 3.23 mg/L (range of 0.09–12 mg/L) and 3.56 mg/L (range of 1.9–8.8 mg/L), respectively (Fig. 2a). After undergoing treatment in SF TWs, the average annual concentrations of TP and Ortho P in the effluent reduced to 1.77 and 2.62 mg/L, equating to removal efficiencies of 45% and 26%, respectively. Similar removal efficiencies were seen for the 21 SF TWs treating effluent with targeted upstream P removal at levels of 50% and 27% for TP and Ortho P, respectively. This is despite the influent to the systems containing an initially lower average level of 0.3 and 0.8 mg/L for TP and ortho P, respectively (Fig. 2b).

For tertiary treatment SF TWs without targeted upstream P removal, the annual average effluent TP concentrations of individual systems can be classified into four groups: <1 mg/L (9 systems), 1–2 mg/L (12 systems), 2–3 mg/L (13 systems), and 3–9 mg/L (10 systems; Fig. 2c). Accordingly, approximately 80% of the 44 tertiary SF TWs without targeted upstream P removal produced annual average outlets TP concentrations of ≤3 mg/L. The influent quality of these systems was variable, with the majority receiving less than 6 mg/L TP. However, systems with inlet TP of up to 12 mg/L resulted in TP effluents above 3 mg/L (green dash line in Fig. 2d). To meet the increasingly stringent TP discharge limit set at 1 mg/L, evidence from the current dataset supports that this is possible for SF TWs fed with an inlet TP concentration lower than 3.2 mg/L and a TP load below 28.5 mg/m$^2$/yr (black lines in Fig. 2c–e). In the case of SF TWs combined with STPs that incorporated P removal (Fig. 2f), the effluent was consistently below 0.35 mg/L, when fed with TP of 0.09–0.75 mg/L (12 sites). One system (SF2-5) had a much higher effluent TP than all the others, which is due to the wetland's lack of P discharge consent target (i.e. it was not designed to achieve low effluent TP).

#### 3.2.2. Secondary treatment SF TWs

In this study, nine secondary treatment systems were included that followed either a septic tank or primary settling tank (Gunes et al., 2012; Ou et al., 2006; Tsihrintzis et al., 2010). The annual average effluent TP (nine systems) and Ortho P (five systems) concentrations of all the systems ranged between 0.31-8.48 and 0.2–8.16 mg/L, respectively (Fig. 3a). Six systems had both inlet and outlet TP data (Fig. 3b), and two

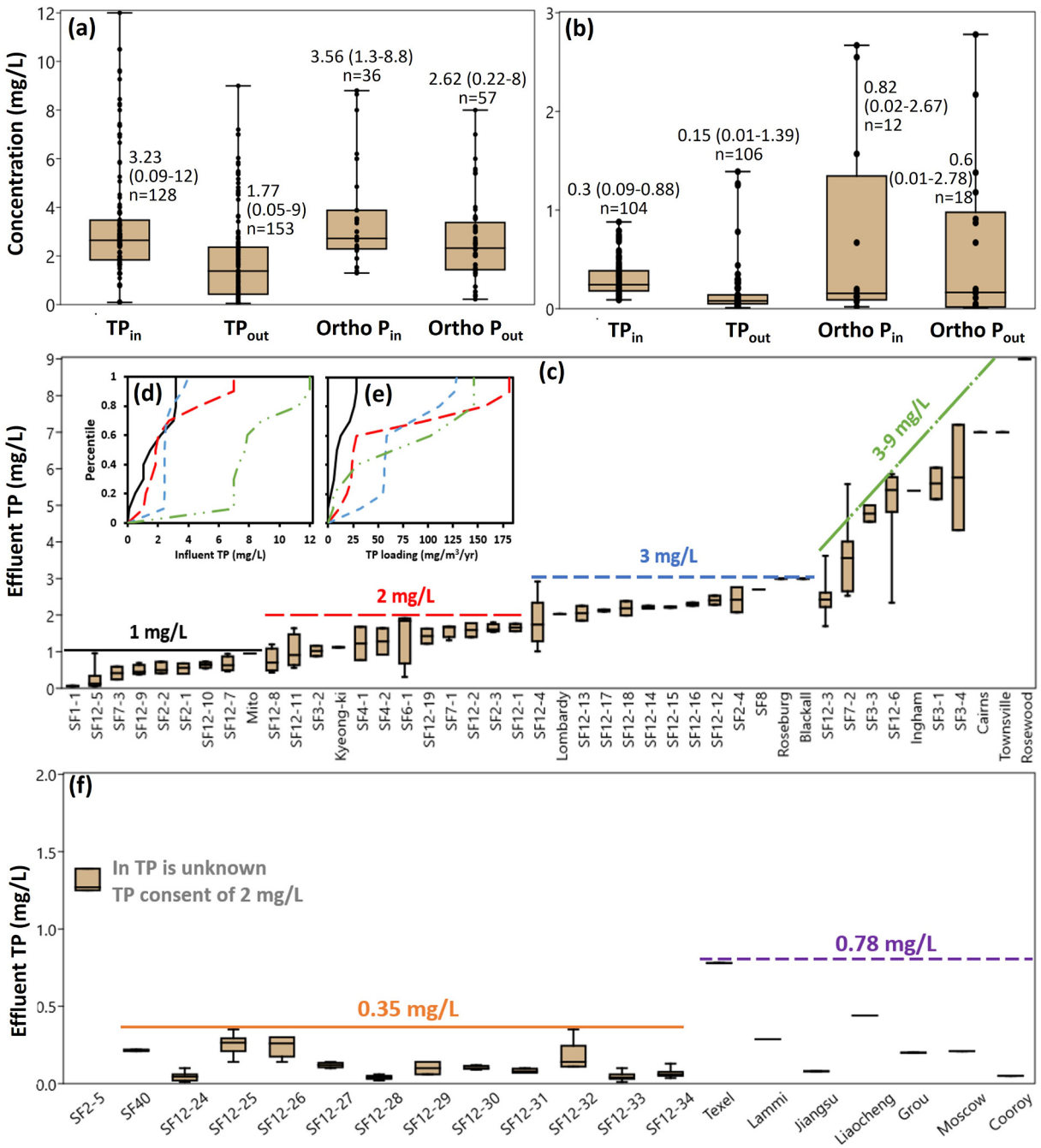



**Fig. 2.** Annual average concentrations of influent total phosphorus (TPin), influent orthophosphate (Ortho Pin), effluent total phosphorus (TPout), and effluent orthophosphate (Ortho Pout) of the SF TWs for tertiary treatment without (a) and with targeted upstream P removal (b). In the box-whisker plots, descriptive error bars represent the whole range of the data. Values above each box shows the mean (min-max). N represents the number of data points. (c) TPout from each SF TW for tertiary treatment without targeted upstream P removal; the percentile distribution of TPin (d) and TP loading (e) based on the four ranges of TPout identified in (c). (f) TPout from the systems for tertiary treatment with targeted upstream P removal. Data under orange solid line represents systems with long-term monitoring data; data under purple dash line represent informative data from literature for comparison purposes. The labelling of systems in the X-axis and associated grouping can be found in Table S1.

systems recorded inlet and outlet Ortho P concentrations (Fig. 3c). Based on the available information, the median annual average concentration reduction of TP and Ortho P was 53% (range from 10% to 81%) and 72% (range from 65% to 79%), respectively. The P removal efficiencies of secondary SF TWs were higher compared to tertiary treatment systems detailed earlier, which may be due to the generally lower hydraulic loading rate applied to the secondary systems (Table S1; Kayranli et al., 2010; Scholz et al., 2010). However, P removal in SF TWs can be affected by various factors, such as temperature, water depth, and vegetation coverage (Kadlec, 2016), and current dataset and recorded parameters were not able to distinguish between these key factors.

### 3.2.3. *Combined sewer overflow (CSO) or storm overflow (CO) SF TWs*

The use of SF TWs for the treatment of combined sewer overflow (CSO) or storm overflow (CO) is increasing. These systems typically combine grey infrastructure and other types of wetlands, such as vertical flow, horizontal, and aerated systems, to achieve treatment goals for solids, organics, ammonia, flow attenuation, pathogen removal, and

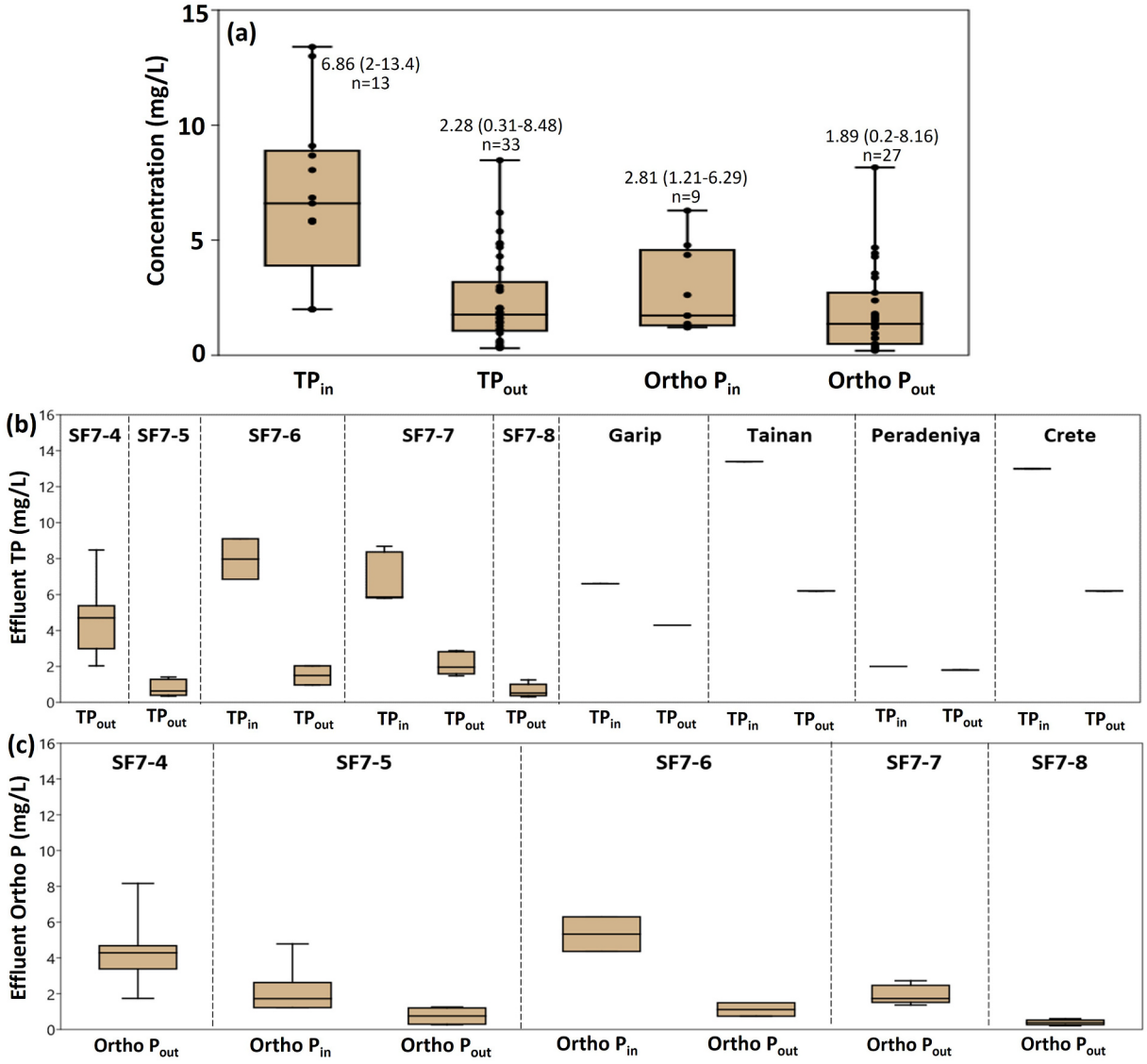



**Fig. 3.** The average concentrations of influent total phosphorus (TPin), influent orthophosphate (Ortho Pin), effluent total phosphorus (TPout), and effluent orthophosphate (Ortho Pout) of the SF TWs for secondary treatment (a); annual average influent and effluent concentrations of TP (b) and ortho P (c) from each secondary treatment wetland. The corresponding system names in the X-axis can be found in Table S1. Error bars represent the minimum and maximum mean values in each dataset and n represents the number of annual average value datapoints from all systems.

additional benefits (Rizzo et al., 2020). As a result, most SF TWs designed for CSO treatment are not intended to retain or indeed monitor P removal. In this study, only three systems reported P data from a total of 18 monitoring events (Hsueh et al., 2014; Ko et al., 2010). The average effluent TP concentrations ranged from 1.4 to 2.2 mg/L with influent concentrations ranging from 1.6 to 3 mg/L (Fig. S2). Obtaining data from such sites has added complexities as many systems operate dynamically, unlike steady-state sewage applications, and data collection relies on event-driven sampling, with a range of methods employed hindering interpretation and meaningful comparison.

### 3.3. System start-up and long-term performance

Due to variations in environmental and operational conditions, such as vegetation growth cycles, climate fluctuations, and changes in influent water quality, there is a need to evaluate whether SF TWs provide a reliable and resilient approach for P capture during sewage treatment in temperate climates. Previous studies have reported that start-up transients for large-scale SF TWs are likely but can be relatively short if a start-up strategy is adopted of holding the system in a no-flow condition until sorption and grow-in processes have stabilised (Kadlec, 2016).

In this study, 30 out of the 32 tertiary systems without targeted upstream P removal showed no long-term variability in average annual P removal. Two of the 32 systems showed a statistically significant increase in outlet annual average TP concentration after the first year of operation but remained relatively stable for the remainder of their monitoring of four to six years (Fig. 4a and Fig. S3). One system (SF12-5) exhibited variability in annual average outlet TP after 15 years, but the final effluent remained below 1 mg/L. Another system (SF12-3) exhibited a slight decrease in effluent TP concentrations, indicating a possible improvement in performance in years 3 and 4. However, a subsequent increase in levels and stabilisation in effluent TP concentrations were observed thereafter (Fig. 4b). Due to the variability within any given year, there was no statistical difference between start-up and subsequent years for these two systems. Tertiary systems with targeted upstream P removal produced highly consistent effluent concentrations for each year, starting from commissioning (Fig. 4c and Fig. S3). Overall,

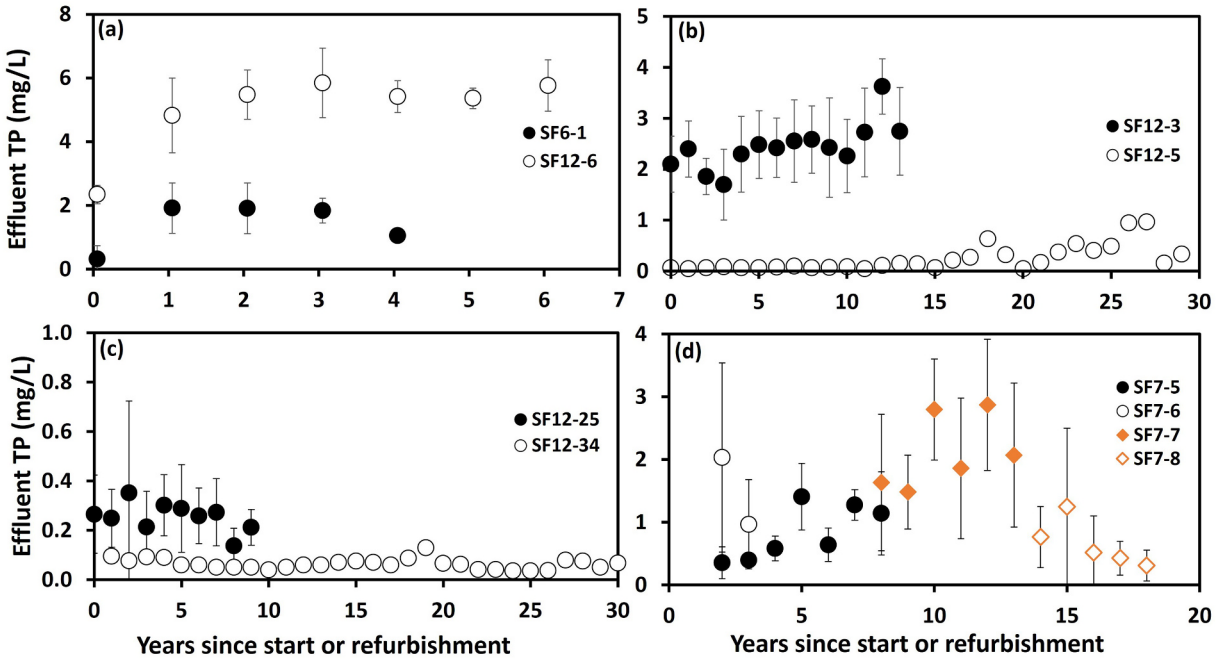



**Fig. 4.** Annual average effluent TP concentrations of (a) two systems with an increase between commissioning and their first year of operation from tertiary SF systems without targeted upstream P removal. Two examples of the other 30 tertiary SF systems without targeted upstream P removal (b), two examples of 12 tertiary SF systems with targeted upstream P removal (c), and four secondary treatment systems (d) showed no clear pattern for year-on-year changes. The error bars in the data indicate the standard variation of the annual values. The system names are shown in Table S1.

96% of tertiary SF TWs, including systems with and without targeted upstream P removal, showed no start-up period in terms of TP removal which remained consistent for the duration of the operational period. Secondary systems showed more variability in effluent concentrations achieved (Fig. 4d). The lack of flow and influent data prevents calculation of areal mass removal rates. However, the variability could be explained by the lack of upstream treatment processing to buffer influent characteristics fluctuations.

### 3.4. Seasonal performance and system robustness

The multi-year records were averaged per calendar month for each system from five secondary SF TWs, 10, and 18 tertiary systems with and without targeted upstream P removal, respectively. Overall, 85% of the systems with sufficient data lacked a seasonal variation in achieved effluent TP (Figs. S4a–d). This included 22 of the 28 tertiary SF TWs systems and all the secondary SF TWs. The remaining six SF TWs (two with targeted upstream P removal and four without) exhibited a seasonal pattern with peak effluent TP concentrations occurring during the summer months (months 4–8 for the Northern Hemisphere and 9–12 for the Southern Hemisphere; Fig. 5a and b). The summer peak in TP concentration, where it occurred, reflects anticipated changes in redox and temperature conditions in the sediment, leading to the temporary release of loosely bound TP, either by accelerating microbial decomposition processes or hastening of geochemical reactions within the buried P (Dunne et al., 2015). Regarding SF40 in Australia (Fig. 6a), zero outflow were occasionally observed in October, corresponding with an increase in outlet TP. This phenomenon is likely associated with the oxidation of dried-out sediment, as well as accelerated biota decomposition leading to TP release.

Further analysis through assessing the robustness of the different SF TWs for P removal revealed that the 89% of the tertiary SF TWs without targeted upstream P removal did not demonstrate robust profiles (Fig. S5). The robustness of tertiary SF TWs was significantly enhanced for system where targeted upstream P removal existed with five out of the six systems identified as robust (Fig. S6). Similarly, three out of the four secondary SF TWs (SF7-5, SF7-6 and SF7-8) had curves indicative of robust technologies, with steep gradients from the 50% tile mark (Fig. 5c and d). One system (SF7-8), albeit robust, exhibited a strong upper tail suggesting it could struggle under specific conditions encountered occasionally. The observed results reflect the lack of a predominant P removal mechanism under relatively high P load encountered in domestic wastewater treatment. The enhanced robustness for tertiary SF TWs with targeted upstream P removal is consistent with a reduction in load, more consistent influent concentrations, and a change in the speciation of the remaining P towards colloidal precipitates and dissolved Ortho P.

### 3.5. Modelling for system design and performance prediction

The data was fit to the P-k-C* model to identify the approximate ranges of removal rates for sizing secondary and/or tertiary SF TWs (Kadlec and Wallace, 2008; Kadlec, 2019). Whilst the model is primarily intended to aid representation of performance, it is widely used for sizing, including in nutrient neutrality schemes in England (Natural England, 2022). For secondary SF TWs, the data was of insufficient quality to be fitted. For tertiary SF TWs, median mass removal rates were almost an order of magnitude higher for systems without targeted upstream P removal (5.01 $g/m^2/yr$) compared to those with targeted upstream P removal (0.67 $g/m^2/yr$). This was primarily driven by the median inlet concentrations (2.6 mg/L) being an order of magnitude higher in those wetlands without targeted upstream P removal (0.2 mg/L) whilst also generally receiving higher hydraulic loading rates (Tables S4–S5). Interestingly, despite these differences, the median calculated rate coefficients (k) were relatively similar with (6.79 m/yr) and without (5.31 m/yr) targeted upstream P removal. However, the median k rates are lower than the median literature value of 12.9 m/year (Kadlec, 2019). Overall, the wetlands in our study exhibited a broad range of load removal rates and k-rates across the years of record. This demonstrates that there is not one universal phosphorus k-rate or mass removal rate which applies to all SF wetlands, but rather a range of possible rates depending on wetland-specific factors, including inlet

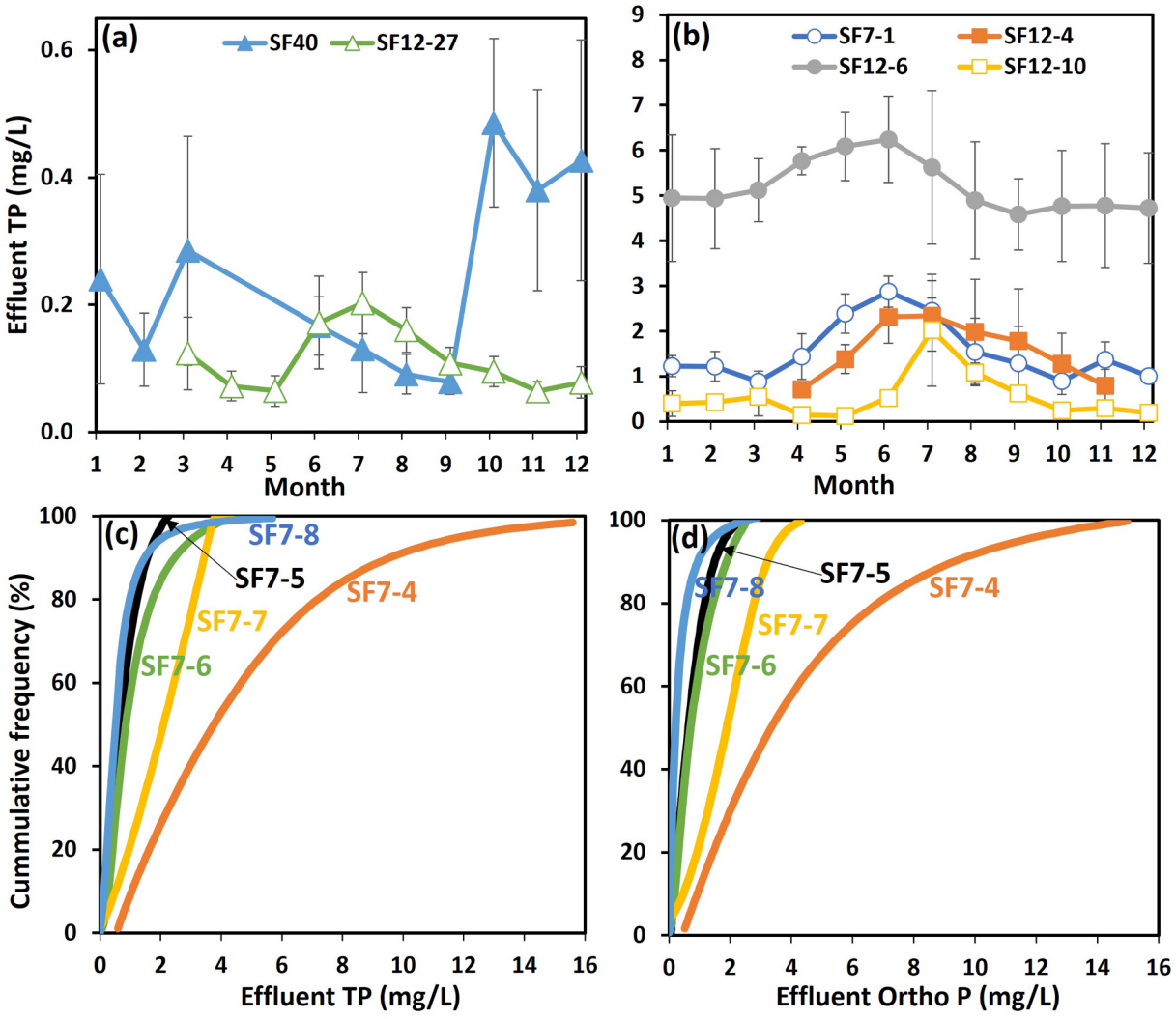



**Fig. 5.** Effluent total phosphorous (TP) concentrations from SF TWs for tertiary treatment based on monthly averages, (a) with targeted upstream P removal, (b) without targeted upstream P removal. The cumulative probability curves of the effluent TP (c) and Ortho P (d) from five secondary treatment systems. More vertical lines are indicative of inherently robust systems.

concentrations and composition, hydraulic loading rates, water depths, hydraulic efficiency, climatic conditions, vegetation type and condition, soil and sediment characteristics, wildlife interactions and other operational variables that each wetland may have been exposed to (e.g. dry-out periods, plant harvesting or sediment disturbance).

Model simulations were conducted based on different ranges of influent TP concentrations for the tertiary SF TWs using the median k rates (Fig. 6). All data sets showed high levels of scatter around the model curves that increased in variability as the influent concentration increased. Overall, this suggests caution when using the model to size for P removal. This finding was consistent with feedback provided by practitioners during workshops, who noted the widespread use of the P-k-C* model for sizing SF TWs, but cautioned against its use for targeting specific TP removal rates. Practitioners reported on using the median k rates from textbooks, along with discretionary safety factors, post-wetland reactive media filters, or coarser sizing methods (such as $m^2$/PE) with an added safety factor.

### 3.6. Construction, operation, and maintenance recommendations

Compacted local soils and plastic liners were used in the reported SF TWs. In the current study, monthly water balances were only able to be conducted on three lined systems (located in the South of England and Wales) which revealed relatively small changes in monthly effluent flows relative to influent flows, with fluxes ranging from increases of +5.4% to losses of −8.6% for the most variable system (Fig. S7a). The greatest water deficit occurred during the summer months, when the evapotranspiration abilities of common marsh plants were twice the average monthly rainfall captured by the system. In comparison, a previous study conducted in Ireland reported a water loss of 5.3 ± 2.7% of the total influent flow due to infiltration, with an additional 24.6 ± 12.7% lost to evapotranspiration in an SF TW lined with natural soil (Dong et al., 2011). Higher infiltration values have been reported from a farm runoff treatment SF TW with an infiltration rate of approximately 50% of the influent flow (Mustafa et al., 2009; Scholz et al., 2007).

To balance the positive impact of plastic liners on infiltration, the economic and environment costs were summarised in Table S6 for seven different artificial liner materials used by wetland contractors based on the capital costs published for two unlined SF TWs constructed in the UK (Cooper et al., 2020). Depending on the chosen liner material, the estimated additional cost to wetland construction could range from 5% to 50% of the unlined values (Fig. S7b). Importantly, the calculations did not include any design fees or additional costs associated with project delivery. For the same costed schemes, the embedded carbon dioxide equivalents ($kgCO_{2eq}$) associated with HDPE, LDPE and PVC (sandwiched between geotextile layers) were also calculated (Table S7). The

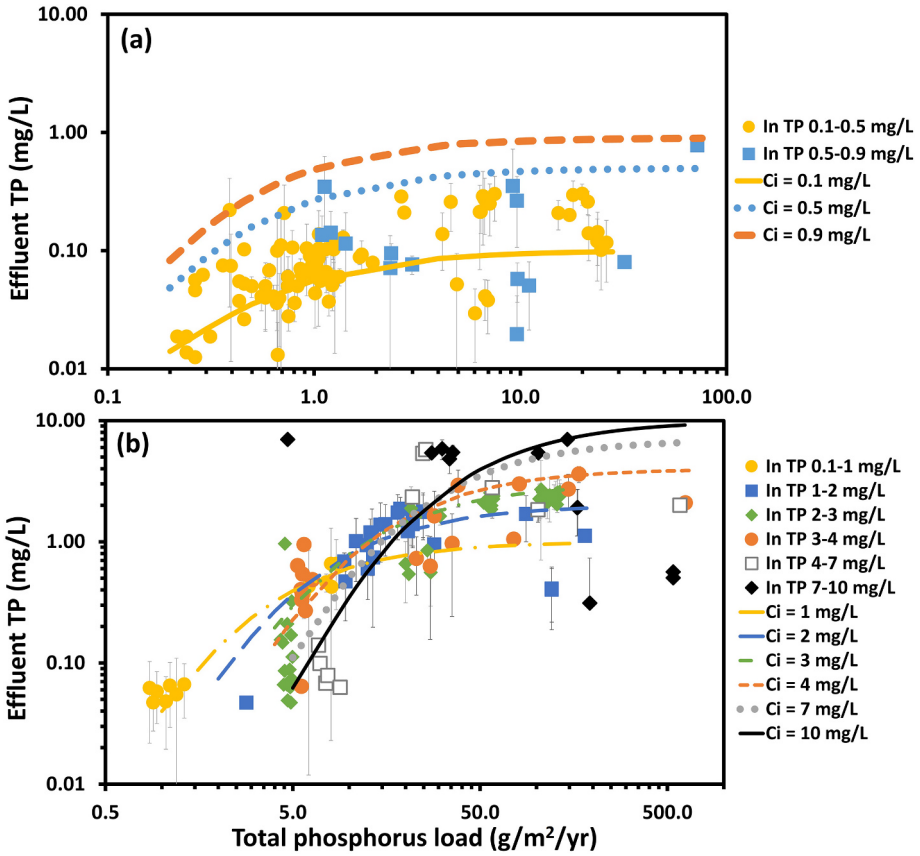



**Fig. 6.** Outlet TP concertation response to inlet TP loading of (a) 18 SF TWs for tertiary treatment with targeted upstream P removal and (b) 30 SF TWs for tertiary treatment without targeted upstream P removal. Symbols represent annual average data. In (a), n = 88 for the 0.1–0.5 mg/L inlet range and n = 14 for the 0.5–0.9 mg/L inlet range. Lines represent bounding model calculation for k = 6.79 m/yr, C* = 0.006, and P = 4. In (b), n = 13 for the 0–1 mg/L inlet range, n = 24 for the 1–2 mg/L inlet range, n = 47 for the 2–3 mg/L inlet range, n = 19 for the 3–4 mg/L inlet range, n = 12 for the 4–7 mg/L inlet range, n = 12 for the 7–10 mg/L inlet range. Lines represent bounding model calculation for k = 5.31 m/yr, C* = 0.006, and P = 4.

embedded emissions were found to be between 700 and 1200 and 23,000–41,000 $kgCO_{2eq}$ for the 0.3 and 1 ha systems, respectively. This is equivalent to between 2 and 95 barrels of oil consumed (USEPA, 2021). In summary, the cost of the liner, rather than the embedded carbon, would be the main concern to apply liner in SF TWs for sewage treatment.

Reported operational practice to enhance P removal included increased frequency of plant harvest (Li et al., 2018; Toet et al., 2010; Vymazal, 2020), selecting special plant species to enhance uptake (Rodrigo et al., 2018) and sediment dredging to improve water depth and hydraulic retention as well as reducing internal P loading from sediment-water interactions (Hernández-Crespo et al., 2016; Wang et al., 2006). Whilst significant emphasis has been placed on vegetation management, it is well-recognised that most of the P will be stored in sediments (Kadlec, 2019). The frequency at which these sediments accrue and therefore require removal and disposal will be a result of multiple factors, including loading rates, organic degradation rates, and water-sediment disturbances. In addition, enhanced removal has been targeted through the use of hybrid systems such as coupling SF TWs to substrate amendment and reactive barriers (Dotro et al., 2017), geochemical augmentation (chemical dosing; Austin et al., 2018) and catchment management approaches (Water Magazine, 2023). Unfortunately, there is a paucity of systematic data collection to provide a robust evidence base about the efficacy of these approaches to date and remains an area for priority activity.

Finally, management practices must also consider unintended risks, such as their potential to act as mosquito breeding grounds. This has been studied for over two decades in tropical and subtropical climates (Greenway et al., 2003). With the impacts of climate change shifting potential vector mosquitoes towards higher latitudes, the implementation of SF TWs will need to consider the learning from warmer climates to ensure the risk of mosquito breeding is minimised. Numerous strategies have been proposed, including encouraging macroinvertebrate populations and diverse plant communities (Greenway et al., 2003), modifying water depths (Diemont, 2006), and discouraging low oxygen environments (Dale et al., 2007).

### 3.7. Perspectives on using SF TWs for P removal

Currently available design guidance is based on mixed data sources, where influent wastewater characteristics and variation in wetland design and operational details are combined resulting in large spread in datasets (e.g., Kadlec, 2019). When limiting the analysis to domestic wastewater treatment and engineered SF wetlands, analysis of the obtained 85 raw datasets suggests variable effluent concentrations in SF systems without targeted upstream P removal (secondary and tertiary applications), partly due to the much higher variability in the inlet loading experienced by these SF TWs. This group included the low proportion of systems that exhibited start-up and/or seasonality effects. This variability is not unique to TWs, with other types of biological treatment systems where design is not optimised for P removal exhibiting a similar behaviour. Because SF TWs have a mechanism for long-term sequestration of P in the form of sediment and soil accretion (Kadlec, 2019), the opportunity lies in developing design criteria that enables robust, predictable performance, harnessing the natural processes that dominates in some but not all the systems analysed in this

work.

The data that better fitted the P-k-C* model corresponded to chemically dosed effluents feeding tertiary SF TWs (RMSE = 0.171) compared to the tertiary systems without targeted upstream P removal (RMSE = 1.682). This suggests that, for this application, designers can apply this tool for the design using removal rates tabulated in this study (Table S4). As common to all wastewater treatment process design, there will be an element of designer's experience and professional criteria in selecting the level of acceptable risk in choosing the removal rates from the percentiles presented. In general, if the P removal performance of upstream treatment processes is more stable, this will result in a more stable outlet concentration from any downstream SF TW. The application of SF TWs as a polishing step to sustainably achieve very low effluent concentrations following chemical or biological P removal systems is becoming increasingly common.

This work has synthetised the available evidence for the use of SF TWs for P capture from domestic wastewater. The opportunities for using multiple benefit SF TWs instead of the grey alternatives require gaps in this study to be addressed as a matter of priority if the right infrastructure will be recommended for rollout. To address these, future research should focus on.

1) Intensive monitoring and mechanistic research through the collection of targeted datasets from either existing sites or new trials for systems relying on biological (and biologically mediated) processes for long-term capture of P as opposed to physical processes.
2) Development of design guidance based on target total phosphorus effluent quality considering spot-based annual averages whilst providing ranges of effluent concentrations expected to enable quantification of acceptable risk.
3) Detailed, flow proportional characterisation of P removal performance in event-driven SF TWs used in CSO and SO applications.
4) Future proofing of developed flowsheets to consider greater emphasis placed on multiple benefits (e.g. carbon, biodiversity, biomass production) and the targeting of other pollutants (e.g. micropollutants).

## 4. Conclusions

Surface flow treatment wetlands have been used for capturing P from domestic sewage treatment plants for over three decades worldwide. This study synthetised the evidence on SF TWs treating domestic wastewater. The analysis showed most tertiary SF TWs without targeted upstream P removal can achieve ≤3 mg/L annual average effluent TP, and <1 mg/L under influent TP < 3.2 mg/L and load <28.5 mg/m2/yr. Tertiary SF TWs with targeted upstream P removal showed robust performance, delivering stable effluent total P < 0.35 mg/L, partly due to the lower and more consistent inlet concentrations delivered to the wetlands by the dedicated P reduction process. Most systems exhibited no seasonal variation in P removal (85%) and stable effluent total P over 30 years (95%). Additionally, 96% of systems showed no start-up variation in P effluent concentrations. The results provide a targeted, robust basis for further development of design guidance and predictive models. Uncertainties remain on how to predict and limit variability in systems receiving higher and more variable inputs of P from treatment plants without dedicated P reduction processes, to unlock the ability of SF TWs to provide sustainable P capture.

## CRediT authorship contribution statement

**Tao Lyu:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tom Headley:** Writing – review & editing, Formal analysis. **Robert H. Kadlec:** Writing – review & editing, Formal analysis, Data curation, Conceptualization. **Bruce Jefferson:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Gabriela Dotro:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Gabriela Dotro reports financial support was provided by Anglian Water, Dwr Cymru Welsh Water, Northumbrian Water, Severn Trent, South West Water, Southern Water, Thames Water, United Utilities, Wessex Water, Yorkshire Water, the Environment Agency, and Irish Water. Gabriela Dotro reports a relationship with Constructed Wetland Association that includes: board membership. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.122392.

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# Phosphorus removal in surface flow treatment wetlands for domestic wastewater treatment: Global experiences, opportunities, and challenges

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