

Article

The Development and Future-Proofing of Treatment Wetlands as Nature-Based Solutions in the UK Water Sector: Southern Water Case Studies

Pramila Bhandari Phuyal ^{1,2}, Joff Edevane ² and Tao Lyu ^{1,*} ¹ Faculty of Engineering and Applied Sciences, Cranfield University, College Road, Cranfield MK43 0AL, UK; pramilabhandari.phuyal@southernwater.co.uk² Southern Water Services Ltd., Yeoman Rd., Worthing BN13 3NX, UK; joff.edevane@southernwater.co.uk

* Correspondence: t.lyu@cranfield.ac.uk

Abstract

Treatment wetlands (TWs) are increasingly deployed as nature-based solutions for water and wastewater management due to their cost-effectiveness, operational simplicity, and provision of wider ecosystem benefits. The UK has been at the forefront of TW application since the 1980s. This study evaluated their development and performance within Southern Water, a water utility in the UK. In total, 35 sewage treatment sites have incorporated TWs since 1991, primarily for tertiary treatment and stormwater overflow control. Performance data were available for 16 sites, comprising 14 horizontal subsurface flow (HSSF) and two surface flow (SF) wetlands. HSSF wetlands achieved substantial reductions in TSSs (up to 97%), NH_4^+ (up to 99%), and BOD_5 (up to 92%). The COD removal showed more variance (0–62%) in the studied sites. In contrast, SF wetlands provided moderate reductions in TSSs (17–79%) and COD (36–67%) but were less effective for NH_4^+ and BOD_5 (14–65%). The TWs operated by Southern Water currently serve more than 100,000 people and illustrate the expanding role of such systems in meeting wastewater treatment needs. However, challenges and further research are needed, including risks of media clogging, the evaluation of emerging micropollutants treatment, and inconsistent maintenance. To address these, the study highlights opportunities for innovation through hybrid and aerated designs, advanced monitoring, and a more detailed understanding of plant–microbe interactions. The findings emphasise both the potential and future research needs of TWs and support their continued integration into wastewater management strategies under evolving environmental and regulatory pressures.

Keywords: constructed wetlands; green infrastructure; storm overflows; UK water industry; wastewater treatment



Academic Editor: Bin Gao

Received: 26 January 2026

Revised: 20 March 2026

Accepted: 22 March 2026

Published: 24 March 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Nutrient discharge from untreated or insufficiently treated wastewater poses a significant environmental risk to rivers, ponds, and ecosystems, leading to eutrophication and degraded water quality [1–3]. Moreover, the increased occurrence of combined sewer overflows (CSOs)/storm overflows (SOs) results in pollutant overloaded discharges that can further harm ecosystems and public health [4]. Fewer than 40% of European rivers and streams achieve good ecological status defined by the European Water Framework Directive, with only 14% of English rivers meeting this standard [5]. The UK has set regulatory targets to improve freshwater quality, including an 80% reduction in phosphorus loadings

from treated wastewater. However, pressures on wastewater treatment plants (WWTPs) and CSO spills are anticipated to increase due to climate change, urbanisation, and rising water demand [6]. Therefore, there is an urgent need for enhancements in wastewater treatment to meet stricter regulations.

With sustainable water management garnering increased attention, nature-based solutions (NbSs) have emerged as a practical solution, gaining significant attention globally and in the UK for their capabilities for water and wastewater management [7]. Previous studies and implementations have demonstrated that NbSs not only improve water quality but also offer flood and drought protection as well as air pollution control [8,9]. Treatment wetlands (TWs) are one of the [10,11] most widely implemented NbSs which have been effectively used to treat various wastewater types, including municipal, industrial, landfill leachate, stormwater, agricultural, and mine drainage [12]. The use of TWs for domestic wastewater treatment has grown worldwide due to their characteristics of effective pollutant removal, low energy requirements, ease of maintenance, and relatively low construction and operating costs.

Pollutants, including organics, nutrients and other micropollutants, can be removed from wastewater in TWs through a combination of physical, chemical, and biological processes. The relative contributions of these processes differ significantly between various types of TWs, depending on whether they operate under predominantly aerobic conditions (e.g., vertical flow TWs) or under anoxic/anaerobic conditions (e.g., surface flow or horizontal subsurface flow TWs) [13]. The UK has been at the forefront of adapting TWs for wastewater treatment, with the first site implemented in the 1980s [14]. UK water utilities deployed and operated the majority of the TWs within their WWTPs, particularly in small works serving fewer than 2000 PE, and have developed relevant guidelines for their application and design. Therefore, this study aims to review the development and performance of TWs in one of the UK's major water utilities, i.e., Southern Water, as well as to compare these with other case studies to support the future development of NbSs in the UK water sector. The specific objectives are to: (1) Summarise the distribution and utilisation of TW types in Southern Water; (2) assess treatment performance and compare it with other selected case studies from other UK water utilities; and (3) identify challenges and propose innovative solutions to enhance treatment performance. Results from this study will generate lessons from UK case studies and provide valuable insights for future scaling and innovation.

2. Materials and Methods

2.1. Data Collection and System Characterisation

Data for this study were obtained internally from Southern Water and included detailed information on a total of 35 TW sites. This covered the types of wetlands utilised, types of treatment, installation years, design specifications, and operational conditions. Notably, each TW site is typically made up of 1–4 wetland cells within a WWTP. The majority of TWs were only monitored for final effluent to assess compliance with discharge consents, while 16 wetland systems had both influent and effluent data available, enabling assessment of treatment performance over monitoring periods of 1–2 years. The dataset spans the period from 1991 to 2024 and was originally collected by company personnel during routine monitoring and reporting processes.

To ensure data quality and consistency, the dataset was reviewed and screened prior to analysis. This process included checking for completeness, consistency of units and parameter definitions, and the removal of duplicate or clearly erroneous entries. Data points with missing key variables required for performance evaluation were excluded from the analysis. The monitoring data were generated using standard sampling and analytical

procedures routinely applied by Southern Water for regulatory compliance monitoring. Following this quality assurance and quality control (QA/QC) process, the dataset was considered suitable for the subsequent analysis.

2.2. Dataset Analyses

Different TW types, design parameters, their application, and performance were explored, including both surface and subsurface flow wetlands. Key aspects such as performance standards, wetland classifications, wetland sizes, population coverage, and process complexity were analysed for all 35 TW sites operated by Southern Water. Due to performance data availability, 16 TW sites were assessed for their treatment efficiency in removing biochemical oxygen demand (BOD₅), chemical oxygen demand (COD), total suspended solids (TSSs), and ammonium (NH₄⁺). For statistical analysis, non-parametric Kruskal–Wallis tests were conducted in SPSS (IBM SPSS Statistics Version 28) to examine differences in treatment performances between the 14 horizontal subsurface flow (HSSF) and two surface flow (SF) TWs. The non-parametric approach was selected due to the relatively small sample size and the non-normal distribution of some variables within the dataset.

2.3. Other Case Studies and Comparison

To supplement the secondary data, an interview was carried out with wetland experts within Southern Water, with consent obtained beforehand. Such consultations were held to explore trends in wetland development, highlighting how systems were selected not only by the availability of alternative technologies but also by regulatory requirements. The qualitative insights gained from the interview helped clarify ambiguous findings and enhance the overall understanding of wetland performance. Challenges such as land availability, effluent quality requirements, and operation and maintenance capability were also discussed. Moreover, various case studies from different UK water companies, as summarised in the Constructed Wetland Association (CWA) report by Dotro and Williams (2025) [14], were reviewed to provide evidence of the practical application of TWs across the UK. Additional industrial publications were also examined to identify wetland case studies and evaluate the key qualities that contribute to sustainability in response to evolving environmental challenges.

3. Results

3.1. The Applications of Treatment Wetland in Southern Water

Southern Water is a regional water utility in the southeast of England that serves an area of approximately 4450 km² and a population of 4.6 million for both water and wastewater treatment services. It has over 360 WWTPs across Kent, Hampshire, Sussex, and the Isle of Wight (location map). The deployment of TWs in Southern Water began in 1991 (Figure 1a); however, the cumulative number of wetlands increased very slowly from 1991 to 2000, with only seven wetlands installed. Afterwards, there was a swift development from 7 to 34 wetlands until 2014, indicating a major wetland expansion in that period. The number reached 35 in 2023, with one additional system constructed that year, showing that the rate of new TW installations has begun to stabilise.

Following the similar deployment trend, the cumulative population served and total surface area of TWs (Figure 1b) remained quite low between 1991 and 2000, except in 1995 when there was a significant spike in population due to the installation of a large wetland of 1.7 hectares. As of 2000, the population served was 24,000. There was another phase of wetland expansion from 2000 to 2014, and the total population served increased from 24,000 to 99,000, while the surface area surged from 1.9 hectares to 3.8 hectares. This

trend reflects not only an expansion in infrastructure but also the optimisation of previous systems to serve larger catchments. After 2014, the growth rate stabilised with minimum changes up to 2023, with a total served population of 103,000 and total surface area of 3.86 hectares. This decline in wetland installation is possibly due to the introduction of new stricter consent from regulators.

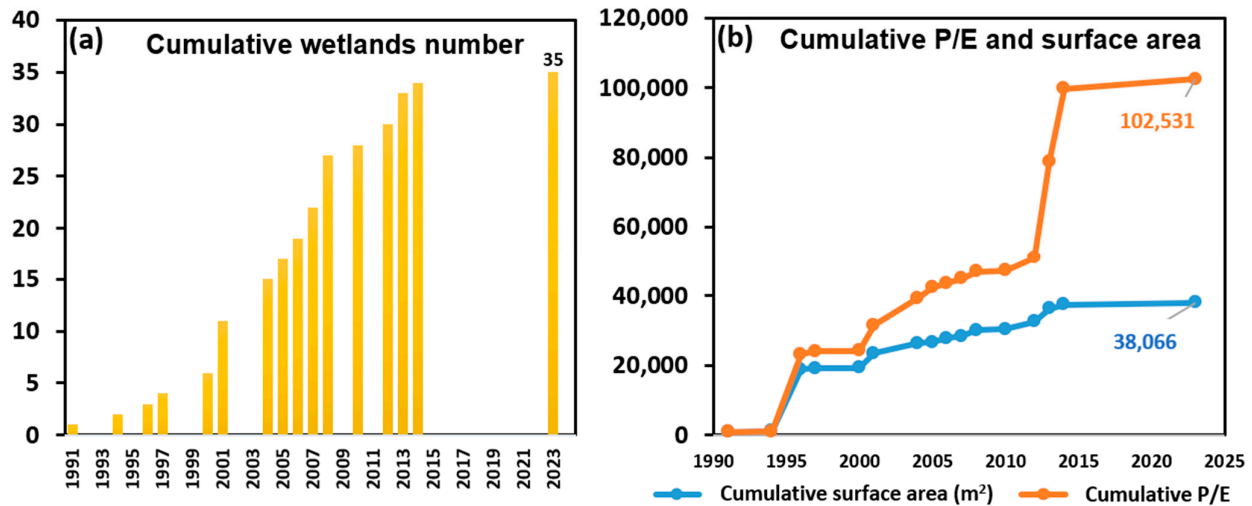


Figure 1. (a) Cumulative treatment wetlands deployed in Southern Water, and (b) the cumulative population served (P/E) and surface area of the treatment wetlands.

3.2. Treatment Wetlands Type and Geographic Distribution

Within the 35 applied TW sites, four wetlands were used for stormwater treatment and the other 31 wetlands for tertiary sewage treatment equipped with existing domestic WWTPs (Figure 2). Regarding the TW types, the sample consisted of 32 HSSF TW sites, one VSSF TW site, and two SF TW sites. Wetland treatment currently serves 0.103 million people out of a total of 2.26 million customers for wastewater and covers approximately 3.8 hectares of land. Among the 35 wetland sites, eight serve populations below 1000, 19 serve population less than 2000, while the remaining eight cover larger customer bases with a population exceeding 2000. The wetlands installations are distributed across all regions, including Kent (nine sites), Sussex (nine sites) and Hampshire (17 sites). Notably, the Isle of Wight has a high density (six sites) of this nature-based solution for wastewater management.



Figure 2. Treatment wetland types and locations in Southern Water, UK.

3.3. Infrastructure and Design Guidelines of Treatment Wetlands

According to the design guidance and suggestions utilised in Southern Water [15], SF wetlands are applied for storm and tertiary wastewater treatment due to the relative lower treatment performances compared to HSSF and VSSF TWs. Additionally, SF wetlands require a large surface area, making them impractical for sites with limited space. Both HSSF and VSSF wetlands are appropriate for secondary, tertiary, and CSO treatment. Moreover, HSSF TWs equipped with mechanical aeration have been used in Southern Water to obtain biological treatment utilising the enhanced growth of aerobic bacteria that are crucial for effectively degrading organic matter and ammonia [16].

TWs can be sized using various methods, including rule of thumb, regression equation, mass loading charts, and the P-k-C* model [6,13]. The design and construction of VSSF and SF TWs in Southern Water were carried out by external suppliers using their own design guidelines. However, Southern Water has developed its own guidelines for HSSF TWs, which is based on the Kickuth equation (Equation (1)), a modified version of the well-known K-C* model [17]:

$$A_h = Q_d \times (\ln C_o - \ln C_t) / K_{BOD}, \quad (1)$$

where A_h = bed plan area, m^2 ; Q_d = average daily flow rate of sewage, m^3/day ; C_o = daily average BOD_5 of feed, mg/L ; C_t = required daily average BOD_5 of effluent, mg/L ; K_{BOD} = rate constant, m/day .

A design minimum of $0.5 m^2/head$ is applied to tertiary or storm TWs if the value calculated using the Kickuth equation is less than the value per head of population served. When constructing a wetland bed, length should be between 10 and 12.5 m, width should be between 0.06 and 0.08 m/head of population served, and depth should be a minimum of 0.6 m. If the wetland area is a crucial factor or where ammonia removal is required, aerated TWs can be provided which can reduce the dimensions required; however, OPEX would be increased due to the application of aeration. A minimum number of two TW cells should be installed, with each sized at 50% of the calculated TW area. The design should allow for separate feed and outlet pipes so that one bed can be removed from service without loss of all treatment wetland treatment, and a rodding point should be provided for both inlet and outlet pipes.

The first 0.5 to 1.5 m of HSSF TWs is constructed with 60 to 100 mm diameter washed gravel to ensure equal flow distribution across the full width of the bed. The rest of the TW is filled with 10 mm diameter washed gravel; bed depth should be 0.6 m at the inlet followed by a gradient of between 1 and 5% falling to the outlet. The surface of the TW should be level and a layer of at least 50 mm of sand placed beneath the liner to ensure there is no damage to the liner.

The outlet collector pipe should be a suitable perforated drainpipe located at the bottom of the treatment wetland, covered by 300 mm of washed gravel (60 to 100 mm in diameter). This pipe connects to a sump for level control, overflow, and drainage, with the sump bottom 150 mm lower than the treatment wetland. Water flows through a vertical Tee connection overflow, rising 400 mm above the gravel, into the sump via an adjustable level control pipe. A swivelling arm controls water levels and can drain the bed completely by rotating over 90 degrees. A chain allows for fixing the outlet pipe in place and an overflow system facilitates the discharge. For most applications, the plants used for constructed wetlands were *Phragmites australis*.

3.4. Performance of Existing Southern Water Treatment Wetlands

TWs in Southern Water have been mostly used for TSS, NH_4^+ , COD and BOD_5 removals aligning with the required discharge permit. Southern Water routinely examines

final effluent performance as part of discharge permit compliance monitoring; therefore, effluent data is available for most sites. However, influent data of the TWs is not consistently collected. As the objective of this study was to understand wetland treatment performance, only 16 sites (out of 35) with both influent and effluent data were included in the analysis. Performance data were collected from spot samples taken in different years, with most site data originating from when the wetlands were initially commissioned. Additional data were obtained from a report in which Southern Water implemented a monitoring plan to assess wetland performance, resulting in a summary of treatment performance across all 16 sites (Table 1).

Table 1. Wetland performance data, including treatment types, wetland types, and average concentrations of four different contaminants (N.A. in the table represents that the data are not available).

Wetland Types	Treatment Types	Surface Area (Hectare)	Wetland Year of Construction	TSS mg/L Inlet	TSS mg/L Outlet	NH ₄ ⁺ mg/L Inlet	NH ₄ ⁺ mg/L Outlet	BOD ₅ mg/L Inlet	BOD ₅ mg/L Outlet	COD mg/L Inlet	COD mg/L Outlet
HSSF 1	Tertiary	0.0916	2001	2	2	1.28	0.64	5.7	5.7	N.A.	N.A.
HSSF 2	Tertiary	0.04	2007	2	2	0.05	0.05	5.7	5.7	N.A.	N.A.
HSSF 3	Tertiary	0.0405	2001	2	2	0.64	0.64	5.7	5.7	N.A.	N.A.
HSSF 4	Storm and Tertiary	0.012	2013	12	10	5.63	0.0749	12	3.78	58	42
HSSF 5	Tertiary	0.135	2004	17.4	11	0.923	0.753	9.94	7.33	N.A.	N.A.
HSSF 6	Tertiary	0.008	2007	5.2	2	0.156	0.05	5.7	5.7	N.A.	N.A.
HSSF 7	Tertiary	0.0349	1997	24.9	8.2	4.9	1.9	21	5.9	147	48
HSSF 8	Tertiary	1.78	1996	15	3	4	1	11	2	N.A.	N.A.
HSSF 9	Tertiary	0.026	2005	11	2	0.88	0.08	7	1.5	50	32
HSSF 10	Storm	0.062	2022	17	3	2.9	2.4	13.4	4.2	N.A.	N.A.
HSSF 11	Tertiary	0.0446	2004	22	3	N.A.	N.A.	12.6	4	72	39
HSSF 12	Tertiary	0.0185	1994	19.2	2	1.14	0.64	5.7	5.7	N.A.	N.A.
HSSF 13	Tertiary	0.09	1991	30	3	2	0.1	20	1.6	N.A.	N.A.
HSSF 14	Tertiary	0.0071	2007	71.6	2	58.2	50.8	75.1	13.7	N.A.	N.A.
SF 1	Tertiary	0.01	2000	87	18	27	29	34	12	214	101
SF 2	Tertiary	0.35	2013	12	10	0.318	0.36	3.5	3	28	20

Table 1 presents the average influent and effluent concentrations of 14 HSSF and two SF TW sites, without distinguishing between individual wetland cells from each site. HSSF 4 is the only TW designed to treat both stormwater and tertiary sewage. The average influent TSS concentration was 12 mg/L, reduced to 10 mg/L after wetland treatment. Similarly, the influent NH₄⁺ concentration of 5.63 mg/L decreased to 0.0749 mg/L in the effluent, demonstrating significant removal performance. The influent BOD₅ concentration was 12 mg/L, while the effluent concentration remained at 3.78 mg/L. This pattern is observed across all listed wetland treatment types in Table 1, with the exception of NH₄⁺ in the effluent of HSSF 14, showing reductions in TSS, NH₄⁺, BOD₅, and COD concentrations from inlet to outlet.

The majority of HSSF TWs performed well for TSS removal, with seven sites (HSSF 8–14) achieving 79–97% of removal under the influent concentrations of 11–71 mg/L (Figure 3a). Extreme lower TSS influent concentrations of 2 mg/L appeared for three HSSF TWs (HSSF 1–3), with the effluent concentrations remaining at the same level of 2 mg/L, with limit reduction. The stormwater treatment HSSF TW (HSSF 10) shows similar levels

of treatment performance (82%) compared to those used for tertiary treatment. A similar TSS removal of 79% was found for the SF TWs (SF1); a lower TSS removal (17%) appeared while both influent and effluent TSS removal were much lower (10–12 mg/L) at the SF2 site compared to those (18–87 mg/L) at the SF1 site.

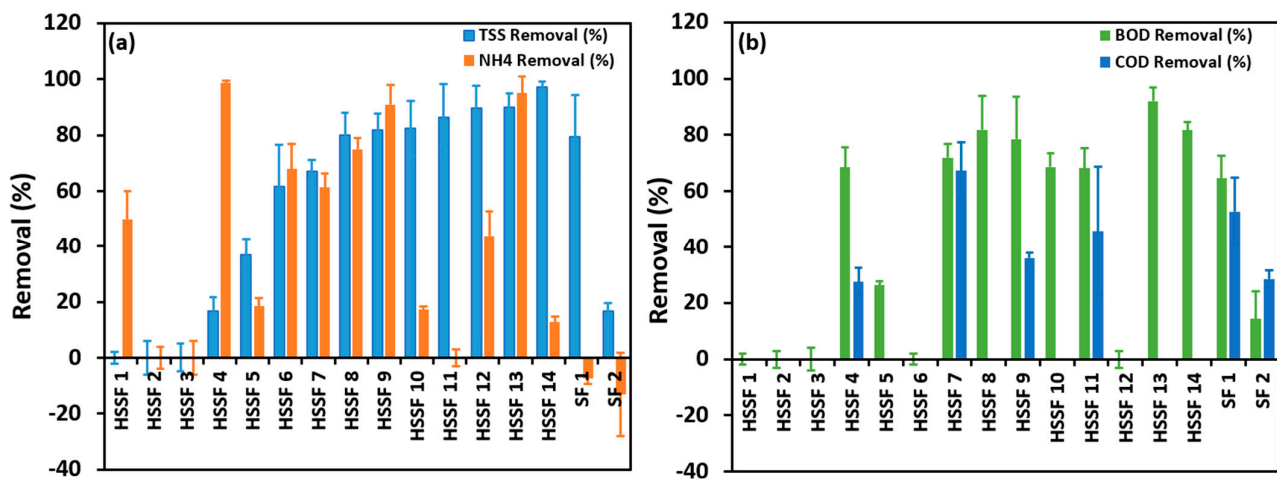


Figure 3. The removal efficiencies of (a) TSSs and NH₄⁺, as well as (b) BOD₅ and COD in the horizontal subsurface flow (HSSF) and surface flow (SF) treatment wetlands in Southern Water, UK. Error bars represent the standard deviation of measurements collected within each individual wetland site.

The highest NH₄⁺ removal was observed in four sites (HSSF 4, 8, 9, and 13), achieving a removal efficiency of 75–99% with the influent concentrations of 2–6 mg/L. Poor performance was observed at three sites with low influent concentrations of 0.05–1 mg/L, with negligible removal. SF sites showed negative NH₄⁺ removal efficiencies of −7% and −13%, with influent concentrations of 27 and 0.3 mg/L, respectively.

HSSF TWs showed the highest BOD₅ removal in four sites (HSSF 8, 9, 13, and 14), achieving 79–92% of removal for influent concentrations in the range of 7–75 mg/L (Figure 3b). No reduction in BOD₅ removal with influent concentrations of 5 mg/L appeared for five HSSF TWs (HSSF 1–3, 6, and 12). The stormwater treatment HSSF TW at two sites (HSSF 4 and 10, Table 1) showed slightly inferior treatment performance (69%) compared to those used for tertiary treatment. A BOD₅ removal of 65% was observed for the SF TW at SF1 with an influent of 34 mg/L compared to a lower BOD₅ removal (14%) with a weaker influent of 3.5 mg/L at the SF2 site.

COD removal data are not consistently available for all treatment sites. Nonetheless, notable removal was seen in three sites (HSSF 7, 9, and 11) of 36–67%, with influent concentrations of 50–147 mg/L. SF1 achieved 53% COD removal, which is relatively high compared to some HSSF TW systems. HSSF TWs demonstrated less removal of COD despite good NH₄⁺ and BOD₅ reductions. Overall, HSSF TWs demonstrated a significant reduction in TSS and NH₄⁺ levels. In contrast, while SF TWs are effective at removing TSSs and COD, they generally perform relatively poorly in reducing NH₄⁺ and BOD₅ compared to HSSF TWs.

4. Discussion

4.1. Treatment Wetlands Application in the UK Water Sector

TWs have become a conventional technology applied in many countries, including the UK, for treating various types of wastewaters [14]. This advancement reflects a growing recognition of the benefits of natural processes in water treatment and a shift towards

nature-based solutions (NbSs). The UK first became interested in TWs in 1985 based on wetlands constructed in Denmark and Germany [18] and site visits by several water authorities and the Water Research Centre (WRC). Visits to Denmark by P. Cooper and WRC colleagues highlighted the potential for TWs, but further research and development was required [18]. A Water Authorities Association RBTS coordinating group was set up in July 1985, and the first wetland in the UK was constructed by Anglian Water in September of that year near Norwich (the Gresham reed bed) [19]. A guideline on the design and operation of treatment wetland systems was first generated by a specialised European Union group (Expert Contact Group on Emergent Hydrophyte Treatment Systems), which was presented at the IWA conference on Constructed Wetlands in Water Pollution Control in Cambridge, UK, in September 1990 [19].

According to P. Cooper (2009) [19], many RBTSs and TWs were accepted by water utilities and regulators from 1990 and were constructed and accepted in the UK as conventional technology. By 1996 there were more than 400 horizontal subsurface flow wetlands; Severn Trent alone had 102 wetland systems providing storm and tertiary treatment [18]. TWs experienced rapid growth after that period: by 2007, there were almost 1012 treatment wetlands operational in the UK with treatment applications in various sectors, including 874 in wastewater, 54 in mining, 24 in landfill leachate, 19 in industrial, 16 in surface run-off, 13 in agricultural run-off and six in road run-off treatment [19]. In 2025, significant efforts by the UK Constructed Wetland Association, together with the mapping interface developed by The Rivers Trust, led to the creation of a visual map of the majority of treatment wetlands in the UK and Ireland, known as the Constructed Wetland Hub (2025) [20].

In 2009, Severn Trent trialled and adopted artificially aerated subsurface flow wetlands, initially brought to the UK by ARM [14]. In the same year, Wessex Water conducted the first demonstration-scale reactive media wetlands as part of the second UK Chemicals Investigation Programme, focusing on their effectiveness in removing pharmaceutical products. This initiative led to follow-up trials by Severn Trent in the Packington Low Phosphorus trials and Thames Water's trials using apatite and steel slag [14].

In 2014, Anglian Water and the Norfolk Rivers Trust pioneered the deployment of surface flow wetlands, known as "integrated constructed wetlands" (ICWs), at their Northrepps site, a trend that continued with a subsequent installation at Ingoldisthorpe in 2018, with an expansion to Langham and Stifkey [14]. In 2025, Anglian Water created its first integrated constructed treatment wetland (ICTW, 18,320 m²) as a tertiary treatment wetland at Everton Water Recycling Centre in Bedfordshire, aiming to meet new consent limits of 1 mg/L phosphorus and 8000 µg/L iron under the Water Industry National Environment Programme (WINEP). In 2021, Yorkshire Water constructed their first secondary treatment surface flow wetland in the UK at Clifton STW. Additionally, other water utilities have introduced various types of wetlands, such as modular wetlands at Anglian and Severn Trent, which have gained renewed interest for their effectiveness in managing nutrient neutrality and storm overflows.

Southern Water built their first treatment wetland in 1991. After privatisation, Southern Water faced significantly tighter standards for TSSs, BOD₅ and NH₄⁺, which prompted the introduction of most HSSFs as a tertiary stage of the treatment process to polish the quality of secondary effluents from biological trickling filters, activated sludge plants, and other secondary biological treatment process. The gradual development of wetlands commenced after that period and continued until 2000 (Figure 1). This growth may be attributed to increased confidence in wetlands due to their performance. From 2000 to 2014, there was a rapid expansion of wetland treatment mainly due to the increased confidence and growing awareness of wetland systems as sustainable, cost effective, low maintenance and reliable solutions. Wetlands are acknowledged as having an important

role to play in improving resilience against climate change impacts, for example, flooding, and addressing water quality challenges. Before 2014, it was rare to have BOD₅ limits lower than 10 mg/L and NH₄⁺ levels below 3 mg/L; however, such standards became more common after 2014, with new discharge requirements being introduced under regulations such as the Water Framework Directive. This change may have resulted in a gap in wetland installation between 2014 and 2023, as Southern Water began to explore other technologies to achieve these stricter consent requirements. At the moment, Southern Water is again constructing wetlands, with some specifically designed for phosphorus removal and stormwater treatment. For example, the aerated wetland at Lavant (Table 1) is intended for the treatment of groundwater infiltration into the sewers and associated storm overflows. Building treatment wetlands is an alternative to storm tanks where the volume of storage required is hard to both provide and determine; where large volumes of storm water occur, tanks cannot be emptied in time for subsequent storms, resulting in septic sewage and associated odour. The implementation of wetlands for storm treatment can treat effluents to final effluent and UPM FIS standards without the need for grey engineered infrastructure, and removes the requirement to return stored storm flows to the treatment process.

4.2. Performances of Treatment Wetlands

Typical removal efficiency range for HSSF TWs is over 80% for TSSs and organic matter, while it is between 20% and 30% for NH₄⁺. In contrast, SF wetlands achieve removal efficiencies of over 80% for TSSs, organic matter, and NH₄⁺ [21]. In this study (Table 1), the data suggests that wetlands, particularly HSSFs, are very effective for tertiary treatment functions—TSS removal exceeded 80% across seven of the systems. This has been followed by high BOD₅ removal of over 65% in eight HSSF TWs, highlighting the capacity of these systems to biologically degrade organic matter and remove BOD₅ associated with solids. HSSF 12–14 are older systems with surface areas above 1 m²/pe which have shown better removal efficiency, possibly due to having large surface areas or more established biological communities. This level of removal is similar to findings by P. Cooper (2001) [22], which stated that by designing a HSSF tertiary treatment wetlands system at 1 m²/pe, effluents with less than 10 mg/L TSSs and 5 mg/L BOD₅ can be possible to achieve. Similar reduction rates have also been found in Severn Trent wastewater sites which were designed at 0.8 m²/pe [22]. By contrast, HSSF 1–3, with appropriate surface areas of 0.75 and 0.55 m²/pe, showed poor performance or no improvement in removal efficiency. This may be due to lower influent concentrations close to background pollutant levels and variations in system performance.

SF systems have underperformed compared with HSSFs in removing TSSs and BOD₅, achieving reductions of 79% and 17% for TSSs and 65% and 14% for BOD₅ (Figure 3). Area requirements for SF systems without a P target is 1.35 m²/pe, which aligns with other designs using the P-K-C* approach [6]. In Southern Water, the surface area used per population for SF TWs is 0.66 and 0.12 m²/pe, which corresponds to their lower performance levels.

For NH₄⁺ treatment, HSSF systems demonstrated high NH₄⁺ removal efficiencies of 99%, 91%, and 95% respectively for HSSF 4, 9, and 13. This suggests optimal nitrification conditions, likely due to sufficient aeration and microbial activity within the media and wetland rhizomes. In contrast, HSSF 2 and 3 showed no NH₄⁺ removal where influent concentrations were low, similar to performance when low strength BOD₅ influent occurred. There is potential for clogging of HSSF TWs causing deleterious NH₄⁺ treatment. Clogging of subsurface gravel-based TW systems is a common issue throughout operational lifespan [23], which can reduce the effective hydraulic residence time available

for treatment processes and compromise effluent quality. A survey in 2008 conducted in the UK involving 255 subsurface flow treatment wetlands (SSF TWs) revealed that 30% displayed signs of surface flow, mainly due to clogging [23]. Negative NH_4^+ removal efficiencies were observed in both SF sites (Figure 3a). This may be due to internal nitrogen release from wetland substrates or sediments, mineralisation processes within the system or limited nitrification under conditions of low dissolved oxygen or short hydraulic retention time [3,6]. In addition, the occurrence of very low concentrations in the dataset may contribute to apparent negative removal values due to the constraints associated with historical operational sampling. COD data are not available for most of the study sites. The highest removal of 67% and 46% was found in HSSF 7 and 11. Less reduction in COD was found for SF systems, with SF1 achieving 53% and SF2 achieving 29% (Figure 3b), which could be due to the ineffective oxidation of readily and slowly biodegradable COD fractions.

This study highlights that treatment wetlands can achieve high removal efficiencies for TSSs, BOD_5 , and NH_4^+ . Notably, the performance data used in this study were largely derived from spot samples collected during commissioning periods of the wetlands. As a result, the dataset may not fully capture seasonal variability, long-term operational dynamics, or fluctuations associated with changing hydraulic and environmental conditions. The number and timing of samples also varied between sites, which limits the ability to draw conclusions on typical or long-term treatment performance. More comprehensive and systematic monitoring, including regular sampling across seasons and under representative operational conditions, would be necessary to provide a more robust evaluation of the long-term performance and stability of treatment wetlands.

Performance is affected by various factors, including wetland design characteristics, hydraulic retention time (HRT), hydraulic loading rates, substrate properties, vegetation type and density, and microbial community dynamics [6,11,13,17]. These factors collectively affect the physical, chemical, and biological processes responsible for pollutant removal within the wetland system. A comprehensive understanding of these controlling parameters and optimisation of design and operation conditions is essential for enhancing the performance and reliability of treatment wetlands. Advancements in wetland treatment technology, such as incorporating aeration and utilising integrated or hybrid systems, can improve treatment efficiency, including nutrient removal, thereby ensuring compliance with stringent regulatory requirements.

4.3. Successful Case Studies of Other UK Utilities

The following sections highlight some of the UK case studies where advanced wetland technologies have successfully addressed challenges such as limited land availability, strict discharge regulations, and the need for consistent treatment capacity. Southern Water could benefit by renewing old wetlands and adopting innovative technologies to enhance the performance of its ageing wetland treatment sites.

4.3.1. Case Study with Multistage Wetland System Adopted by the Scottish Water

Scottish Water upgraded a rural septic tank incorporating a multistage wetland system for enhanced treatment in 2011. The process included a septic tank, an “interceptor”, and four constructed wetlands: one floating wetland and one HSSF TW for primary treatment, followed by two sets of parallel VSSF wetlands for secondary treatment, and a final set of parallel HSSF TWs for polishing and biodiversity. The total specific area for the wetland treatment units was $5.3 \text{ m}^2/\text{pe}$. Performance was closely monitored over the first three years of operations post-installation in 2013. The trial concluded that there was a risk of solids washout from the septic tank during high flows; however, the wetlands demonstrated

their ability to handle significant flow and load variations, achieving 96% and 92% removal rates for BOD₅ and COD, respectively, alongside 80% removal for both TSSs and NH₄⁺ [14]. This system has demonstrated higher efficiency in nutrient removal than Southern Water sites and has maintained better performance during peak flows than other Southern Water wetlands. This could be due to advanced multistage design features and water retention management. Most of the Southern Water TWs have a simpler design, require larger space, are less robust under variable flows and lack treatment diversity.

4.3.2. Case Studies on Successful Introduction of Aeration System at Severn Trent and Thames Water

In one of the sewer treatment works at Severn Trent, with a process configuration of a rotating biological contactor (RBC) followed by a 420 m² HSSF treatment wetlands for tertiary treatment, performance declined over the period. This was due to a reduction in the effectiveness of the RBC, which resulted in higher loads overwhelming the treatment wetlands and causing clogging from excessive biomass growth and elevated levels of NH₄⁺. To address this issue, and to meet the tightened discharge consents, an aeration system was introduced in the wetland as part of a new upgraded refurbishment solution that did not require area expansion but provided a consistent treatment capacity by optimising current asset performance [24]. Similar success has been observed by Thames Water in one of their sites which frequently had breaches during an increased load from the village served by the works. To address the challenge, an aerated SSVF TW was installed as a tertiary final polishing system. This vertical flow layout minimised the area of the required bed, whilst the aeration provided enhanced microbial treatment to bring the BOD₅, TSS and NH₄⁺ site discharges within the consent [24].

As some Southern Water TWs have simple wetland designs and larger treatment area footprints, there is the opportunity to introduce aerated wetland systems for tertiary treatment to achieve stricter discharge requirements, especially in areas where land availability is a concern. This approach would also promote biodiversity, and increase the natural capital and amenity value of rural areas.

4.4. Current Practices and Future-Proofing Strategies

Although TWs have proven their effectiveness in removing many pollutants, various gaps still exist in current practices that need to be addressed. TW design manuals and guidelines have limited standardisations; various sources are widely available [21], but best practice guidelines for wetlands for UK conditions are not readily available. Wetland effectiveness varies due to site-specific conditions, and updated design standards and guidance are required to enhance performance. Dykes et al. (2025), in their recent studies on the interseasonal treatment performance and water quality status of integrated constructed wetlands, have identified that mass removal rates are affected by seasonal and climate variations [5]. The outcome of the study was a recommendation for the optimisation of operational parameters to improve treatment efficiency according to seasonal variation and associated vegetation condition. Climate adaptive designs are necessary to future-proof wetland treatment technology.

Insufficient maintenance programmes have caused the accumulation of contaminants in the media and associated clogging which affects performance and the sustainability of constructive wetlands [25]. D. Cooper et al. (2005) showed that the major maintenance problems were weed infestation/growth of saplings, poor inlet distribution, sludge deposition and surface flooding [26]. It is well recognised that clogging frequently occurs at the surface of vertical flow CW and in the influent section of horizontal flow CW systems. The application of an appropriated TW maintenance plan is essential to maintain process performance.

Most utilities usually perform only final effluent analysis, since this is the focus for regulatory compliance for look-up table percentile compliance or annual averages based on spot samples. However, monitoring both influent and effluent offers valuable data that can improve future designs. Consequently, the lack of monitoring and performance evaluation fails to provide information on whether the system is appropriately sized for effluent compliance requirements. Monitoring of effluent throughout the process stream would be beneficial to informing future design. Continuous monitoring of wastewater quality parameters could be achieved through an introduction of smart monitoring technologies.

Pinho et al. (2023) conducted an experiment using electrochemical probes, a low-cost and reliable technology, to measure electrical conductivity as a key water quality parameter [27]. Electrical conductivity was used as an indicator of treatment performance. The results showed a variation of up to 20% in treatment efficiency when comparing daily sampling with a higher-frequency 15 min sampling regime. This highlights the importance of monitoring frequency in accurately capturing system performance. Thus, the installation of sensors combined with an automated control system would enable real-time monitoring of water quality parameters, and would provide flexibility to adjust parameters as per operational conditions, thereby improving performance [28].

It is important to recognise that ecosystem-based interventions may exhibit time-dependent responses. During the establishment phase, vegetation growth, microbial community development, and substrate conditioning may lead to variable treatment performance before the system reaches functional stability. Similar short-term trade-offs, where initial ecological disturbance is followed by longer-term recovery, have been observed in other ecosystem restoration interventions [29]. This highlights the importance of long-term monitoring and adaptive management to ensure stable wetland performance over time.

There is still limited understanding of the complex processes occurring in treatment wetlands. This knowledge gap can impact the ability to design systems for different treatment objectives and to enhance performance of existing systems. TWs are either a single unit process or a combination of complementary unit processes, and they should be designed with a solid understanding of process engineering concepts [19]. Increased investment in research and development aimed at innovative technologies and a better understanding of treatment wetland processes and design is crucial. Ongoing research and innovation are also required to address future challenges, including the removal of emerging pollutants and the adaptation of constructed wetlands to the specific needs of various regions [28]. Emerging pollutants, including microplastics, pharmaceuticals, personal care products, hormones, steroids, and perfluoroalkyl and polyfluoroalkyl substances (PFASs) have been found in wastewater and pose challenges to the ecological health of freshwater and marine waterbodies. Limited studies have been conducted to assess the capability of TWs to mitigate such micropollutants, particularly in real-scale applied systems [30,31].

Stringent discharge limits for phosphorus, as low as 0.15 mg/L, have been introduced for many UK sewage works under the Water Industry National Environment Programme (WINEP). Recent research on advanced materials, such as Lanthanum-quaternized chitosan-modified zeolite, has demonstrated superior phosphorus removal performance [32], suggesting that such materials could be considered as novel substrates for wetland applications. Continued research and innovation are required to investigate mechanisms and processes to effectively remove emerging pollutants whilst adapting TW systems to meet the specific needs of different locations.

Currently, there is limited public and stakeholder acceptance of treatment wetland systems. Improving regulatory frameworks and educating communities and stakeholders on the environmental and public health benefits of functioning TW systems can help foster community acceptance, adoption and support [28]. Souliotis and Voulvoulis in 2022

discussed that the broad adoption of nature-based solutions (NbSs) faces several barriers, such as a lack of standardised evidence regarding long-term performance, which need to be tackled by both researchers and practitioners [33]. Successful implementation of NbSs requires coordinated effort amongst different stakeholders who often focus on their specific operations and responsibilities while neglecting the diverse aspects of NbSs.

5. Conclusions

This study reviewed the development and performance of TWs within Southern Water's sewage treatment network, where 35 sites have been installed since 1991 to provide tertiary treatment and stormwater management. Performance data from 16 sites show that HSSF TWs consistently deliver effective reductions in TSSs, NH_4^+ , BOD_5 and COD. SF wetlands perform less reliably when meeting stringent tertiary standards; however, numerous published studies support that SF wetlands can offer greater benefits for biodiversity, carbon sequestration, and other ecosystem services due to their larger land footprint. Despite their demonstrated effectiveness and capacity to support sustainable wastewater treatment alongside wider ecological benefits, the broader deployment of treatment wetlands remains constrained by inconsistent design standards, limited operation and maintenance regimes, and a predominant focus among practitioners on effluent quality, with less attention given to understanding and optimising the treatment processes and mechanisms within the systems. To address these barriers, future work should prioritise standardised design guidance, improved operational strategies, and deeper process-level understanding alongside research into seasonal dynamics and long-term resilience. By overcoming these limitations, TWs could play an expanded role in delivering robust wastewater treatment solutions while contributing to biodiversity, climate resilience, and other ecosystem services.

Author Contributions: Conceptualization, P.B.P., J.E. and T.L.; methodology, P.B.P. and T.L.; validation, P.B.P.; investigation, P.B.P.; resources, P.B.P. and J.E.; data curation, P.B.P.; writing—original draft preparation, P.B.P.; writing—review and editing, J.E. and T.L.; visualisation, P.B.P.; supervision, T.L.; project administration, T.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data available within the article.

Acknowledgments: This work is derived from P.B.P.'s MSc thesis at Cranfield University, undertaken as a part-time student while working at Southern Water. The authors gratefully acknowledge the support of Southern Water in enabling this study, as well as for providing important information and guidance for the research. T. Lyu also acknowledges support from the UK Engineering and Physical Sciences Research Council (EPSRC) through his award on nature-based solutions research (EP/Y003101/1).

Conflicts of Interest: Authors P.B.P. and J.E. are employed by the company Southern Water. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Pu, Y.; Li, Y.; Zhu, L.; Cheng, Y.; Nuamah, L.A.; Zhang, H.; Chen, H.; Du, G.; Wang, L.; Song, C. Long-term assessment on performance and seasonal optimal operation of a full-scale integrated multiple constructed wetland-pond system. *Sci. Total Environ.* **2023**, *862*, 161219. [CrossRef] [PubMed]

2. Zhang, H.; Lyu, T.; Liu, L.; Hu, Z.; Chen, J.; Su, B.; Yu, J.; Pan, G. Exploring a multifunctional geoengineering material for eutrophication remediation: Simultaneously control internal nutrient load and tackle hypoxia. *Chem. Eng. J.* **2020**, *406*, 127206. [CrossRef]
3. Lyu, T.; Song, L.; Chen, Q.; Pan, G. Lake and River Restoration: Method, Evaluation and Management. *Water* **2020**, *12*, 977. [CrossRef]
4. Petrie, B. A review of combined sewer overflows as a source of wastewater-derived emerging contaminants in the environment and their management. *Environ. Sci. Pollut. Res.* **2021**, *28*, 32095–32110. [CrossRef]
5. Dykes, C.; Pearson, J.; Bending, G.; Abolfathi, S. Impact of seasonal climate variability on constructed wetland treatment efficiency. *J. Water Process Eng.* **2025**, *72*, 107350. [CrossRef]
6. Lyu, T.; Headley, T.; Kadlec, R.H.; Jefferson, B.; Dotro, G. Phosphorus removal in surface flow treatment wetlands for domestic wastewater treatment: Global experiences, opportunities, and challenges. *J. Environ. Manag.* **2024**, *369*, 122392. [CrossRef]
7. Dorji, N. Designing and Evaluating Nature-Based Solutions for Water Reuse in Eastern England: A Case Study. 2021. Available online: <https://mta-cranfield-ac-uk.eu1.proxy.openathens.net/handle/1826.1/17170> (accessed on 1 June 2025).
8. Debele, S.E.; Leo, L.S.; Kumar, P.; Sahani, J.; Ommer, J.; Bucchignani, E.; Vranić, S.; Kalas, M.; Amirzada, Z.; Pavlova, I.; et al. Nature-based solutions can help reduce the impact of natural hazards: A global analysis of NBS case studies. *Sci. Total Environ.* **2023**, *902*, 165824. [CrossRef]
9. Wu, Y.; Lu, Y.; Yan, Z.; Shi, M.; Wang, Q.; Lyu, T.; Jia, R.; Huang, L.; Chen, Z.; Chen, J.; et al. Nature-based stormwater management for aquifer recharge: Exploring bioclogging-induced challenges. *Environ. Technol. Innov.* **2025**, *39*, 104228. [CrossRef]
10. Sun, G.; Cooper, D. A statistical analysis on the removal of organic matter in subsurface flow constructed wetlands in the UK. *Environ. Technol.* **2008**, *29*, 1139–1144. [CrossRef]
11. Wu, S.; Lyu, T.; Zhao, Y.; Vymazal, J.; Arias, C.A.; Brix, H. Rethinking Intensification of Constructed Wetlands as a Green Eco-Technology for Wastewater Treatment. *Environ. Sci. Technol.* **2018**, *52*, 1693–1694. [CrossRef]
12. Agaton, C.B.; Guila, P.M.C. Ecosystem Services Valuation of Constructed Wetland as a Nature-Based Solution to Wastewater Treatment. *Earth* **2023**, *4*, 78–92. [CrossRef]
13. Kadlec, R.H.; Wallace, S.D. *Treatment Wetlands*; CRC Press: Boca Raton, FL, USA, 2009.
14. Dotro, G.; Williams, J. Treatment Wetlands in the UK. 2025. Available online: <https://constructedwetland.co.uk/news/41> (accessed on 1 June 2025).
15. Southern Water. *Technical Specifications Manual Wastewater Treatment: Vol. PSWWT 4014*; Southern Water Services Ltd.: Worthing, UK, 2020; *Unpublished Internal Report*.
16. Southern Water. *Wetlands Design Standard PSWWT 4014*; Southern Water Services Ltd.: Worthing, UK, 2025; *Unpublished Internal Report*.
17. Dotro, G.; Langergraber, G.; Molle, P.; Nivala, J.; Puigagut, J.; Stein, O.; Von Sperling, M. Treatment Wetlands. 2017. Available online: <http://iwaponline.com/ebooks/book-pdf/894754/wio9781780408774.pdf> (accessed on 1 June 2025).
18. Cooper, P.; Green, B. Reed bed treatment systems for sewage treatment in the United Kingdom—The first 10 years' experience. *Water Sci. Technol.* **1995**, *32*, 317–327. [CrossRef]
19. Cooper, P. What can we learn from old wetlands? Lessons that have been learned and some that may have been forgotten over the past 20 years. *Desalination* **2009**, *246*, 11–26. [CrossRef]
20. Constructed Wetland Hub. 2025. Available online: <https://storymaps.arcgis.com/collections/6543a2f8de0348f683187ff268a79687?item=5> (accessed on 1 June 2025).
21. Langergraber, G.; Dotro, G.; Nivala, J.; Rizzo, A.; Stein, O.R. *Wetland Technology: Practical Information on the Design and Application of Treatment Wetlands*; IWA Publishing: London, UK, 2020.
22. Cooper, P. Constructed wetlands and reed-beds: Mature technology for the treatment of wastewater from small populations. *Water Environ. J.* **2001**, *15*, 79–85. [CrossRef]
23. Hickey, A.; Arnscheidt, J.; Joyce, E.; O'Toole, J.; Galvin, G.; O'Callaghan, M.; Conroy, K.; Killian, D.; Shryane, T.; Hughes, F.; et al. An assessment of the performance of municipal constructed wetlands in Ireland. *J. Environ. Manag.* **2018**, *210*, 263–272. [CrossRef]
24. Arm Group Ltd. Water Company. 2017. Available online: <https://armreedbeds.co.uk/wp-content/uploads/2017/02/Water-Company.pdf> (accessed on 1 June 2025).
25. Knowles, P.; Dotro, G.; Nivala, J.; García, J. Clogging in subsurface-flow treatment wetlands: Occurrence and contributing factors. *Ecol. Eng.* **2011**, *37*, 99–112. [CrossRef]
26. Cooper, D.; Griffin, P.; Cooper, P. Factors affecting the longevity of sub-surface horizontal flow systems operating as tertiary treatment for sewage effluent. *Water Sci. Technol.* **2005**, *51*, 127–135. [CrossRef]
27. Pinho, H.; Barros, M.; Teixeira, A.; Oliveira, L.; Matos, P.; Ferreira, C.; Mateus, D. Smart Monitoring of Constructed Wetlands to Improve Efficiency and Water Quality. In *Proceedings of the 5th International Symposium on Water Resource and Environmental Management*; Xu, H., Ed.; Environmental Science and Engineering; Springer: Cham, Switzerland, 2023; pp. 189–197. [CrossRef]

28. Santos, J.; Rodrigues, S.; Magalhães, M.; Rodrigues, K.; Pereira, L.; Marinho, G. A state-of-the-art review (2019–2023) on constructed wetlands for greywater treatment and reuse. *Environ. Chall.* **2024**, *16*, 100973. [[CrossRef](#)]
29. Zhang, E.; Meng, C.; Qu, J.; Zhu, Z.; Niu, J.; Wang, L.; Song, N.; Yin, Z. Dual effects of *Caragana korshinskii* introduction on herbaceous vegetation in Chinese desert areas: Short-term degradation and long-term recovery. *Plant Soil* **2025**. [[CrossRef](#)]
30. Savvidou, P.; Dotro, G.; Campo, P.; Coulon, F.; Lyu, T. Constructed wetlands as nature-based solutions in managing per- and poly-fluoroalkyl substances (PFAS): Evidence, mechanisms, and modelling. *Sci. Total Environ.* **2024**, *934*, 173237. [[CrossRef](#)]
31. Sarti, C.; Souleymane, A.A.; Dotro, G.; Cincinelli, A.; Lyu, T. Partitioning and removal of per- and polyfluoroalkyl substances (PFAS) in full-scale surface flow treatment wetlands with different upstream wastewater treatment. *J. Water Process Eng.* **2025**, *71*, 1077236. [[CrossRef](#)]
32. Wang, L.; Zhang, J.; Sha, H.; Wang, Y.; Wang, H.; Zhu, G.; Lu, Y. Lanthanum-quaternized chitosan-modified zeolite for long-lasting operation of constructed wetland: A bifunctional strategy for simultaneous phosphorus removal and microbial clogging mitigation. *Water Res.* **2026**, *288*, 124688. [[CrossRef](#)]
33. Souliotis, I.; Voulvoulis, N. Operationalising nature-based solutions for the design of water management interventions. *Nat.-Based Solut.* **2022**, *2*, 100015. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.



DSPACE

<https://dspace.org/>

The development and future-proofing of treatment wetlands as nature-based solutions in the UK water sector: Southern Water case studies

Phuyal, Pramila Bhandari; Edevane, Joff; Lyu, Tao

2026-04-01

MDPI

<https://doi.org/10.3390/app16073135>

Phuyal PB, Edevane J, Lyu T. (2026) The development and future-proofing of treatment wetlands as nature-based solutions in the UK water sector: Southern Water case studies. Applied Sciences, Volume 16, Issue 7, April 2026, Article number 3135