Assessing the environmental and economic efficacy of two integrated constructed wetlands at mitigating eutrophication risk from sewage effluent

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Abstract

The nutrient removal efficiency of two integrated constructed wetlands (ICWs) installed at commercial wastewater treatment plants (WWTPs) in Norfolk, UK, is assessed – the River Ingol ICW (1 year old) and the River Mun ICW (5 years old). Analysing water samples collected across the ICWs between February and September 2019, significant reductions in both effluent nutrient concentration and load were recorded. At the River Mun ICW, mean nitrate and phosphate concentrations were reduced by ~63% across the wetland, whilst nutrient loadings were reduced by ~57%. At the River Ingol ICW, mean nitrate and phosphate concentrations were reduced by ~30%, whilst nutrient loadings were reduced by ~70%. Economically, the total capital cost of both ICWs were comparable at £31-39 per person served. Overall, this study demonstrates ICWs can significantly reduce the eutrophication risk associated with WWTP discharges and can do so whilst providing a cost-effective alternative to conventional tertiary wastewater treatment.

Keywords: municipal waste; nitrogen; organic carbon; phosphorus; rivers; wastewater treatment plant.

1. Introduction

Nutrient enriched sewage effluent discharged from wastewater treatment plants (WWTPs) is a major global driver of freshwater eutrophication (Neal *et al.*, 2005; Jarvie *et al.*, 2006; Bowes *et al.*, 2012; Roberts and Cooper, 2018). In order to reduce the environmental toxicity of sewage effluent, wastewater undergoes numerous stages of processing at WWTPs, including screening through filters to remove coarse material (pre-treatment), holding in settling tanks to encourage sedimentation of suspended fines (primary treatment) and promoting the degradation of organics through biological oxidation (secondary treatment) (Spellman, 2013). However, post-treatment,

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the effluent typically remains rich in nutrients and requires further tertiary treatment to mitigate eutrophication risk. Whilst tertiary treatment can be highly effective, the technology can also be expensive and its application is generally limited to larger WWTPs discharging into more environmentally sensitive waterbodies (Sedlak, 2018).

In this regard, integrated constructed wetlands (ICWs) have the potential to provide an alternative, cost-effective, natural treatment for sewage effluent (Babatunde *et al*., 2008; Kayranli *et al*., 2010a; Chang *et al*., 2012). ICWs are wetlands engineered to remediate polluted water prior to its release into surface waterbodies using natural biological, chemical and physical processes instead of industrial chemical treatments (Dunne *et al*., 2005; Scholz and Lee, 2005; Harrington *et al*., 2007). Typically consisting of a series of interconnected ‘cells’ or pools, ICWs are unlined, free surface flow systems characterised by shallow water depths (~20-40 cm), emergent vegetation and a bed constructed from in-situ soil rather than artificial liners as typically found in non-integrated constructed wetland designs (Harrington *et al*., 2007; Kadlec *et al*., 2010). ICWs are planted with a range of native aquatic plants which support diverse periphyton communities that act as important biofilters, absorbing excess nutrients from sewage effluent and reducing water velocities to encourage sedimentation of entrained particulate material (Almuktar *et al*., 2018; Cooper *et al*., 2019). With the additional aim of enhancing biodiversity and ‘integrating’ into the local environment, ICWs are designed to be environmentally sustainable, robust and largely self-managing, thus making them a cost-effective pollution mitigation option (Scholz *et al*., 2007a).

The aim of this study was to evaluate the environmental and economic efficacy of two ICWs at contrasting stages of maturity installed at WWTPs in 2018 on the River Ingol (1 year old) and in 2014 on the River Mun (5 years old) in Norfolk, UK. This was achieved through the following objectives, to:

i. Assess the spatial and temporal dynamics of nitrogen, phosphorus and carbon concentrations across the ICWs between February and September 2019;
ii. Compare the performance of established versus new systems at reducing nutrient loading into surface waterbodies;
iii. Evaluate ICW cost-effectiveness on a per capita basis relative to conventional wastewater treatment.

As the first two ICWs to be installed at commercial Anglian Water WWTP facilities, the novel results of this study will help inform decision making on the suitability of future ICW installations at other WWTPs across the Anglian Water region, whilst more broadly providing evidence on the effectiveness of sustainable water treatment solutions.

2. Materials and Methods

2.1 River Ingol Wetland

The River Ingol is a 10.3 km length, lowland, calcareous, groundwater dominated river draining an area of 35.3 km^2 in Norfolk, UK. Sections of the river have Site of Special Scientific Interest (SSSI), Special Area of Conservation (SAC) and Ramsar status, however the river is classified as having failing status for invertebrates, fish and phosphate concentrations under the EU Water Framework Directive (WFD) (van Biervliet, 2015a). The Anglian Water WWTP near the village of Ingoldisthorpe (52^{o}51'53"N 0^{o}31'18"E) was identified as a major driver of elevated phosphate concentrations and in autumn 2017 construction began on an ICW to treat the WWTP effluent prior to its discharge into the River Ingol (**Figure 1**). Covering a total area of 1.08 ha, the wetland consists of four, unlined, shallow cells with areas of 1972 m^2 (cell 1), 2450 m^2 (cell 2), 3560 m^2 (cell 3) and 2806 m^2 (cell 4), with water depths maintained across the cells at ~0.2 m. The wetland was planted with 25,000 native aquatic plants, including *Iris pseudacorus*, *Cyperaceae* sp., *Glyceria maxima, Juncaceae* sp., *Caltha palustris* and *Typha latifolia*. The site was also planted with 1400 native tree species, including *Quercus robur*, *Ilex aquifolium*, *Crataegus monogyna*, *Acer campestre*, *Corylus avellana* and *Carpinus betulus*, to provide shading and to help integrate the ICW into the wider landscape.

Effluent from the WWTP, which serves a population of 6,238 people, flows continuously into the top of cell 1 and flows through each cell, interconnected by a short (3-4 m) section of pipe, before discharging into the River Ingol at the end of cell 4. Prior to discharge into the ICW, the sewage effluent is treated within the WWTP with primary settlement tanks, trickling filters, humus tanks and a nitrifying sand filter. Effluent discharge into the wetland is permitted up to 1400 m^3 day^{-1} under dry weather conditions, with discharge entering into storm tanks at flows above 3640 m^3 day^{-1} under wet conditions. The River Ingol ICW was fully operational in April 2018.

2.2 River Mun Wetland

The River Mun is a 7.9 km length, lowland, groundwater dominated river draining a 22 km^2 catchment in Norfolk, 55 km east of the River Ingol. Sections of the river have County Wildlife Site status, however the river is classified as being in '*poor*' condition for fish and overall ecological status under the EU WFD (van Biervliet, 2015b). Outflow from the Anglian Water WWTP at Northrepps (52°53’46”N, 1°20’41”E) contributes ~70% of the River Mun discharge in the headwaters and therefore an ICW was constructed in October 2014 to treat the effluent. Covering a total area of 0.3 ha, the wetland consists of three unlined shallow (~0.2 m water depth) interconnected cells with areas of 1600 m^2 (cell 1), 700 m^2 (cell 2) and 600 m^2 (cell 3) (**Figure 1**). The wetland was planted with 15,000 native aquatic plants including *Iris pseudacorus*, *Carex riparia*, *Sparganium erectum*, *Alisma plantago-aquatica*, *Mentha aquatica* and *Veronica beccabunga*.

Sewage effluent is transported through a 180 m long pipe from the WWTP, which serves a population of 772 people, and is discharged into cell 1 at a mean rate of 160 m^3 day^{-1} under dry weather conditions. Prior to discharge into the ICW, the sewage effluent is treated with activated sludge, an aeration tank and a final settlement tank. The River Mun ICW was fully operational in November 2014. Both ICWs experience a temperate maritime climate with a mean annual temperature of 10.2°C and a mean precipitation total of 652 mm (1981-2010).

2.3 Field Campaign

Water samples were collected at monthly intervals from the top and bottom of each wetland cell and from the neighbouring river upstream and downstream of the wetland outflow pipe between February and August 2019 at the River Ingol ICW (n = 70) and between April and September 2019 at the River Mun ICW (n = 48). All water samples were collected in 250 mL PET bottles, transported on ice and immediately frozen on return to the laboratory. Water temperature and dissolved oxygen (DO) concentrations were recorded in-situ using a handheld thermometer and a Hanna 9146 DO probe (accuracy ±1.5%). Water flow into and out of the wetlands was measured at the WWTP outflow pipe discharging into cell 1 and at the wetland outflow pipe discharging from cell 3/4 into the river. Additionally, at the River Ingol ICW, sediment samples were collected at the same locations from the bed of the wetland cells using a trowel, with samples collected across 1 m^2 bulked together to form a composite sample for analysis. Sediment volume within the wetland was calculated by measuring sediment depth and wetland surface area.

2.4 Laboratory Analysis

All water samples were filtered through a 0.45 μm syringe filter to remove particulate material. Nitrate (NO_3-N) concentrations were then determined using a Dionex ICS-2000 ion chromatograph with a precision of 0.19 mg L^{-1}. Phosphate (PO_4-P) concentrations were determined colorimetrically (molybdate) using a spectrophometer (885 nm) with a precision of 3 μg L^{-1}. Total carbon (TC) and dissolved organic carbon (DOC) concentrations were determined using a Skalar Formacs CA15 TOC/TN analyser with precisions of 1.38 mg L^{-1} and 0.49 mg L^{-1}, respectively. Sediment samples were disaggregated, oven-dried at 80°C and then combusted at 550°C for 8 hours to determine the loss-on-ignition (LOI), with particulate organic carbon (POC) concentrations taken to be 58% of the LOI. Sediment bulk density was determined gravimetrically by weighing a known volume of oven-dried sediment and was used to calculate the mass of sediment retained within the wetland.

2.5 Data Analysis

Nutrient and carbon removal efficiencies across the ICWs were calculated based on the percentage change in both concentration and load between the wetland inlet and outlet pipes, whilst *t*-tests were performed to determine if these changes were significant. The hydraulic residence time (*HRT*) was calculated as follows:

$$HRT\ (days) = \frac{wetland\ volume\ (m^3)}{outflow\ rate\ (m^3 day^{-1})}$$

The hydraulic loading rate (*HLR*) was calculated as follows:

$$HLR\ (m\ day^{-1}) = \frac{inflow\ rate\ (m^3 day^{-1})}{wetland\ surface\ area\ (m^2)}$$

3. Results and Discussion

3.1 Nitrogen Dynamics

At the River Mun ICW, mean nitrate concentrations were significantly ($p < 0.05$) reduced by 62.1% between the wetland inlet (60.7 mg N L^{-1}) and outlet (23.0 mg N L^{-1}) pipes (**Figure 2**; **Table 1**), whilst mean nitrate loading into the River Mun was reduced by 55.7% relative to the loading into the ICW from the WWTP (**Table 2**). These removal efficiencies are consistent with previous studies of constructed wetlands, which have typically reported nitrate reductions of 40-60% (Vymazal, 2007; Almuktar *et al*., 2018; van Biervliet *et al*., 2020). Nitrate reduction is dominantly caused by bacterially driven aerobic nitrification of ammonia to nitrate, followed by anaerobic denitrification to nitrous oxide and nitrogen gas within the root zone, coupled with assimilation by plants and periphyton (Scholz and Lee, 2005; Xiong *et al*., 2011; Vymazal, 2013).

Temporally, monthly mean nitrate reductions were 59.3% in April, 58.9% in May, 53.0% in June, 81.3% in July, 68.2% in August and 26.0% in September in the River Mun ICW. This indicates a reduction in nitrate removal performance towards the end of the growing season, with higher nitrate concentrations likely caused by a combination of incomplete denitrification and the mineralisation of organic matter stored within the wetland during the summer (Scholz *et al*., 2016). Spatially, the largest mean nitrate reductions occurred across cell 1 with 78.8% of nitrate removed in the first 58 m, with a further 17.5% removed across cell 2 after 116 m and 3.7% removed across cell 3 after 180 m. Given that macrophyte surface coverage in the River Mun ICW was >80% across all cells and plant assemblages were similar, this spatial trend appears to driven by reduced denitrification rates in cells 2 and 3 rather than differences in plant assimilation.

At the River Ingol ICW, mean nitrate concentrations were significantly (p <0.05) reduced by 33.8% between the wetland inlet (28.4 mg N L^{-1}) and outlet (18.8 mg N L^{-1}) pipes (**Figure 2**; **Table 1**), whilst mean nitrate loading into the River Ingol was reduced by 71.7% due to lower outflow rates from the ICW than inflow rates from the WWTP (**Table 2**). Temporally, monthly mean nitrate reductions were 38.6% in March, 12.5% in early May, 36.8% in late May, 32.6% in June, 45.3% in July and 41.2% in August. The reduced nutrient removal efficiency relative to the River Mun ICW can be explained by the lack of well-developed plant-microbial interactions within the wetland during the first full growing season (Kayranli *et al*., 2010b; Ceschin et al., 2019), with macrophyte surface coverage ranging from ~50% in cell 1 to <20% in cell 2 (**Figures SI1-SI4**). Spatially, 38.5% of nitrate was removed across cell 1 in the first 68 m, a further 3.1% was removed across cell 2 after 142 m, 31.3% was removed across cell 3 after 250 m and 27.1% was removed across cell 4 after 301 m. Again, therefore, the greatest nitrate reductions were observed in the first cell of the ICW, with the poor performance in cell 2 potentially explained by a combination of low primary productivity and elevated dissolved oxygen concentrations reducing rates of denitrification (**Figure SI9**).

Despite the strong nitrate removal performance of both ICWs, mean riverine nitrate concentrations were higher downstream of the wetlands than upstream, emphasising the WWTPs were still enhancing eutrophic conditions (**Table 1**). However, upstream nitrate concentrations also regularly exceeded the EU Drinking Water Directive (98/83/EC) standard of 11.3 mg N L^{-1} at both sites, demonstrating that measures targeting nitrate pollution from non-sewage sources (e.g. agricultural fertilisers) are required in order to mitigate eutrophication risk.

3.2 Phosphorus Dynamics

Mean phosphate concentrations at the River Mun ICW were significantly ($p < 0.05$) reduced by 64.3% between the wetland inlet (8.65 mg P L^{-1}) and outlet (3.09 mg P L^{-1}) pipes (**Figure 2**; **Table 1**), whilst mean phosphate load entering the River Mun was reduced by 58.0% (**Table 2**). These reductions compare favourably with previous studies which have reported widely varying phosphorus removal efficiencies in constructed wetlands (Scholz *et al*., 2007b; Kayranli *et al*., 2010b; Zhang *et al*., 2014). Phosphate is predominantly removed through assimilation into aquatic organisms and through co-precipitation with iron, aluminium and calcium, a process commonly thought to decline in efficiency with wetland age as sediment sorption sites for phosphorus become saturated over time (Vymazal, 2007; Almuktar *et al*., 2018). However, the high phosphate removal efficiencies recorded at the River Mun ICW after five years of operation indicate the wetland remains in good operational condition.

Temporally, monthly mean phosphate reduction efficiencies were 67.5% in April, 73.1% in May, 71.1% in June, 27.7% in July, 56.8% in August and 63.0% in September. A low inlet phosphate concentration (2.5 mg P L^{-1}) recorded during July due to rainwater dilution explains the apparent poor nutrient removal performance observed during this month. Spatially, as with nitrate, the greatest reductions in mean phosphate concentration occurred across cell 1 where 73.7% of phosphate was removed, with a further 16.3% removed across cell 2 and 10.0% removed across cell 3.

At the River Ingol ICW, mean phosphate concentrations were significantly ($p < 0.05$) reduced by 27.0% between the inlet (2.04 mg P L^{-1}) and outlet (1.49 mg P L^{-1}) pipes (**Figure 2**; **Table 1**), whilst mean phosphate loading into the River Ingol was reduced by 68.9% (**Table 2**). Temporally, phosphate removal efficiencies were 12.9% in March, 25.5% in early May, 32.4% in late May, 27.8% in June, 16.4% in July and 37.9% in August, with no obvious seasonality apparent. The reduced performance relative to the River Mun ICW can again be explained by the lack of well-developed plant-microbial interactions during the first year of operation. Spatially, phosphate was removed fairly consistently across the first three cells, with 25.6% removed across cell 1, 34.9% removed across cell 2, 30.1% removed across cell 3 and 9.4% removed across cell 4.

Phosphate concentrations were significantly ($p < 0.05$) higher downstream of the wetlands than upstream in both the River Mun and River Ingol (**Table 1**). The EU WFD physico-chemical status of the River Mun can be classified as ‘*poor’* upstream and ‘*bad’* downstream, whilst the River Ingol can be classified as ‘*moderate’* upstream and ‘*bad’* downstream with respective to phosphate concentrations (UKTAG, 2013). As with nitrate, this indicates that sewage effluent is still a notable driver of eutrophication in these river systems, despite the high treatment efficiencies of the ICWs.

3.3 Carbon Dynamics

Due to the complex cycling of carbon in wetland environments, previous studies have shown that wetlands can act as both a source (Scholz *et al*., 2016) and sink (Pinney *et al*., 2000; Hamersley and Howes, 2002) for DOC. Sinks occur through biodegradation of organic carbon by heterotrophic bacteria, fungi and protozoa resulting in mineralisation and release as CO_2 and CH_4 (Kayranli *et al*., 2010b). Sinks also occur through organic carbon immobilisation as POC within aquatic plants and sediments. Conversely, sources occur when bacterial decomposition releases DOC into the water column from stored POC pools, whilst aquatic plants can also leach DOC into the water leading to elevated concentrations (Pinney *et al*., 2000).

Here, the River Ingol ICW was found to be a source of DOC, with mean concentrations increasing by 9.4% between the wetland inlet (6.4 mg L^{-1}) and outlet (7.0 mg L^{-1}) (**Table 1; Figure 2**). Mean riverine DOC concentrations also increased by 95% downstream (3.9 mg L^{-1}) of the wetland compared to upstream (2.0 mg L^{-1}), demonstrating the impact of the ICW and sewage effluent on river water quality. However, lower outflow rates from the ICW meant that ICW was acting as a sink for DOC load, with a 53.3% reduction in DOC load leaving the wetland (**Table 2**). Temporally, there was no obvious seasonality in mean monthly DOC concentrations, contrasting with previous studies which found DOC concentrations to be higher during the summer months due to greater plant leaching (Pinney *et al*., 2000).

Mean TC concentrations also increased by 32.2% between the wetland inlet (29.5 mg L^{-1}) and outlet (39.0 mg L^{-1}). Whilst part of this increase reflects the autochthonous release of DOC within the ICW, the majority likely comes from dissolved inorganic carbon (DIC) released into the wetland from exchange with the carbonate-rich shallow groundwater. TC concentrations were significantly ($p < 0.05$) higher in the both the wetland and the river during late May and June compared to February and March, which likely reflects increased evaporative concentration of carbonate material during the summer and reduced rainwater dilution. As with DOC, the TC load discharging from the ICW was 43.5% lower than the load entering from the WWTP.

The mean soft sediment depth within the Ingol ICW was 14.9 cm, with a mean bulk density of 1286 kg m^3 and a total mass of 1,951,669 kg. With a mean sediment POC content of 1.34%, the total mass of POC stored within the wetland during the first year of operation was 26,477 kg. This is eight times greater than the flux of TC into the wetland from the WWTP (3,241 kg a^{-1}), thereby indicating the majority of POC within the wetland sediments was already present within the soil prior to ICW construction.

3.4 Hydraulic Residence Times and Loading Rates

Wetland nutrient removal efficiency is widely considered to be dependent upon both the HLR and the HRT (Dong *et al*., 2011). A high effluent loading rate coupled with a short residence time will typically overload the ICW, giving insufficient contact time for physical, chemical and biological removal of pollutants. For this reason, HRTs of 5-30 days and HLRs of <0.1 m day^{-1} have been recommended (Wu *et al*., 2015). Shallow water depths (<50 cm) are also recommended to increase the contact time between effluent and wetland sediment, whilst also keeping water oxygenated through good contact with the atmosphere (Wu *et al*., 2015).

For the River Ingol ICW, a mean HRT of 16.8 days was calculated based on a water volume of 2,158 m^3 and an outflow rate of 128.7 m^3 day^{-1} (**Table 3**). A mean HLR of 0.028 m day^{-1} was calculated based on a surface area of 10,792 m^2 and an inflow rate of 301.1 m^3 day^{-1}. Therefore, the River Ingol ICW was operating within the range suggested for optimal pollutant removal performance and thus explaining the relatively good nutrient removal efficiency during the first year of operation. Unfortunately, whilst increasing the HRT can improve nutrient removal performance, DOC removal performance is typically reduced due to an extended time for plant leaching, as seen in **Table 1**. Note that the outflow rate from the River Ingol ICW was just 43% of inflow rate from the WWTP, meaning 57% of effluent entering the wetland was lost through a combination of evapotranspiration and infiltration into the shallow groundwater.

Conversely, the River Mun ICW had a mean HRT of just 3.1 days, thus below the recommended period, due to a comparatively high outflow rate (187.1 m^3 day^{-1}) relative to the total volume (580 m^3). Previous studies have reported poor phosphorus removal performance when HRTs are short due to insufficient contact time between the sewage effluent and the sediments limiting phosphorus sorption and deposition (Almuktar *et al*., 2018), however no evidence of this was detected here. The HLR was also higher (0.055 m day^{-1}) than recorded at the River Ingol ICW, although it was still below the recommended maximum of 0.1 m day^{-1}. The River Mun ICW outflow rate was 16.9% higher than the inflow rate from the WWTP, indicating the wetland was gaining water from the shallow groundwater and that evaporation rates were likely lower due to a smaller surface area and less open water as a consequence of more established surface plant coverage (**Figure 1**).

3.5 Economic Performance

For ICWs to be adopted as a catchment-wide pollution mitigation measure they need to be cost-effective and economically competitive with conventional wastewater treatment technologies. The total capital cost for the River Ingol ICW was £194,000, of which planning, design and management accounted for 8%, construction accounted for 83% and the purchasing of aquatic plants accounted for 9% (**Table 4**). This equated to a total cost per person served by the WWTP of £31, based on a population of 6,238 people. The total capital cost of the River Mun ICW was £30,021, of which planning, design and management accounted for 4%, construction accounted for 72% and aquatic plants accounted for 23%. This equated to a total cost per person served by the River Mun WWTP of £39, based on a population of 772 people. For comparison, Anglian Water estimated that installing chemical phosphorus stripping at the River Ingol WWTP, which has the potential to reduce phosphorus concentrations by ~90%, would incur a capital cost of £1 million with an additional operating cost of £0.5 million per annum (van Biervliet, 2015a). Given such high capital costs of installing ion exchange and chemical precipitation technologies at WWTPs to remove nitrogen and phosphorus (Sengupta *et al*., 2015), these ICWs provide a natural, cost-effective, alternative to conventional tertiary wastewater treatment.

3.6 Wetland Maintenance

Previous studies have recommended that periodic harvesting of wetland vegetation should be carried out after the growing season to prevent decomposing organic matter releasing nutrients and DOC back into the waterbody, thereby reducing ICW performance (Vymazal, 2007). Whilst some vegetation removal has been conducted at the River Mun ICW in order to achieve ~20% open water, as previously recommended for optimal pollutant removal (Almuktar *et al*., 2018), maintenance in general has been very limited. Despite minimal intervention, wetland performance does not appear to have been deleteriously impacted, as evidenced by the high nutrient removal efficiencies observed five years after construction (**Table 1**). No maintenance has been conducted to date at the River Ingol ICW as large expanses of open water were still present at the time of sampling.

4. Conclusions

1. Sewage effluent threatens the sustainable ecosystem functioning of freshwater environments globally and mitigation strategies are urgently required to improve water quality;
2. Investigating the performance of the first two ICWs installed at commercial Anglian Water WWTPs, this study demonstrates the potential of ICWs to significantly reduce eutrophication risk associated with sewage effluent discharge;

3. Mean nutrient concentrations were reduced by 34-62% for nitrate and 27-64% for phosphate, whilst nutrient loads were reduced by 56-72% for nitrate and 58-69% for phosphate;
4. The higher nutrient removal performance of the five year old ICW demonstrates that the operational efficiency of ICWs is enhanced during the early years of operation, with minimal maintenance required during this time;
5. At a cost of £31-39 per person served, ICWs provide a natural, cost-effective alternative to conventional tertiary wastewater treatment;
6. Whilst further monitoring during the winter is essential to determine if nutrient removal efficiencies are maintained, there remains strong evidence presented here to support the wider adoption of ICWs at smaller WWTPs that currently have no legal obligations to minimise effluent nutrient concentrations through conventional treatment.

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Figure Captions

Figure 1: Aerial photographs of **(a)** the River Ingol ICW in April 2018 and **(b)** the River Mun ICW in October 2014 during construction. Photographs of **(c)** the River Ingol cell 1 and **(d)** the River Mun cell 3 showing vegetation establishment. Further photographs are provided in the Supporting Information.

Figure 2: Concentrations of **(a)** nitrate, **(c)** phosphate, **(e)** dissolved organic carbon and **(f)** total carbon recorded at the River Ingol ICW between February and August 2019. Concentrations of **(b)** nitrate and **(d)** phosphate recorded at the River Mun ICW between April and September 2019.

Tables

Table 1: Summary of the water quality across the River Ingol and River Mun ICWs between February and September 2019. Values presented as means with one standard deviation in parentheses. Change refers to the percentage difference between wetland inlet and outlet concentrations.

	River Ingol					**River Mun**				
Parameter	**Upstream (mg L^{-1})**	**Inlet (mg L^{-1})**	**Outlet (mg L^{-1})**	**Change (%)**	**Downstream (mg L^{-1})**	**Upstream (mg L^{-1})**	**Inlet (mg L^{-1})**	**Outlet (mg L^{-1})**	**Change (%)**	**Downstream (mg L^{-1})**
Nitrate-N	12.15 (2.7)	28.4 (9.9)	18.8 (7.4)	**-33.8**	14.4 (8.2)	14.3 (3.4)	60.7 (26.3)	23.0 (8.7)	**-62.1**	17.9 (4.7)
Phosphate-P	0.11 (0.11)	2.04 (0.40)	1.49 (0.23)	**-27.0**	1.06 (1.30)	0.41 (0.58)	8.65 (3.42)	3.09 (1.09)	**-64.3**	1.57 (0.62)
DOC	2.0 (0.7)	6.4 (2.1)	7.0 (1.3)	**+9.4**	3.9 (2.0)	-	-	-	**-**	-
Total Carbon	44.9 (16.1)	29.5 (7.9)	39.0 (9.3)	**+32.2**	43.3 (13.5)	-	-	-	**-**	-
Dissolved Oxygen (%)	82.9 (2.7)	76.5 (13.0)	67.1 (41.7)	**-12.3**	87.4 (5.1)	-	-	-	**-**	-
Temperature (^{o}C)	10.7 (0.6)	12.0 (2.6)	13.3 (2.1)	**+10.8**	12.0 (0.0)	-	-	-	**-**	-

Table 2: Summary of the mean nitrogen, phosphorus and carbon loads at the inlet and outlet of the River Ingol and River Mun ICWs between February and September 2019. Change refers to the percentage difference between wetland inlet and outlet loads.

River Ingol	**River Mun**

Parameter	**Inlet (kg day^{-1})**	**Outlet (kg day^{-1})**	**Change (%)**	**Inlet (kg day^{-1})**	**Outlet (kg day^{-1})**	**Change (%)**
Discharge (m^3 day^{-1})	301.1	128.7	**-57.3**	160.0	187.1	**+16.9**
Nitrate-N	8.55	2.42	**-71.7**	9.71	4.30	**-55.7**
Phosphate-P	0.61	0.19	**-68.9**	1.38	0.58	**-58.0**
DOC	1.93	0.90	**-53.3**	-	-	**-**
Total Carbon	8.88	5.02	**-43.5**	-	-	**-**

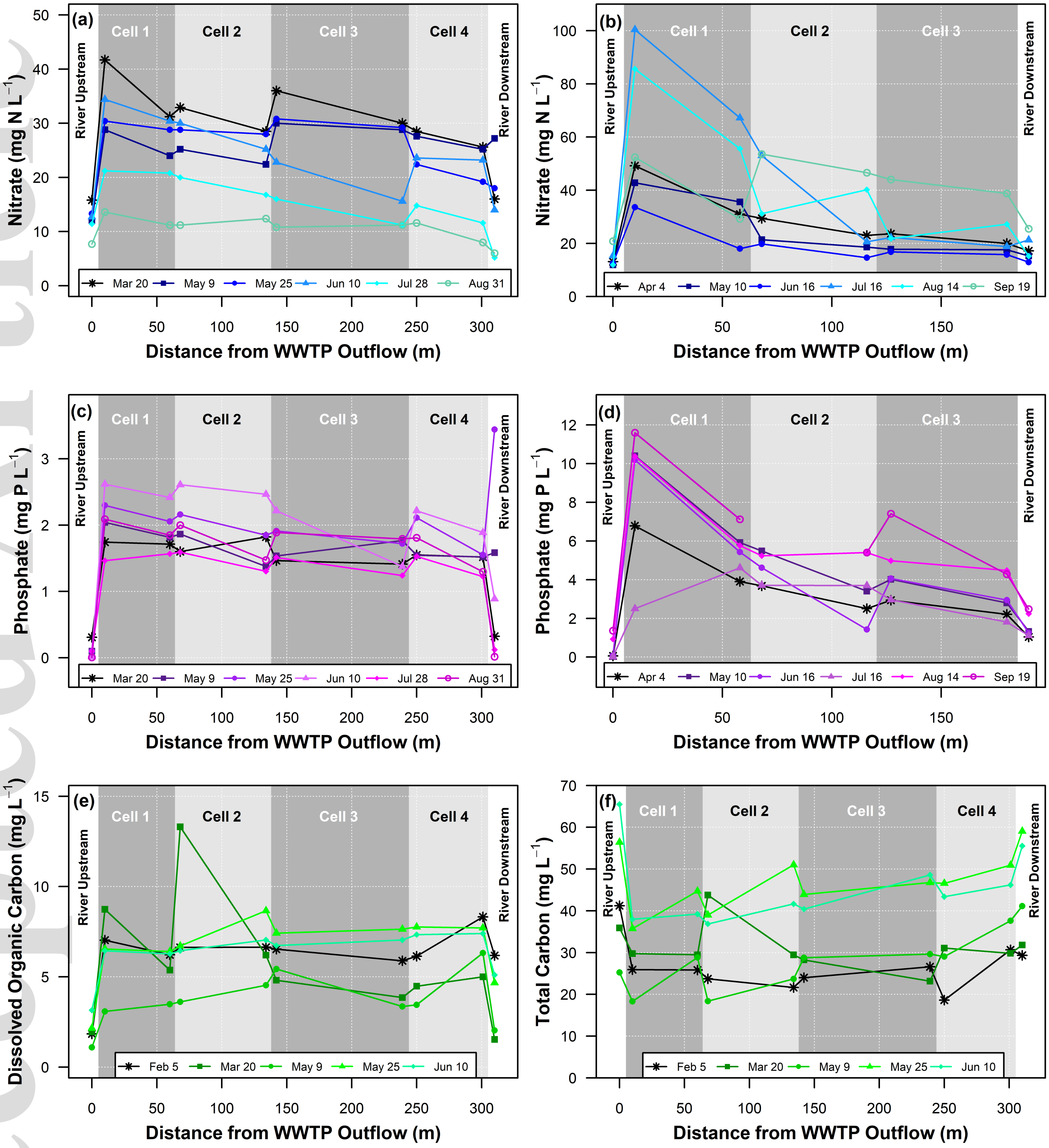
Table 3: Hydraulic properties calculated for the River Mun and River Ingol ICWs. Values are presented as means with one standard deviation in parentheses.

Parameter	**River Ingol**	**River Mun**
Inflow (m^3 day^{-1})	301.1 (18.4)	160.0 (9.0)
Outflow (m^3 day^{-1})	128.7 (21.9)	187.1 (33.3)
Area (m^2)	10,792	2,900
Depth (m)	~0.20	~0.20
Water volume (m^3)	2,158	580
HLR (m day^{-1})	0.028 (0.002)	0.055 (0.002)
HRT (days)	16.8 (3.1)	3.1 (0.6)

Table 4: Capital costs for the construction of the River Ingol and River Mun ICWs.

Parameter	**River Ingol**	**River Mun**
Planning, design & management	£15,000	£1,305
Construction	£161,000	£21,712
Wetland planting	£18,000	£7,004
Population served	6,238	772
Total cost	**£194,000**	**£30,021**
Cost per person	£31	£39


a
WWTP
River Ingol
Cell 4
Cell 3
Cell 2
Cell 1
b
Cell 3
River Mun
Cell 2
Cell 1
WWTP
c
d



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