Treatment wetlands in the UK:

Case studies of an established biological treatment technology

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The Constructed Wetland Association was founded in 2000 by a concerned group of professionals spanning academia, designers and end users (including Severn Trent, Anglian Water and Wessex Water). The CWA "works to promote the awareness of constructed wetland technology in water pollution control and takes a lead role in advocacy for the application of constructed wetlands in pollution prevention and the delivery of multiple benefits" (CWA, 2024). The CWA was approached on 21st November 2024 by Stantec to provide evidence on the use of treatment wetlands in the UK for biological treatment. This information was needed to inform discussions with the Environment Agency. As part of the mission of the CWA is to support and inform wetland implementation, the Management Committee appointed two experienced members to compile the information and provide feedback on the description of the technology used by Stantec in said discussions. This report is the result of that effort.

1. Introduction

The use of planted wetlands for wastewater treatment emerged in Germany in the 1950s and 1960s through the work of Seidel and Kickuth. Kickuth pioneered the Root Zone Method where reeds grew in a soil substrate and wastewater passed horizontally through the system, whereas Seidel's design were what are now vertical flow wetlands. The technology spread across Europe in the 1980s and 1990s. Modifications of the technology were known by a variety of names (e.g. Artificial Wetlands, Gravel Bed Hydroponics, etc) until Constructed Wetlands became the generally accepted name in the early 1990s. Promoted by a series of international conferences and publications, the Constructed Wetland concept spread around the world as a cost-effective alternative than grey infrastructure. In 2009, the global community shifted from the phrase "constructed wetlands" to "treatment wetlands", as wetlands can also be constructed for objectives that do not include treatment (e.g., mitigation wetlands in the USA, habitat creation). Nowadays treatment wetlands are a mainstream technology with thousands of installations in almost every country used for treating a wide variety of wastewaters.

There are many configurations of wastewater treatment constructed wetlands. These were summarised in the Treatment Wetlands book issued by the International Water Association as part of their Biological Wastewater Treatment Series (Dotro et al 2017).

Microbial Activity in Treatment Wetlands

Treatment wetlands provide a variety of treatment processes including physical filtration, microbial breakdown of pollutants, microbial nutrient cycling and a variety of mechanisms of pathogen inactivation.

The role of microbial activity in treatment wetlands has been recognised since the early days, with the Root Zone Method name referring to the role of many wetland plants in creating oxidised conditions in their rhizospheres to promote aerobic microbial treatment mechanism in reduced\anoxic wetland environments. Treatment wetlands therefore provide very

heterogeneous environments for microbial activity with biofilms on substrates and reed surfaces interacting with microorganisms and chemical conditions in the bulk water. The importance of these environments in close proximity to each other has been recognised and studied for over 30 years with microbial activity assays, microelectrodes and more recently metagenomic studies of wetland microbial populations. The influence of these microbial processes is clearly seen in the removals of soluble pollutants, as well as particulates, seen in many treatment wetland case studies. This includes evidence of complex microbial communities able to provide biological treatment of the pollutants in CSOs (Ruppelt et al., 2020). A review of microbial communities found in different types of biological treatment processes ranging from activated sludge to treatment wetlands summarised the diversity of biological microorganisms that operate in this established technology (Ferrera and Sanchez 2016).

To illustrate, in Austria, secondary vertical flow (VF) wetlands are an established treatment alternative to sequencing batch reactors, activated sludge, trickling filters and rotating biological contactors (Engstler et al 2022). Austrian wetlands need to reduce ammonia even in small works, with their cold temperature clause being activated at 12°C. A recent study compared performance across the various secondary treatment technologies, showing the ability of wetlands to match or provide better quality effluent than grey technologies (Engstler et al 2022). The thresholds for compliance applied to the data sets between 2009-2018 were 25 mg/L for BOD and 90 mg/L for COD, the latter being lower than Urban Wastewater Treatment Regulations (UWWTR) that apply to sites serving over 2,000 pe (Table 1).

Table 1. Performance of different biological treatment technologies for BOD and COD at small WWTP (reproduced from Engstler et al 2022)

TABLE 2 | BOD$_5$ effluent concentrations of small WWTPs with different technologies (threshold: 25 mg BOD$_5$/L).

BOD$_5$	SBR	SBR & VF bed	CAS	CAS & VF bed	VF wetland	Trickling filter	RBC	MBR	Filtration	All data
Number of WWTPs [ ]	493	252	540	52	491	85	36	25	7	1'981
Number of values [ ]	3'358	1'563	4'402	422	3'235	700	279	185	54	14'198
Values above threshold [ ]	5	3	5	3	3	8	7	4	6	5
[%]	0.1	0.2	0.1	0.7	0.1	1.1	2.5	2.2	11.1	0.0
Median [mg/L]	**7**	**5**	**7**	**5**	**5**	**9**	**9**	**5**	**8**	**6**
Mean [mg/L]	7	3	8	4	3	6	7	5	5	7
Standard deviation [mg/L]	55	10	72	19	10	35	44	20	27	44

Bold values indicate the median values.

TABLE 3 | COD effluent concentrations of small WWTPs with different technologies (threshold: 90 mg COD/L).

COD	SBR	SBR & VF bed	CAS	CAS & VF bed	VF wetland	Trickling filter	RBC	MBR	Filtration	All data
Number of small WWTPs [ ]	493	252	540	52	491	85	36	25	7	1'981
Number of values [ ]	3'365	1'568	4'406	422	3'245	703	283	185	54	14'231
Values above threshold [ ]	48	7	53	1	4	11	4	0	0	128
[%]	1.4	0.4	1.2	0.2	0.1	1.6	1.4	0.0	0.0	0.9
Median [mg/L]	**37**	**24**	**35**	**24**	**21**	**44**	**43**	**27**	**33**	**31**
Mean [mg/L]	42	28	41	40	25	47	47	31	34	36
Standard deviation [mg/L]	25	16	38	249	14	22	21	15	14	51

Bold values indicate the median values.

SBR = sequencing batch reactor, VF = vertical flow wetland, CAS = conventional activated sludge, RBC = rotating biological contactor, MBR = membrane bioreactor.

2. Treatment wetlands in the UK

2.1. General overview of wetlands in the UK

Treatment wetlands have been in use in the UK for secondary and tertiary treatment since the WRc visit to Europe back in the late 80s. Initially most of these were soil systems based on the German Root Zone Method (e.g. Wessex Water at Marnhull), but it was soon realised that the low hydraulic conductivity of soil caused short circuiting, especially in secondary treatment applications and gravel substrates became the norm. The experience of operating these systems resulted in the first European Guidelines for the use of treatment wetlands published in 1990 (Cooper 1990).

Severn Trent pioneered the use of gravel-based subsurface flow wetlands ("reed beds"), storm overflow dedicated wetlands ("storm reed beds"), and what they called "combined reed beds". The latter receive a combination of secondary effluent from package treatment plants/trickling filters as well as the storm overflow (>6DWF) at the works producing a combined final effluent that meets a numeric consent (Griffin 2004). Severn Trent also trialled and pioneered the adaptation of artificially aerated subsurface flow wetlands (imported to the UK by ARM Ltd) in 2009 (Butterworth et al 2013) and adapted the French Wetland technology for implementation at Hulland Ward in 2015 (Pereira Gomez 2016). In Scotland, there are sites that have operated for over 20 years for secondary and tertiary treatment (Otero and Ergan 2015).

Wessex Water trialled the first demonstration-scale reactive media wetlands in 2009, which were included as part of the second UK Chemicals Investigation Programme for their ability to remove pharmaceuticals. This was followed by Severn Trent in the Packington Low Phosphorus trials (Murujew 2019) and Thames Water's apatite and steel slag trials (Fonseca 2018). In 2014, Anglian Water and the Norfolk Rivers Trust pioneered the use of surface flow wetlands ("ICWs") at their Northrepps site, followed by Ingoldisthorpe in 2018 and now extending to Langham and Stifkey. In 2021, Yorkshire Water built the first secondary treatment surface flow wetland in the UK at Clifton STW. Other water utilities also implemented wetlands in different variations (e.g., modular wetlands at Anglian and Severn Trent) before the most recent interest in surface flow systems for nutrient neutrality and storm overflows. Exemplar case studies are detailed below, with a list of additional studies and applications included in the Appendices.

2.2 Secondary treatment

National Guidance for secondary treatment wetlands

The CWA has produced guidelines for the design of conventional vertical flow wetlands for treating small domestic discharges. The design has been based on 15 years of UK experience and will produce an effluent of 20/30/20 mg/L (BOD/TSS/NH$_4$-N) when fed from a conventional septic tank. They were developed by a team of wetland professionals and peer reviewed by the international wetland community (Weedon et al 2017).

In Ireland, ICWs are a standard technology for delivering secondary treatment. Their guidelines were published in 2010 and monitoring has shown that they can bring very high strength wastewater loads (>1000 mg/L COD) to well within UWWTD standards with very low indicator organism counts (DEHLG, 2010).

Outside the UK & Ireland, national design standards for secondary treatment applications exist for Denmark, Germany, Austria, and the USA, among others (Dotro et al 2017).

Site 1: Integrated Constructed Wetland (YW)

As part of capital maintenance and an impending TP target on a descriptive works, Yorkshire Water implemented the first surface flow wetland (ICW) for secondary treatment at Clifton STW (Site 1), which serves a population of 160. It has a primary tank followed by four cells in series that are step fed as and when water flows require them to deliver treatment. It has a consent of 4 mg/L TP but is descriptive for sanitary pollutants (i.e., not designed to achieve a specific BOD or COD numeric consent). The wetland was commissioned in October 2021 and has been sampled by YW as part of the trial agreed with the EA, with 26 matched inlet-outlet samples analysed over 669 days (Jan 23 – Nov 24; Table 2). The 95%ile values for effluent BOD and COD are 15 mg/L and 111 mg/L, respectively, despite influent values of 372 mg/L and 731 mg/L, respectively. This translates to 95% removal efficiency for BOD and 85% for COD from the *inlet of the wetlands,* showing compliance with UWWTR for secondary treatment (concentration AND removal based). It should also be noted the Clifton works has occasional no flows in the outlet as the cells have been designed to fill progressively. This can result in samples that are concentrated in the final effluent when there is high evapotranspiration.

Table 2. Influent and effluent characteristics for Clifton STW (Jan 2023 – Nov 2024)

Parameter	Inlet to wetland (mg/L)			Outlet (mg/L)			% Removal
	95%ile	Min	Max	95%ile	Min	Max	
BOD	312	50	376	15	2	39	95
COD	731	193	769	111	33	118	85
NH_4-N	78.6	21	84	41.3	7	43	47

Site 2: Scottish Water Site A

In 2011, Scottish Water were required to upgrade a septic tank rural works and, with SEPA's agreement, developed a trial based on a multistage wetland to deliver enhanced treatment. The flowsheet consisted of a septic tank, an "interceptor" and four sets of wetlands, in the following order: one floating wetland (primary treatment), one conventional horizontal subsurface flow wetland (primary treatment), two sets of parallel vertical flow wetlands in series (secondary treatment), and a set of parallel horizontal flow wetlands for polishing and biodiversity value. The specific area sizing for the entire wetland treatment system was 5.3 m^2/pe. The flowsheet was commissioned in 2013 and intensively monitored for performance during the first three years (Table 3). The trial provided learning in terms of the risk of solids washout from septic tank/interceptor onto the downstream wetlands during high flows (DWF = 34 m^3/d; FFT = 260 m^3/d) but also showed the robustness of the wetlands to deal with wide variations in flow and load, achieving removals of 96% and 92% for BOD and COD, respectively, and 80% removal for both TSS and ammonia.

Table 3. Summary of influent (to wetlands) and effluent characteristics for Site A (2013-16)

Parameter	Inlet to wetland (mg/L)			Outlet (mg/L)			% Removal
	95%ile	Min	Max	95%ile	Min	Max	
BOD	154	7	741	7	2	13	96
COD	356	27	1916	28	10	69	92
NH4-N	41.9	3	53.4	8	0.5	14.6	81
TSS	128	8	1385	26	2	103	80

Site 3: Scottish Water Site B

Built around 1996, this site serves a population of 3,000 pe. It consists of preliminary treatment and two horizontal flow wetlands in parallel. It has a consent for UWWTR regulations (25 mg/L BOD and 125 mg/L COD) as well as a 100 mg/L TSS consent. This means the wetlands are performing both primary and secondary treatment. The network has significant infiltration, resulting in average per capital flows of 400 L/d (instead of SW's average of 180 L/d). Historic performance data from 2014/5 based on seven matched pairs of inlet and outlet composite samples show average 93% and 85% removal efficiencies for BOD and COD (Table 4). Average effluent values were 3 and 19 mg/L for BOD and COD, respectively. Based on 13 spots samples in the same period, 95%ile effluent values were 10 and 30 mg/L for BOD and COD, respectively.

Table 4 Summary of performance at SWB based on composite samples

Parameter	Inlet to wetland (mg/L)		Final effluent (mg/L)		% Removal*
	Mean	95%ile	Mean	95%ile	
BOD	40	92	3	6	93
COD	133	266	20	27	85

*based on averages

Site 4: French wetland systems in the UK – Hulland Ward (Severn Trent)

In 2014, Cranfield University facilitated the introduction of French wetland technology to the UK in collaboration with Severn Trent, MWH and ARM. Hulland Ward was chosen as the first full-scale trial site, serving a population of 941 people and needing to achieve a 30/50/15 mg/L BOD/TSS/NH$_4$-N consent. The site previously had trickling filters that were at the end of their life cycle. The solution was a conventional French Wetland installation, i.e., three gravel-based parallel VF beds for combined sludge and primary treatment, and two parallel VF wetlands for secondary treatment. Because the technology originated from France, Cranfield had two projects to help with developing the adaptations of the design to suit UK conditions. As part of that, the team compared composite samples taken at inlet, after primary (wetland) treatment, and at the outlet of the secondary wetland (FE) over five months, three times a week (Table 5), to compare against systems in France. The rest of the three-year monitoring was on spot samples to determine compliance with UK consents (Khomenko 2019).

Table 5. Performance of secondary treatment wetland based on composite samples July – December 2015 (Pereira Gomez 2016)

Parameter	Inlet to 2ry wetland (mg/L)			Final effluent (mg/L)			% Removal
	Mean	St Dev	Samples	Mean	St dev	Samples	
BOD	46	18	32	5	1.7	32	88
COD	169	59	36	39	11.3	33	75
NH$_4$-N	28	7	32	5.8	3.8	39	78
TSS	56	21	35	6	2.5	34	88

Sites 5 and 6: Aerated secondary wetlands, Severn Trent

In 2009, Severn Trent engaged ARM to retrofit artificial aeration in a few selected rural works that had an ammonia (quality) driver. With Cranfield University and co-funded by EPSRC, a PhD project conducted intensive monitoring of four key works and produced a number of peer reviewed publications. Of relevance here are two sites: Site D, which was the only secondary treatment wetland in the study and Site B, which was a combined wetland site that experienced a catastrophic secondary treatment process failure and had to treat all flows during ~50 days (Butterworth et al 2016).

Site D was retrofitted with aeration in March 2011, and consisted of a septic tank followed by a secondary subsurface flow wetland. The site serves 58 pe and had a descriptive consent. The driver for the aeration was reducing the occurrence of sewage fungus and minimising corrosion from the anaerobic systems onsite, as the bed was significantly undersized. Results for the studied period confirmed the site was delivering effluent BOD < 21 mg/L and either fully or partially nitrifying (Table 6).

Table 6. Summary of performance at Site D: Secondary aerated wetland (Adapted from Butterworth et al 2016).

Parameter	Inlet (mg/L)			Outlet (mg/L)			Sample size	% Removal
	Median	Min	Max	Median	Min	Max		
BOD	79	40	98	5	2	21	19	94
TSS	57	10	150	20	4	90	17	65
NH4-N	29.4	1.0	59.6	0.8	0.1	2.6	16	97

Site B was a single integrated RBC followed by a single combined wetland, serving a population equivalent of 396. It was retrofitted with aeration in October 2010 as a new ammonia consent came into force, requiring the works to deliver 14/45/3 for BOD/TSS/NH$_4$-N. The site's RBC failed during the monitoring period during the winter, when water temperatures averaged 9.5 to 13ºC. The wetland went from receiving influents of < 5 mg/L NH$_4$-N to 33 mg/L NH$_4$-N. After ten days, the wetland was able to treat this increased load, producing an effluent NH$_4$-N sub 1 mg/L after 30 days despite influent concentrations between 15 and 35 mg/L (Figure 1).
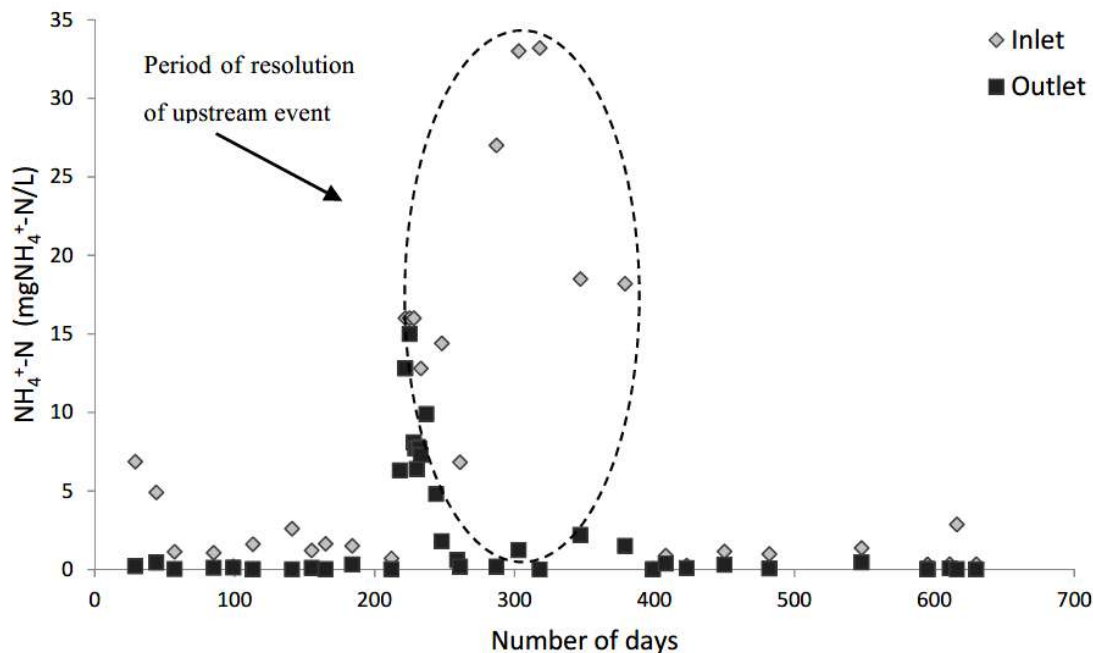
Figure 1. Influent and effluent concentrations of ammonium at Site B showing the period of increased loadings and time to reach steady state (30 days). From *Butterworth et al 2016*.

Site 7: Aerated saturated vertical flow, Scottish Water

This site was designed and installed by ARM Ltd after Scottish Water identified the need for an upgrade to a small WWTW in 2011. The treatment wetlands provide secondary treatment for 4.7 m^3/d of sewage plus runoff (peak 37.8 m^3/d), with primary treatment in a septic tank. Two wetland beds (171 and 25 m^2) have been reported to bring the strong load (BOD 320 mg/L and NH_4-N 42.7 mg/L) to withing discharge consents of 25 and mg/L for BOD and NH_4-N respectively (ARMa undated p20).

Site 8: Vertical flow wetland, Thames Water

This vertical flow wetland also follows a septic tank as a primary stage and is designed to treat 31 m^3/d (ARMb undated p16). The 484 m^2 treatment wetland is fed by a siphon batch feed. The results on the ARM case study page show effective treatment bringing the septic tank effluent BOD of about 200 mg/L and TSS of about 100 mg/l down to 5 mg/L for both parameters.

Severn Trent's secondary horizontal flow wetlands

Following the introduction of horizontal flow wetlands in Severn Trent in the late 80s, in 2005 nineteen sites were evaluated to determine performance after years of operation, with the oldest bed built in 1987 (18 years at the time of measurement). By then, Severn Trent was recommending parallel beds wherever possible, sized at a minimum of 5 m^2/pe. Although the company later removed horizontal flow wetlands as a template solution for secondary treatment systems due to their anaerobic nature, they are presented here as they did meet UWWTR discharge standards (Table 7).

Table 7. Summary of nineteen secondary HF wetland sites *(Severn Trent, 2005)*

	All sites		Single Beds		Two in series	
	BOD	Solids	BOD	Solids	BOD	Solids
Mean	9	23	20	23	5	21
Max	41	50	41	50	12	46
Min	1	2.5	8	10	1	2.5
Std. Dev	10.0	13.0	12.7	14.1	2.9	13.0
Number	28	30	8	9	16	16

2.3 Stepped high flows applications for secondary and tertiary treatment

Combined final effluent streams

This approach has been in use since the introduction of wetland technology to the UK in the late 80s/early 90s. There are many examples across England, Wales and Scotland with this setup, where flows exceeding a certain DWF multiplier are diverted to the inlet of the tertiary treatment wetland ("reed bed"), blending with secondary treated effluent for combined treatment. The FE sampling point is downstream of the wetland (example on Figure 2).
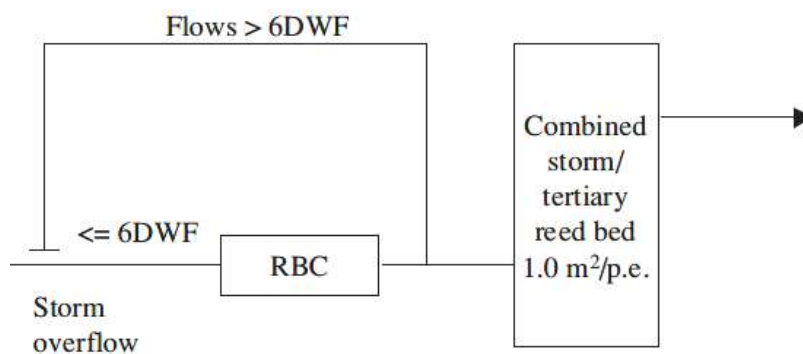

Figure 2. Typical layout of a combined reed bed works in Severn Trent

As of 2003, Severn Trent had 52 rural works with combined and tertiary wetlands. An analysis of their performance showed consistently good performance, delivering BOD< 5mg/L and TSS < 10 mg/L (Griffin, 2004) (Figure 3).
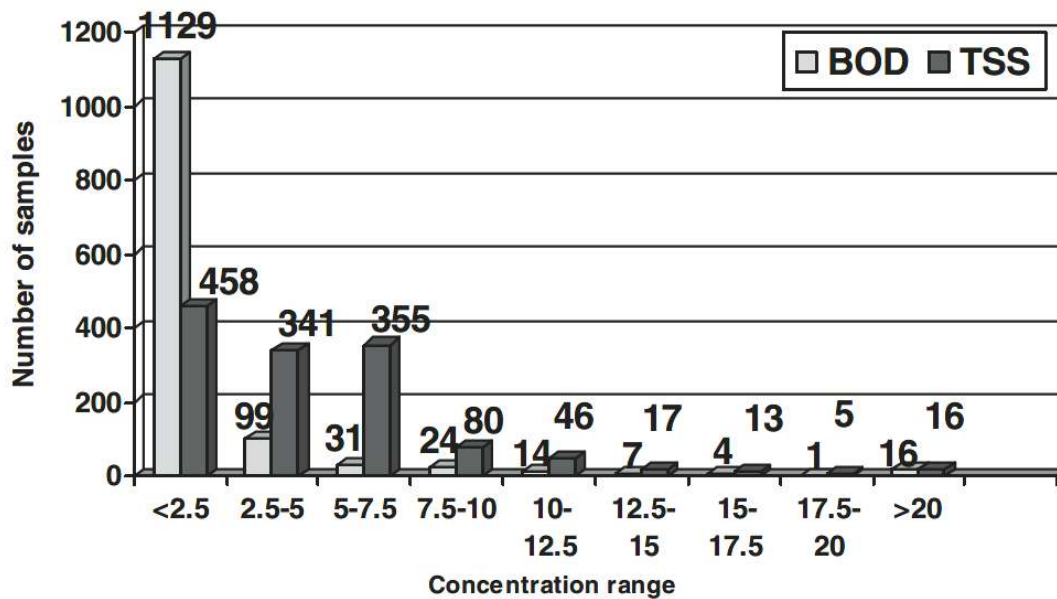
Figure 3. Effluent BOD and TSS distribution ranges for 52 combined reed bed sites from January 1999 to June 2002. Ranges expressed in mg/L. (Griffin 2004).

Site 9 is an example of this arrangement for a medium sized works.

Site 9: Large combined reed bed, Severn Trent

This mature site has had a stepped-high-flows combined wetland since 1997 and serves a population equivalent of 7,642. The flowsheet consists of primary settling tanks, trickling filters, hummus tanks and combined wetlands ("reed beds"). The wetlands receive secondary treated effluent from the main flowsheet up to 42 L/s. Flows above this value and up to 106.5 L/s bypass primary and secondary treatment and are solely treated by the wetland. The site was upgraded in 2019 to meet a phosphorus consent with the addition of tertiary treatment so results are summarised for the period before the upgrade (Table 8).

Table 8. Summary of data between 2010 – 2018 at Site 9.

Parameter	Outlet (mg/L)		Sample size
	Average	95%ile	
COD	40.9	60.3	36
BOD	2.6	6.8	144
NH4-N	2.3	5.7	108

Separate high-flows treatment

Severn Trent also trialled separate "storm" beds at the works, which were dedicated to replace storm tanks and treat solely storm overflows, with a separate discharge point. Whilst the beds were effective in biologically treating wastewater (Griffin 2004), the company found the reeds struggled during the long periods where they received no influent and looked unhealthy. Rather than bleed wastewater constantly to top up the storm beds, they switched to the combined reed

bed flowsheet described in the previous section. This meant a better utilisation of both the assets, as the beds were in continuous operation, and land (Griffin 2004).

In recent years, new stepped high-flows flowsheet have been trialled by other companies with different types of wetlands.

Site 10: Surface flow wetland side treatment, United Utilities

This works treats all flows (no storm outfall permit, all flows to undergo biological treatment) with a flow range of 1 to 26 l/s (1 in 30 year flow). A 3-cell surface flow wetland (ICW) receives up to 15 l/s and replaced what would have been 850 m^3 grey storage whilst treating screened flows to the required standards (Figure 4). A snapshot of data was presented by UU at the European Water and Wastewater Management Conference in 2023 (Betts 2023; Table 9).
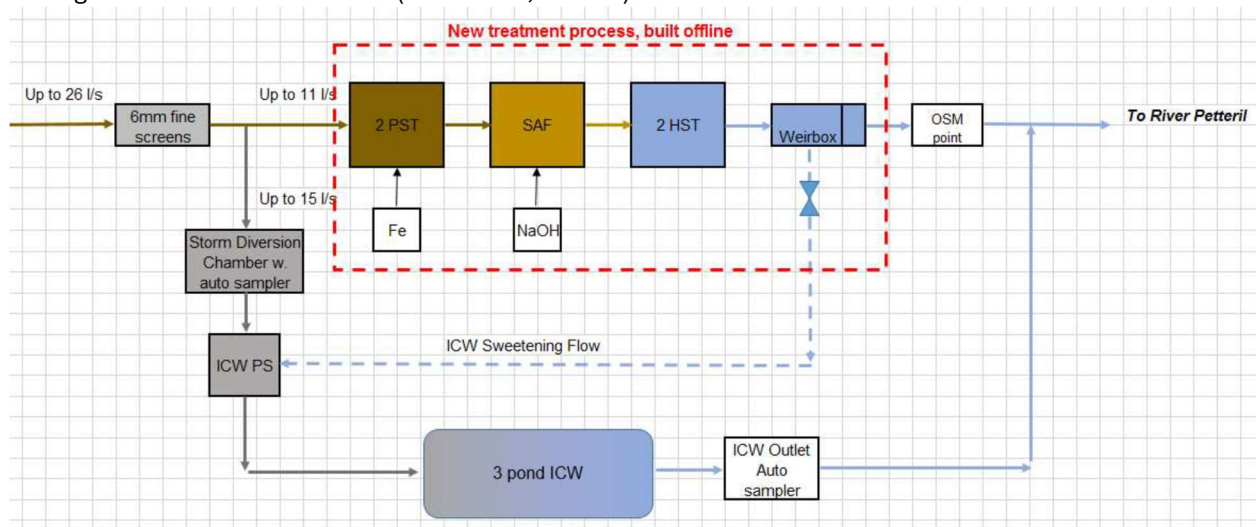

Figure 4. Dedicated storm bed for stepped high flows. From Betts 2023.

Table 9 Summary of performance for storm bed at UU (Betts 2023)

Date	Inlet BOD Concentration	Outlet BOD Concentration
27/07/2022	No data	23.9 (SN)
22/09/2022	464 (SN)	21.7 (SN)
01/10/2022	398 (CO)	11.3 (CO)
06/10/2022	271 (CO)	28.0 (CO)
10/01/2023	37.5 (SN)	35.0 (SN)
11/01/2023	64.5 (CO)	17.0 (CO)
Average	247 (All samples)	22.8 (All samples)

Additional examples of CSO applications can be found in Appendix B.

3 Pathogen removal

A key part of the current public concerns about wastewater and CSO discharges to the environment is the exposure of water users to pathogens and bacteria with anti-microbial resistance. In addition to removal of organic matter and ammoniacal-N treatment wetlands can contribute removals of indicator bacteria and viruses from wastewater. This results from a variety of processes such as adsorption, inactivation and predation. Generally, these removals tend to be similar to conventional plants and often can enhance removals in previous processes, especially when deployed as tertiary treatment systems.

Subsurface treatment wetlands for secondary treatment generally remove 2 – 3 log orders (99-99%) of indicator bacteria and this translates into similar removals of pathogenic bacteria and viruses (Dotro et al., 2017). This is also seen in aerated tertiary wetlands which can give an additional >1 log removal from already well treated effluents (Stefanakis et al., 2019) giving effluents in the 1-2 log range for E coli. In Germany, France and Italy CSO wetlands have also been reported to give 1-2 Log reductions in faecal indicator counts in lab and field studies from typical inlet values of 10^4 to 10^6 MPN or CFU·100 mL^{-1}, with much higher removals reported for specific events and separate sewer systems (Ruppelt et al 2018).

Similar removals are seen in wetlands treating CSOs in groundwater affected catchments. For example, the E coli and Enterococci counts in the CSO treatment wetland at Hanging Langford (Wessex) are compared to the receiving water in Fig. 5, as per data supplied by Wessex Water. More details on this site can be found in Appendix B.
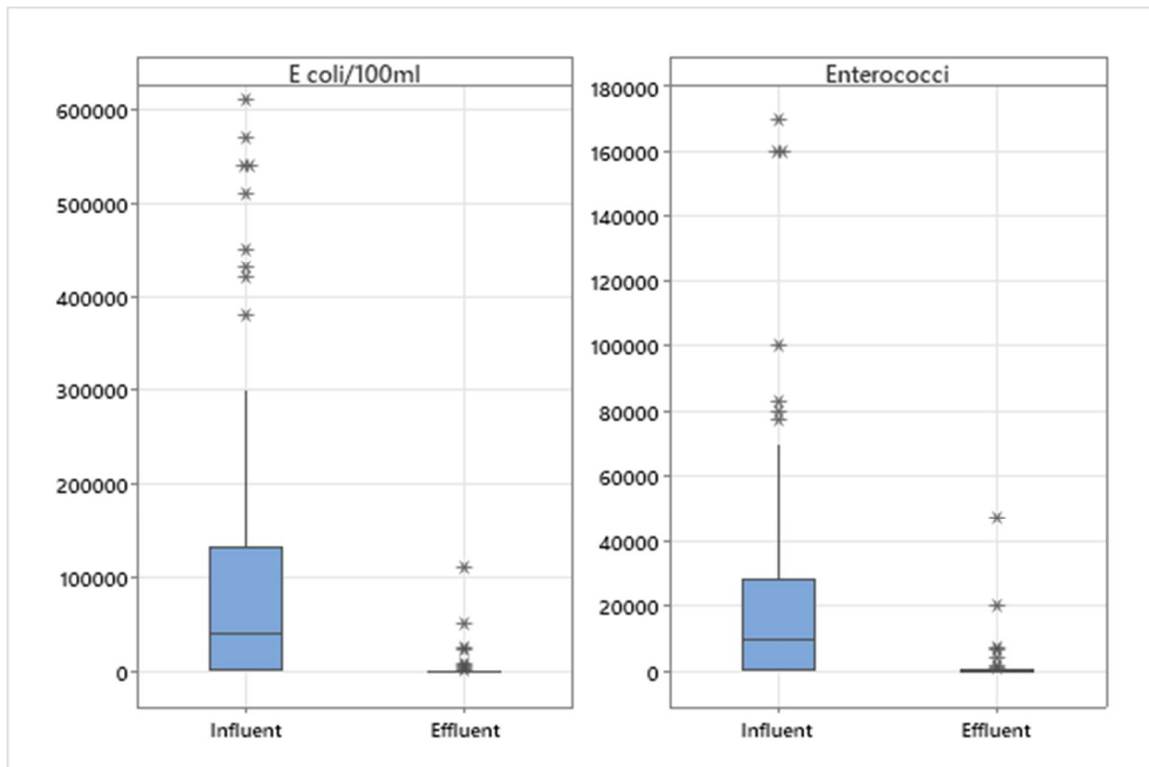

Figure 5. Hanging Langford: E coli and Enterococci counts in CSO treatment wetlands inlet and outlets (2 x Influent outliers have been truncated).

The wetland consistently provides 1-3 Log orders reduction in indicator organism counts, but also has lower median counts than the river (70 vs 430 E Coli/100 ml and 50 vs 160 Enterococci/100ml) with both the effluent and the river having similar maximum values (Figure 6).
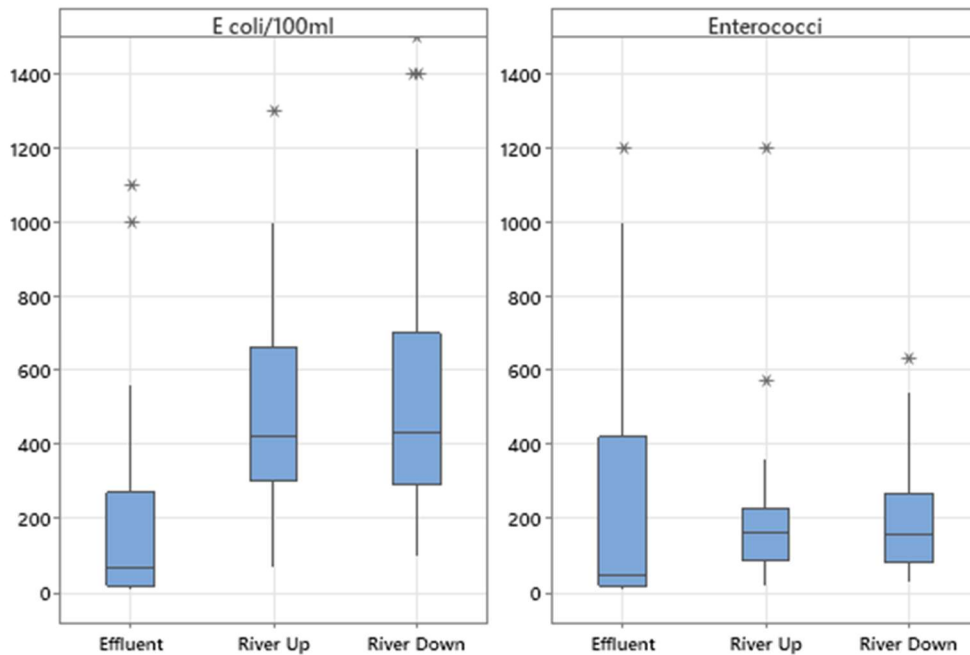

Figure 6. Hanging Langford: E coli and Enterococci counts in CSO treatment wetlands effluent compared to river values (some outliers have been truncated).

Southern Water's aerated CSO wetland at Lavant has also shown between 1.5 and 2.5 Log order reductions in indicator organisms (Figure 7) with median effluent values of 6500 and 1800/100mL respectively for E coli and Enterococci.
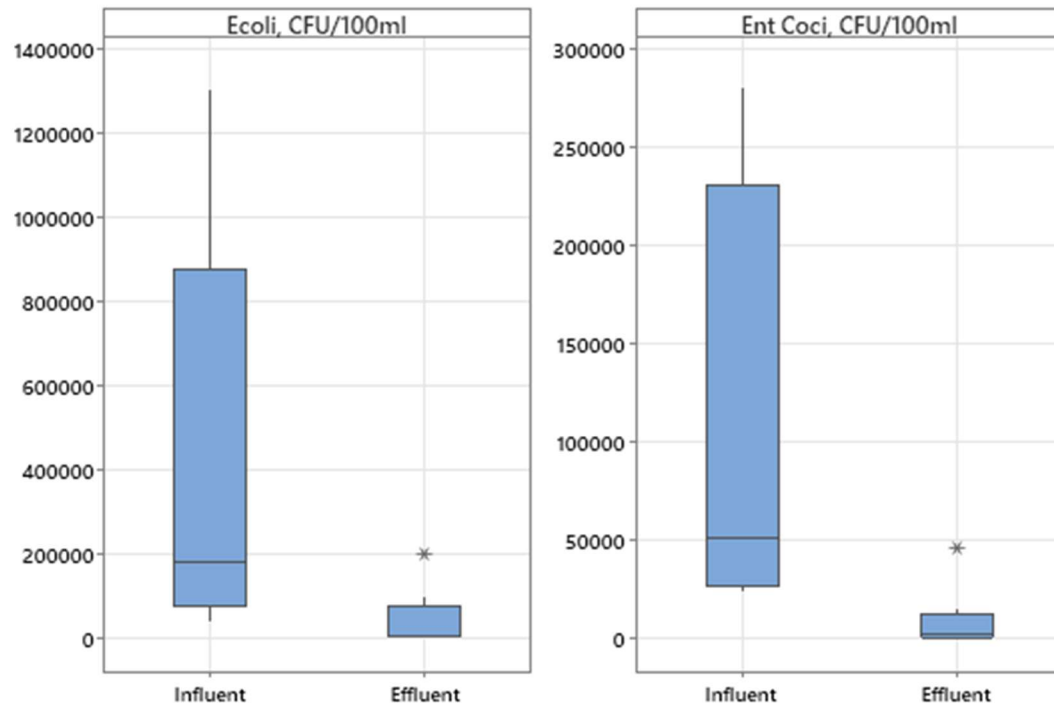
Figure 7 Lavant: E coli and Enterococci counts in CSO treatment wetlands inlet and outlet.

4 Conclusions

Treatment wetlands are an established biological treatment technology, successfully implemented in many applications in the UK. Indeed, the UK pioneered the use of gravel substrates for horizontal flow wetlands back in the early 90s and has evidence of use of all main variants of the technology (horizontal, vertical, and surface flow; French wetlands) for sewage applications, including stepped high flows at sewage treatment works and for CSO in the network. Experience from both the UK and European countries show they are able to deliver secondary treatment that meets or surpasses the requirements associated with UWWTR even when applied to sites smaller than 2,000 pe.

Appendix A. Overview of treatment wetland terminology

The simplest classification of treatment wetlands is based on their water table and direction of flow (Figure A1). Profile schematics of each main variation were summarised in Dotro et al (2017) and are reproduced below (Figure A2).
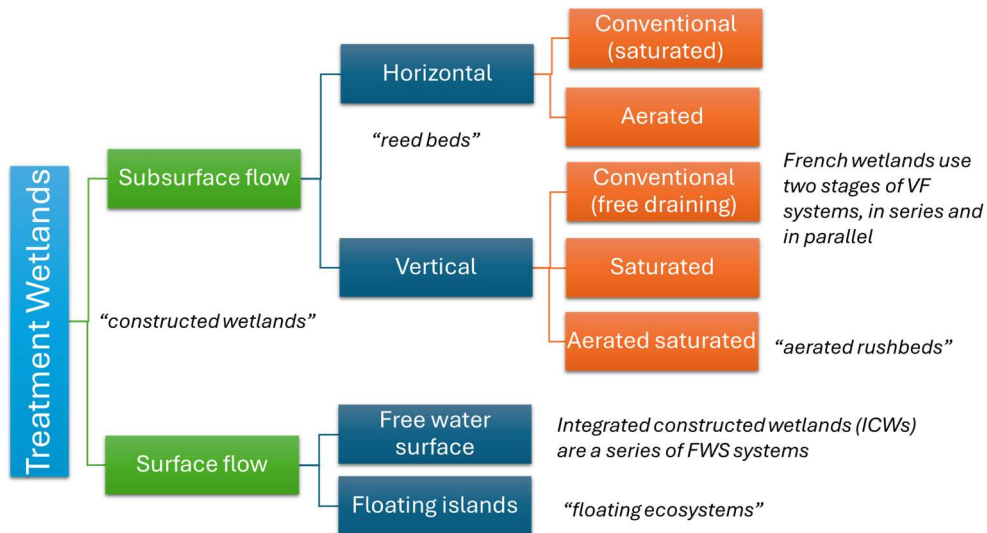

Figure A1 Standard classification of treatment wetlands and colloquial names associated with key technology variations
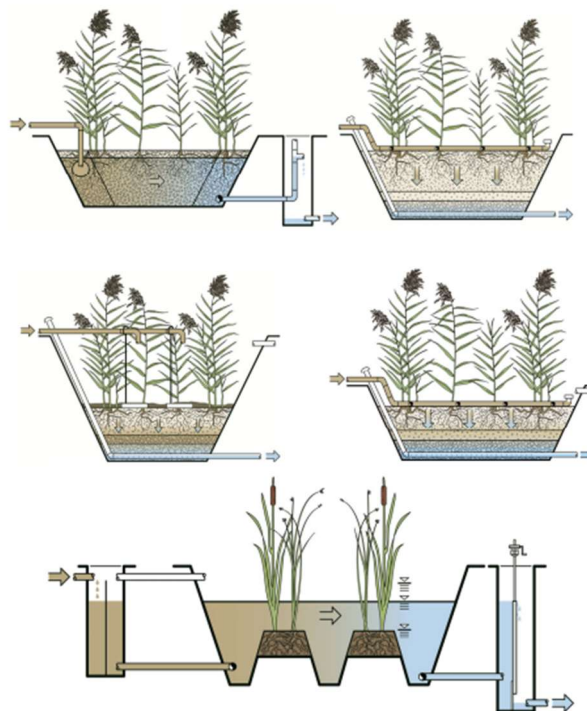

Figure A2. Main types of treatment wetlands: Top Left – Horizontal Flow; Top Right – Vertical Flow; Middle Left – French First Stage; Middle Right – French Second Stage; Bottom –Surface Flow (Dotro et al 2017)

Appendix B. Summary of case studies for storm overflow applications

A. Groundwater impacted storm overflow treatment systems

Site A1: Shrewton. Wessex Water

Shrewton WRC (1,987 pe) inflow is heavily influenced by groundwater ingress with 139 spills over 2969 hours in 2022. Wessex have undertaken a programme of sewer sealing (1.7 km) but own less than a 1/3 of the network, they still calculate that 129,000 m^3 of storage would be required, dwarfing the plant. A TW has been constructed to treat storm flows. The reed bed effluent reported by Wessex over the winters of 2022 and 23 have approximately 10 mg/L BOD and 6 mg/L mg-N/L NH$_4$-N compared to permits of 45 and 15 mg/L respectively (Wessex per comm., 2024).

Site A2: Lavant. Southern Water

The Lavant WWTW scheme, 2600 pe, is considered more detail as Southern Water have made monitoring data available. This site is in a chalk catchment and has groundwater ingress when levels are high. In this scheme an aerated TW has been added downstream of a storm tank that has been converted into a sedimentation tank, the schematic process flow is shown in Fig B1. This Increases the treatment capacity from 34 L/s FFT to 70 L/s. Lavant WWTW has discharge permits standards of 40 mg/L TSS, 20 mg/L BOD and 20 mg-N/L NH$_4$-N.

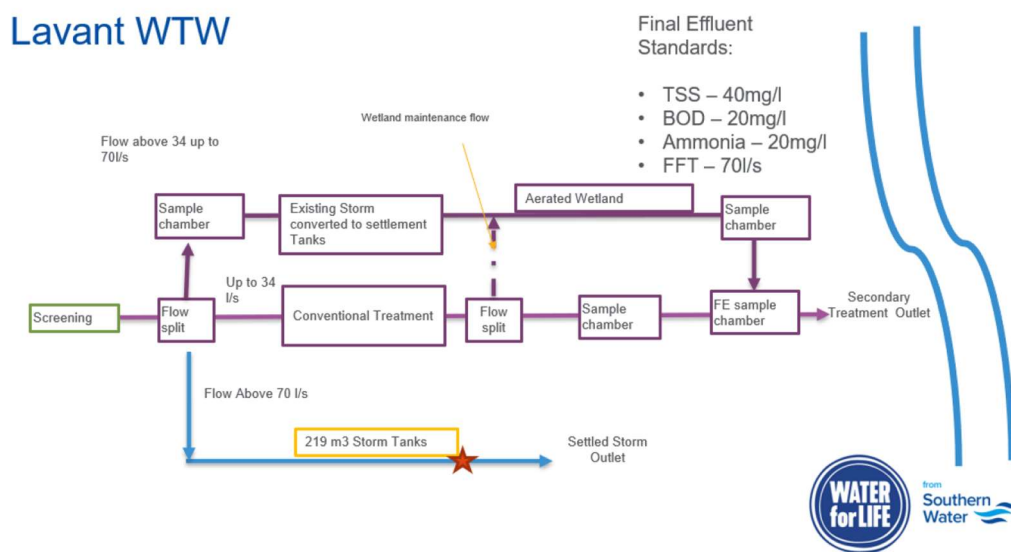Fig. B1. Schematic process flow at Lavant WTW

The boxplots of water quality through the plant are shown in Fig B2, with the horizontal line showing the median, the boxes the inter quartile ranges and stars showing outliers. The effect of the groundwater and stormwaters can be seen in the low crude mean values of 46 mg/L BOD and 11 mg/L TSS, although spikes of NH$_4$-N are seen (max. 51) giving a mean of 22 mg-N/L.
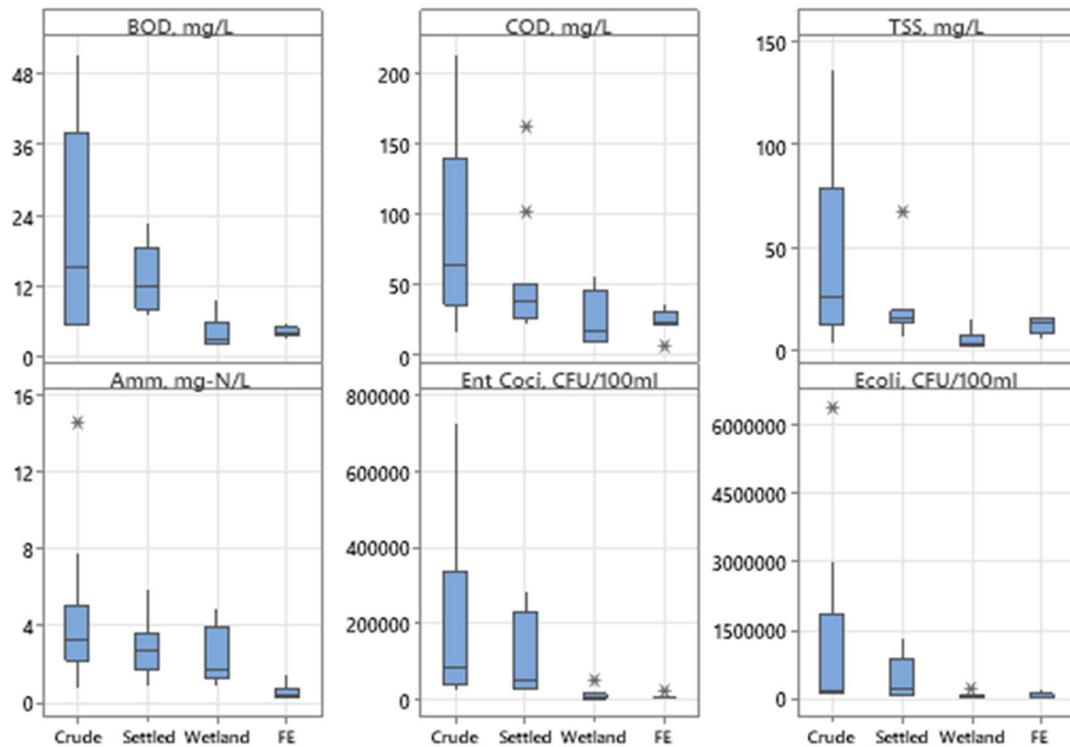
Fig. B2. Box Plots of water quality through Lavant WTW

There are good removals of a range of parameters across the plant. These are considered in more detail in Table B1 which considers both the mean and median values as the sample (n 8 to 10) was a bit small to undertake normality tests. The values are considered for the storm overflow pathway from the crude, through the settling tank, then onto the TW before mixing with the main treatment stream from the trickling filters. Table B1 also considers the cumulative % removals of each pollutant through the plant and also the specific % removal seen across the TW.

The mean final effluent COD was 24.4 mg/L compared to the UWWD limit of 125 mg/l. The influent was very dilute at 85.8 mg/L, so despite a very clean effluent the overall % removal was 72%. A similar pattern was seen for BOD with median wetland effluent concentrations of less than 4 mg/l with a similar picture for TSS at 3.9 mg/L with slightly higher levels in the final effluent (FE) blended with the TF effluents. For indicator organisms (E coli and Ent Cocci) these are constantly 1-2 log order reductions with at least 1 log reduction across the TW. NH_4-N removals were also slightly lower but spikes in the influent were effectively buffers and the effluent at about 4 mg/l was well within consent. Overall removals of TN in the WWTW were seen but removals of TP were less which is consistent with the expectations of this type of wetland. TN removal; across wetland is minimal, but this is to be expected at the low C:N in the sewage and the wetlands will be predominantly aerobic and unsuitable for high rates of heterotrophic denitrification, also the levels of TN are also low. The % removals across the wetland are included to assess their performance at these low concentrations. As many treatment mechanisms have underlying first order reaction rates it is common to see much higher removal rates for stronger sewage, particularly over the first unit processes in a WWTW

Table B1: Data Summary through Lavant WTW Showing Cumulative % removals (n=8-10)

	Location	Mean	SD	∑ Mean % Removal	Median	IQR	∑ Median % Removal
COD, mg/L	Crude	85.8	65.2		64.1	104.3	
	Settled Overflow	51.9	40.9	40	39.5	23.2	39
	Aerated Wetland	26.3	18.4	69 (49*)	18.2	35.7	72 (54*)
	FE	24.4	9.4	72	25.6	9.8	62
BOD, mg/L	Crude	22.0	17.3		15.4	32.5	
	Settled Overflow	13.4	5.7	53	12.1	10.2	21
	Aerated Wetland	4.2	2.7	88 (75*)	3.0	3.9	80 (75*)
	FE	4.4	0.9	72	4.1	1.4	73
Ent Cocci, CFU/100ml	Crude	188778	268059		80000	300000	
	Settled Overflow	112750	108170	40	51000	203500	36
	Aerated Wetland	8811	15894	95 (92*)	1800	12005	98 (96*)
	FE	4713	6227	98	3100	1750	96
E.coli, CFU/100ml	Crude	1236667	2150727		140000	1750000.0	
	Settled Overflow	446250	482403	64	180000	797500	-29
	Aerated Wetland	41913	71917	94 (91*)	6500	72750	95 (96*)
	FE	47000	73155	96	10000	89500	93
NH4-N	Crude	4.4	4.0		3.3	2.8	
mg-N/L	Settled Overflow	2.9	1.6	35	2.7	1.9	17

		Location	Mean	SD	∑ Mean % Removal	Median	IQR	∑ Median % Removal
		Aerated Wetland	2.4	1.5	66 (15*)	1.7	2.7	48 (38)
		FE	0.5	0.4	88	0.4	0.5	89
TSS, mg/L		Crude	46.0	48.2		26.2	66.4	
		Settled Overflow	21.8	19.0	53	16.4	5.8	37
		Aerated Wetland	5.5	4.7	90 (75*)	3.9	5.8	78 (76*)
		FE	12.7	4.0	72	13.6	7.5	48
TN		Crude	11.2	7.4		8.8	2.9	
mg-N/L		Settled Overflow	9.4	3.5	16	8.7	2.9	2
		Aerated Wetland	5.7	0.8	93 (39*)	5.7	1.2	87 (34*)
		FE	8.0	0.9	28	7.9	1.7	10
TP		Crude	1.1	0.7		0.9	0.6	
mg-P/L		Settled Overflow	0.7	0.3	31	0.7	0.5	22
		Aerated Wetland	0.6	0.3	45 (20*)	0.5	0.3	46 (31*)
		FE	0.8	0.2	20	0.8	0.2	14

()* values are % removals only across the TW

Fig. B3. focuses on the wetland influent, effluent and the combined FE with a time series plot. The plot show that the wetland was able to reduce spikes in the influent for BOD, TSS and NH_4-N, with TW effluent values below the combined FE. The indicator organisms also show the wetland reducing numbers but in particular the high spikes seen in the influent are effectively balanced and smoothed.
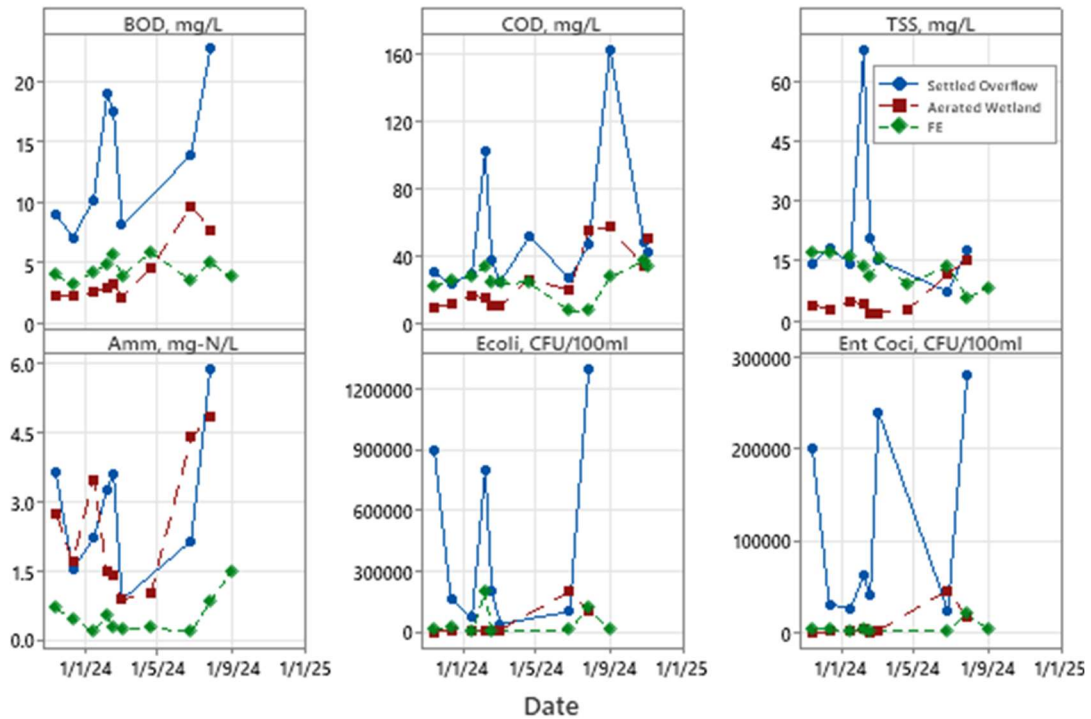
Fig. B3. Time series plots of water quality through the settling tank\aerated wetland system.

Additional sampling was also undertaken at the influent, effluent and mid-point in 7/24. These spot samples have similar low effluent values but apart from TSS removals are generally lower than the combined data set.

Table B2: Southern Water Sampling additional sampling, 16/7/24

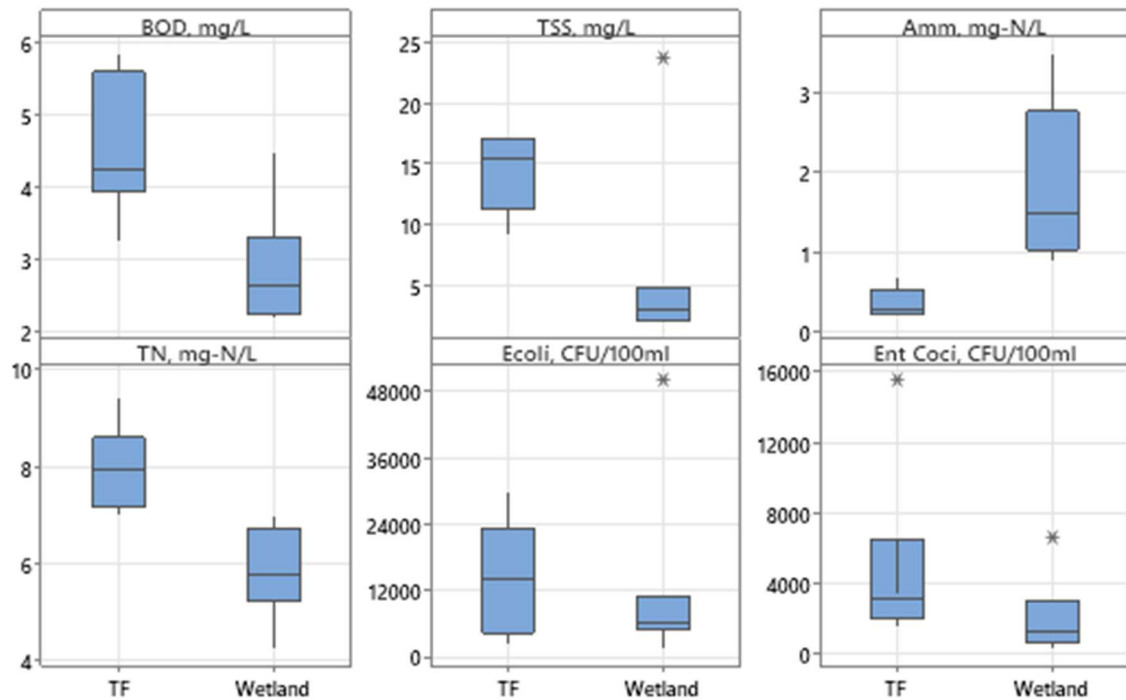| Location	NH$_4$-N, mg/L	BOD, mg/L	COD, mg/L	NO$_3$-N, mg-N/L	NO$_2$-N, mg-N/L	TP, mg-P/L	SS, mg/L	TN, mg-N/L
Wetland In	5.53	17.90	55.0	0.90	0.405	1.320	30.2	6.81
Mid-point	5.60	24.40	57.3	0.95	0.454	1.270	44.8	7.06
Wetland Outlet	4.96	6.48	33.5	0.75	0.458	0.918	4.4	6.56

Fig. B4. Box Plots comparison of water quality from the TW and trickling filters at Lavant WTW

B. Wetlands in the network

Site B1: Aerated wetland, Scottish Water.

The Cowdenbeath TW was commissioned by Scottish Water to treat increased CSOs from urban expansion. A vertical flow forced bed aeration wetland was installed by ARM Ltd (ARMStorm™) with flows fed to the bed at a maximum rate of 46 L/s from a 3000 m^3 holding tank. The bed was deeper than usual at 2 m to save space with an area of 4,000 m^2 and a 4000 m^3/d treatment capacity. It operates at a consent of 9.0 mg/L BOD and 1.5 mg N/L NH_4-N (ARM, undated).

Site B2: Wetland, Wessex Water.

Hanging Langford Pumping Station has a 2625 m^2 TW for an initial 3-year trial from 1/2024 in agreement with the Environment Agency. It is close to Shrewton and has similar issues with groundwater infiltration. Wessex had already taken measures to reduce river ingress that reduced spills from 360 to 109 between 2019 and 2023.
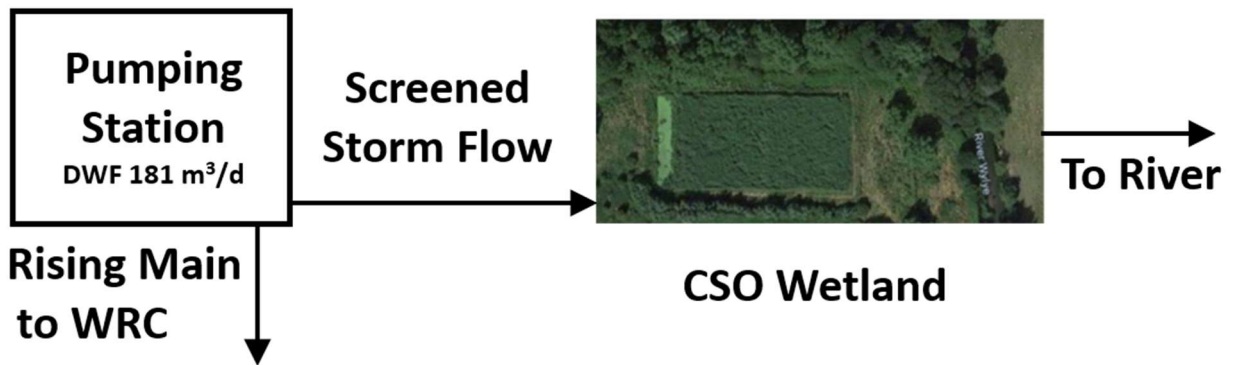
Fig. B6. Schematic process flow at Hanging Langford Pumping Station

The water quality improvements across the wetland are shown in Fig B7 and Table B2. BOD and COD in the influent are relatively low at with medians of 32 and 5 mg/L respectively. These low levels were often below the Limit of Detection (LOD) so the % removals of about 70 and 60% are not very representative. There is evidence of ammoniacal N removals of 73% with a median effluent of 1.3 mg-N/L suggesting nitrification in the wetland. Very good removals of the indicator bacteria were seen with 99% (2 log order) reductions of both E. coli and Enterococci. The CSO wetland is therefore producing a very good effluent with concentrations of some parameters below that normally expected from a small WWtW.
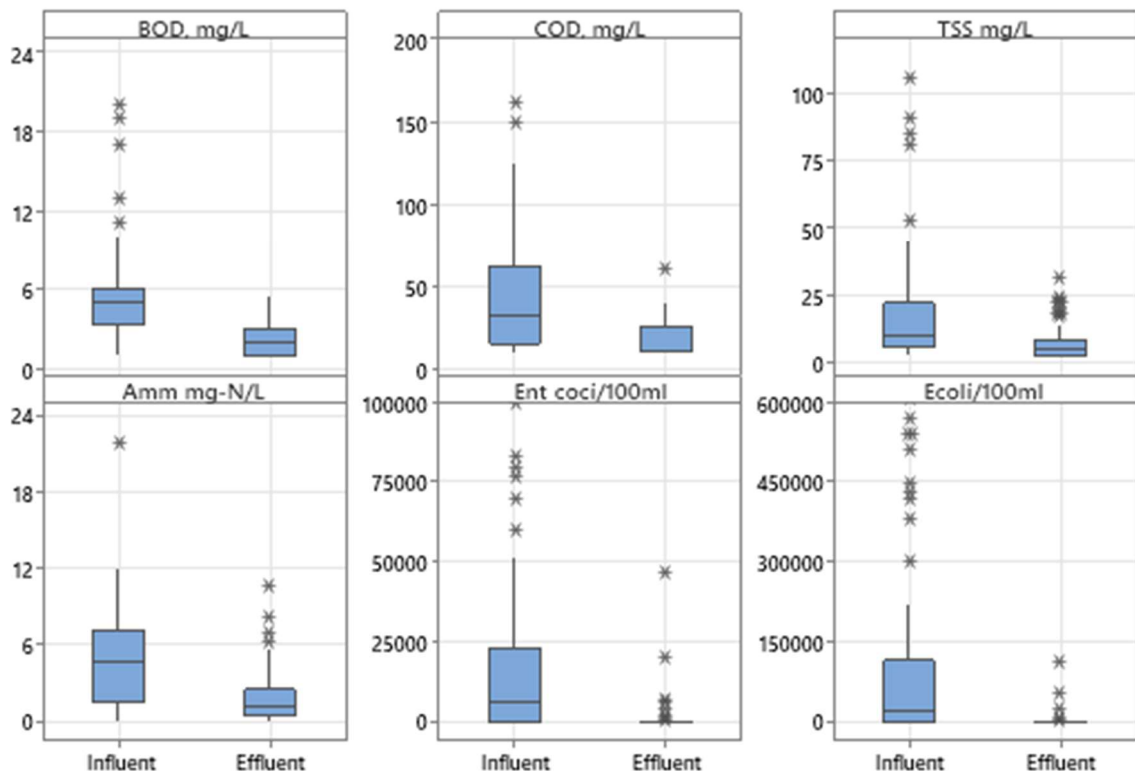

Fig B7. Box Plots of water quality through Hanging Langford CSO wetland and river

Table B2 also summarises the data recorded upstream and downstream of the outfall, these are also compared in the box plots in Fig 8 .

Table B2: Data Summary through Lavant WTW Showing Cumulative % removals (n=)

Parameter	Location	n	Mean	SD	Mean % Removal	Median	Median % Removal
COD, mg/L	Influent	33	54.1	67.5		32.0	
	Effluent	32	18.0	12.6	66	10.0	69
	River Up	27	13.2	10.4		10.0	
	River Down	27	18.4	39.8		10.0	
BOD, mg/L	Influent	64	7.0	11.3		5.0	
	Effluent	62	2.2	1.1	68	2.0	60
	River Up	30	1.9	1.8		1.0	
	River Down	30	1.4	0.7		1.0	
Ent Cocci, CFU/100ml	Influent	76	27314.1	56865.0		6150.0	
	Effluent	55	1644.5	6896.7	94	20.0	99
	River Up	43	2840.5	12710.0		140.0	
	River Down	43	186.7	146.0		140.0	
E.coli, CFU/100ml	Influent	76	121628.0	235310.0		19400.0	
	Effluent	72	3563.3	14765.6	97	45.0	99
	River Up	43	14768.8	76844.5		420.0	
	River Down	43	707.2	873.6		430.0	
NH4-N	Influent	75	8.3	13.8		4.7	
mg-N/L	Effluent	70	2.0	2.2	76	1.3	73
	River Up	42	0.1	0.3		0.0	

Parameter	Location	n	Mean	SD	Mean % Removal	Median	Median % Removal
	River Down	42	0.0	0.0		0.0	
TSS, mg/L	Influent	75	21.2	36.7		10.0	
	Effluent	70	7.2	6.3	65	5.0	50
	River Up	42	9.6	12.5		7.0	
	River Down	42	8.6	8.9		7.0	
TON	Influent	42	1.4	1.9		0.2	
mg-N/L	Effluent	37	0.4	0.6	69	0.1	50
	River Up	29	6.0	0.8		6.1	
	River Down	29	6.1	0.5		6.1	
SRP	Influent	59	1.7	2.3		1.1	
mg-P/L	Effluent	53	1.0	0.7	40	1.0	7
	River Up	42	0.1	0.1		0.1	
	River Down	42	0.1	0.0		0.1	

LODs included as LOD/2 *all values below LOD

Figure B8 show that BOD from the CSO wetland was similar to the river, with many values of both sample below the LOD. The boxplots show a slightly higher COD range but the median bar is at 10 mg/l the same as the river upstream and downstream. This is due to an outlier of 60 mg/L in November 2022 and a few values around 40 mg/l at other times which are still very low and below the UWWTD value of 125 mg/l.
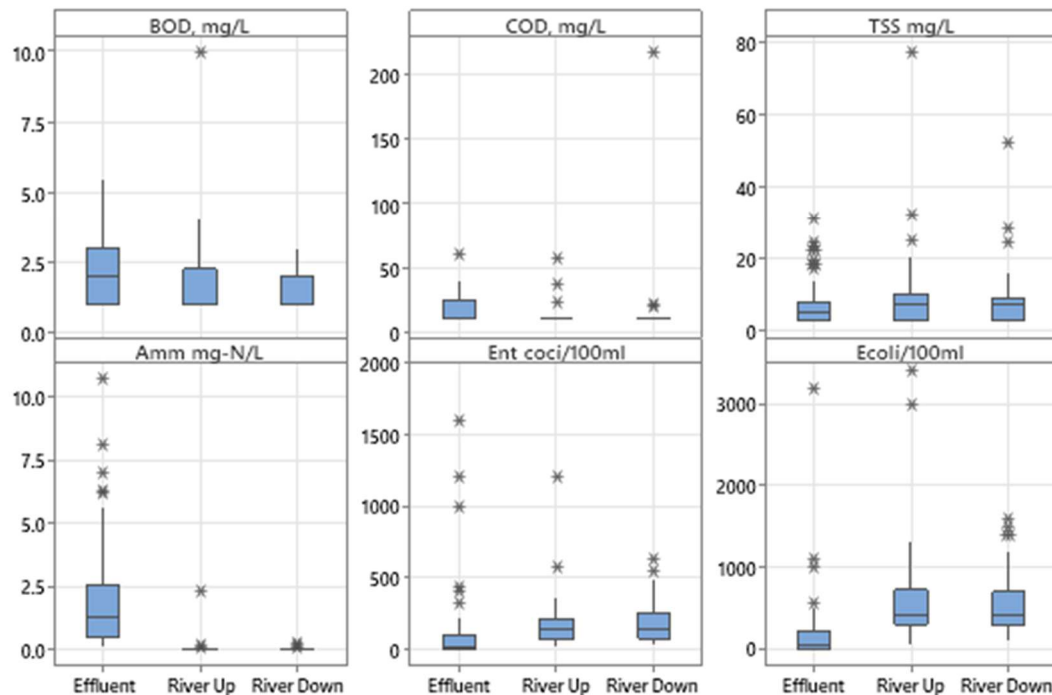
Fig B8, Box Plots comparing the CSO effluent with river upstream and downstream of the outfall (Note: 2 To allow data to be seen more clearly 2 outliers from Effluent and River up not shown for Ent Cocci and 1 outlier from effluent and two from River up not shown for E. coli).

Indicator bacteria in the effluent from the wetland were generally lowers than that in the river upstream and down-stream of the discharge. There is the wide variation that is usually encountered in microbial counts, but it is reassuring that the wetland is potentially reducing the pathogen load in the river. This is an agricultural area so further investigations would be required to assess the sources of the bacterial load in the river.

C. Historic data from Severn Trent wetlands ("reedbeds")

The paper cited in the body of the report (Griffin 2004) summarised Severn Trent's 10 years of experience with wetland applications. As part of that report, there was a detailed assessment of a dedicated storm overflow wetland (Ligthhorne Heath) and a combined storm and tertiary treatment wetland (Stretton on Fosse). Results included a detailed profile of inlet and outlet concentrations (Table C1) and a summary of performance for the combined wetland/stepped flow wetland for eight years (Table C2).

Table C1. Detailed results of storm event surveys at storm overflow only and combined wetlands. (Griffin 2004).

| | Date of storm survey | | | | |
| | Lighthorne Heath | | | Stretton on Fosse | |
	11–13th June 93	13–15th Nov 93	5–6th Jan 94	07th Feb 96	08th Feb 96
Storm duration (hr)	32	36	27	24	52
Peak flow rate ($l\,s^{-1}$)	11.1	9.7	11.1	7.8	
Cumulative vol. treated (m^3)	237	417	301	371	601
Hydraulic load ($cm\,d^{-1}$)	25	40	38	98	73
Mean influent BOD ($mg\,l^{-1}$)	35	45	51	21	20
Peak influent BOD ($mg\,l^{-1}$)	86	363	147	37	37
Mean effluent BOD ($mg\,l^{-1}$)	8.4	10.3	10.3	6.0	1.9
Peak effluent BOD ($mg\,l^{-1}$)	11.6	18	13.2	12	5.7
Mean influent TSS ($mg\,l^{-1}$)	85	109	127	39	27
Peak influent TSS ($mg\,l^{-1}$)	266	1,070	292	80	80
Mean effluent TSS ($mg\,l^{-1}$)	15.6	17.3	25.9	7.8	5.3
Peak effluent TSS ($mg\,l^{-1}$)	25	48	36	22	22
Mean influent NH_4-N ($mg\,l^{-1}$)	4.1	4.2	5.8	2.27	1.5
Peak influent NH_4-N ($mg\,l^{-1}$)	20.4	40.4	12.4	6.7	6.7
Mean effluent NH_4-N ($mg\,l^{-1}$)	2.4	1.8	2.9	1.8	1.2
Peak effluent NH_4-N ($mg\,l^{-1}$)	3.0	2.3	3.7	4.1	4.1
Mean influent TON ($mg\,l^{-1}$)	6.6	5.1	4.7	13.4	13.8
Peak influent TON ($mg\,l^{-1}$)	9.8	6.5	6.4	18.9	18.9
Mean effluent TON ($mg\,l^{-1}$)	1.5	1.3	1.4	13.8	13.3
Peak effluent TON ($mg\,l^{-1}$)	3.8	3.2	3.1	16	16

Table C2 Annual average and 95% percentiles for combined storm overflow and tertiary treatment bed at Stretton on Fosse during 1994-2002. Concentrations in mg/L (Griffin 2004).

Year	Mean BOD_5	BOD_5 95%ile	Mean TSS	TSS 95%ile	Number of samples
1994	4	11.7	6.9	16.9	12
1995	1.5	3.2	2.2	4.9	12
1996	1.1	2.0	2	3.5	12
1997	1.3	3.2	2	3.5	12
1998	1	1.8	1.9	3.5	12
1999	3.8	14.5	5.9	10.5	11
2000	1.9	3.4	5.2	9.5	11
2001	3.8	9.8	6.1	14.1	7
2002 to August	3.8	10.6	5.3	16.8	8

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About the authors

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John Williams is Professor of Environmental Technology in the School of Civil Engineering and Surveying at the University of Portsmouth. His PhD (1988-93) examined the use of constructed wetlands for wastewater treatment in the UK and Egypt, with particular focus on nitrogen cycling and pathogen removal. He has worked on many research projects examining wastewater treatment and has maintained his active interest in constructed wetlands, working in Colombia and Greece. John has also studied the use of vegetated systems for Sustainable Drainage of runoff from highways and housing developments, with a recent collaboration in Thailand examining wetlands for pesticide removal from irrigation waters contaminated with agricultural runoff.