

Appendix 2. Methodology

A2.1 *Wetland design and construction*

Ten field wetlands were constructed at the four sites, covering a range of sizes, designs and runoff sources. Details of the wetlands are in Table A2.1. The wetlands are unlined ponds, excavated using small diggers in naturally wet areas in field corners or margins or areas where runoff was known to accumulate. For wetlands designed to capture surface runoff, a soil bund was created around the wetland to channel the flow through an inlet flume for monitoring purposes. This would not be necessary where monitoring was not required. For in-ditch or in-stream wetlands a stainless steel V-notch weir was installed to hold the water in the wetland. Concrete rectangular flumes or stainless steel H-flumes were installed at the inlet and outlet of the other wetlands, to enable monitoring. For wetlands in grazed pasture, fencing was installed to prevent livestock access.

A2.2 *Annual sediment survey*

Deposited sediment and associated nutrients trapped in each field wetland were measured by an annual sediment survey. After construction, the wetlands were surveyed using a Trimble S6 Total Station (Trimble Navigation Ltd., Sunnyvale, California, USA). In August 2010, the depth of accumulated sediment at the bed of each wetland (for the six wetlands established in 2009) was measured at nine locations in each cell and sediment samples were collected for determination of bulk density. The total mass of sediment trapped was estimated as the product of the wetland cell area, the average depth of sediment in each cell and the average bulk density of sediment in that cell. Sediment traps were used in 2010/11 and 2011/12 in an attempt to improve accuracy when accretion rates were small. The traps, constructed of squares of artificial grass (0.25 m x 0.25 m) in a wire frame, were placed at nine positions on the base of each cell (for all ten wetlands). In August 2011 and August 2012, these sediment traps were lifted, where possible, and dried to determine the mass of sediment trapped. New mats were placed for the following year. Where there was too much sediment to lift the sediment traps, the wetlands were re-surveyed using a Trimble S6 Total Station, to determine the depth of sediment accumulation, and sediment samples were collected to determine bulk density and nutrient content. For the field wetlands which were surveyed, the mass of sediment trapped in each season was calculated as the total mass trapped minus the mass trapped in previous seasons. The total mass of nutrient trapped was estimated as the product of the mass of sediment and the mean nutrient content of the sediment in that cell.

A2.3 *High temporal resolution monitoring*

The water depth was measured continuously at each pond inlet and outlet, using either Campbell PDCR1830 pressure transducers (Campbell Scientific Ltd., Shepshed, UK) or Impress IML Submersible Hydrostatic Level Transmitters (Impress, Aldermaston, UK). Turbidity was measured continuously at each pond inlet and outlet (Partech IR15C, Partech Instruments, St Austell, Cornwall, UK). An ARG100 tipping bucket rain gauge (Campbell Scientific Ltd., Shepshed, UK) recorded rainfall at each site. All sensors at each wetland were connected to a Campbell Scientific CR800 or CR1000 data logger.

A2.4 *Sample collection and chemical analysis*

Upon receipt, where required, an aliquot of sample was filtered through a washed 0.45 μm Sartorius cellulose acetate membrane (Fisher Scientific, Loughborough, UK). Up to 150 ml of unfiltered sample was reserved for the measurement of total solids content by evaporation at 105 °C^[1].

Filtered samples were analysed for soluble reactive phosphorus (SRP)^[10], nitrite (NO₂-N)^[14] and ammonium (NH₄-N) as total ammonia^[12, 13] following standard colourimetric methods using an AQ2+ discrete analyser (Seal Analytical, UK). Filtered samples were also measured for nitrate (NO₃-N) by ion chromatography^[2] using a Dionex ICS2500 (Dionex UK Ltd.).

Filtered and unfiltered samples were analysed for total phosphorus (TDP & TP)^[11], following an acid-persulphate digest^[7], total nitrogen (TDN & TN)^[3] and total organic carbon (DOC and TOC)^[4]. Due to relatively low concentrations of organic carbon, TOC and DOC were analysed as non-purgeable organic carbon (NPOC)^[4] and

measured for total carbon (TC)^[4] alongside unfiltered samples. TN, TDN and TC (including DOC/TOC as NPOC) were measured using a Thermalox analyser (Analytical Sciences Ltd., Cambridge, UK). The Thermalox uses catalytic thermal oxidation followed by a chemiluminescence detection method for nitrogen and an infrared detection method for carbon. It is also adapted to accommodate samples with a high particulate load.

Sediment samples were dried at 105°C (air-dried for Olsen P), lightly ground and sieved to 1 mm. Sediments were measured for TP^[11] on the AQ2+ discrete colourimetric analyser following a wet oxidation digestion^[9], for Olsen P^[6, 8] and for TN and TC using a Vario-EL elemental (CNS) analyser (Elementar Analysensysteme, Germany) according to a UKAS accredited method (SOP3102, CEH Lancaster, UK)^[5].

References

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12. Seal Analytical 2005 *AQ2 Method No: UKAS-500-A Rev. 2 Ammonia-N in Drinking, Saline and Surface Waters, Domestic and Industrial Wastes*
13. Seal Analytical 2005 *AQ2 Method No: UKAS-501-A Rev. 2 Ammonia-N in Drinking, Saline and Surface Waters, Domestic and Industrial Wastes*
14. Seal Analytical 2005 *AQ2 Method No: UKAS-512-A Rev. 1 Nitrite-N in Drinking, Saline and Surface Waters, Domestic and Industrial Wastes*

A2.5 Residence time

The hydraulic residence time distribution in some of the wetlands was measured using dye tracing tests. A known mass of Rhodamine WT dye was added at the inlet of the wetland and the fluorescence was measured at the outlet (and between paired ponds where relevant). Cyclops-7 fluorometers (Turner Designs, Sunnyvale, CA, USA), pre-calibrated in the laboratory with known concentrations of rhodamine dye, were mounted at the wetland outlet in black pipes (to remove reflections due to sunlight). Dye concentrations were recorded at regular intervals (interval varied between 30 s and 10 minutes depending on the wetland and discharge). Discharge was measured at the start of each test and calculated for the duration of the test from the measured changes in stage. Dye recovery fraction was calculated from

$$QC(t)\Delta t / M_0$$

where Q is discharge (l s⁻¹), C(t) is time-varying concentration of rhodamine (g l⁻¹), Δt is the time interval (s) between measurements of C(t), M₀ is initial mass of active dye (g). Time to peak (T_p) concentration was observed from C(t). Median residence time (T₅₀) was calculated as the time from dye input to the time at which 50% of the total recovered dye had been recorded.

A2.6 Pollution swapping

Surface water – groundwater exchanges

The risk of pollution swapping between surface and sub-surface flows is being examined at WHSD Drain wetland at Whinton Hill, Cumbria. The objectives of this work are: i) to establish the magnitude and direction of hydraulic gradients acting between wetland water and the underlying aquifer units; and ii) to monitor shallow groundwater quality beneath and adjacent to the wetland to establish whether there is recharge of polluted water from the wetland into the underlying aquifer.

Multi-level samplers and nested piezometers were installed through the base and immediately surrounding WHSD Drain wetland. Multi-level samplers allowed groundwater to be collected from 0.5 and 1.0 m below the base of the wetland and at 50 cm intervals from 0.5 m to 4.0 m below ground surface around the perimeter of the wetland. Groundwater samples were analysed for dissolved organic carbon, soluble reactive phosphorus, nitrate and total ammonium. Nested piezometers with intakes at 2.0 and 4.0 m below ground surface around the perimeter of the wetland, and 1.0 m below the base of the wetland, enabled hydraulic head and hydraulic gradients to be determined. These same piezometers were also used for determination of water pH, EC, temperature and dissolved oxygen using peristaltic pumps and an in-line flow cell.

Greenhouse gas emissions

Fluxes of carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) (from combined diffusion and ebullitive bubbling) from WHSD Drain wetland were monitored at monthly intervals from mid-July 2012 to mid-November 2012. Gas flux at the air-water interface was observed using replicate floating Perspex non-steady state chambers (Devol et al., 1990), area 0.7 m², with enclosed headspace sampled at 0, 10, 20 and 30 minute intervals. Samples were analysed using gas chromatography. Additional physico-chemical measurements e.g. water temperature were also taken. Emissions from nearby riparian areas were measured on the same dates to compare emissions from wetlands with emissions from areas without wetlands.

Reference

Devol, A.H., Richey, J.E., Forsberg, B.R., Martinelli, L.A., 1990. Seasonal dynamics in methane emissions from the Amazon River floodplain to the troposphere. *Journal of Geophysical Research-Atmospheres*, 95(D10): 16417-16426.

A2.7 Data analysis

The intention was to use the samples alongside the turbidity measurements to build a (site-specific) turbidity-suspended sediment relationship and then to use the high frequency turbidity data with the high frequency discharge data to estimate annual sediment and nutrient loads, and the effectiveness of the wetlands in terms of a percentage reduction in load. However, due to fouling of turbidity sensors, incomplete turbidity records, uncertainties in stage-discharge ratings at high flows, backwater effects and non-unique turbidity-suspended sediment relationships, it was not possible to calculate annual loads from the turbidity data. Instead, effectiveness has been based on the difference in concentration of each determinand between inlet and outlet, either from the daily composite samples or the manual fortnightly samples.

The daily composite samples at Whinton Hill represented a continuous record of the concentration at the inlet and outlet, covering both events and baseflow. The effectiveness of the wetland was based on the reduction in the total concentration load, integrated over the whole of the monitoring period for composite samples (April 2011 – October 2012), i.e.

$$\% \text{ Reduction} = 100 * (\text{mean conc. at outlet} - \text{mean conc. at inlet}) / \text{mean conc. at inlet}$$

For the fortnightly samples, for each determinand, the reductions in concentration have been calculated for each sample as:

$$\begin{aligned} \text{Absolute reduction in concentration} &= \text{Inlet concentration} - \text{Outlet concentration} \\ \text{Percentage reduction in concentration} &= 100 * (\text{inlet conc.} - \text{outlet conc.}) / \text{inlet conc.} \end{aligned}$$

The cumulative frequency was calculated as:

$100 * \text{ranked sample number} / \text{total number of samples}$

It is recognized that this method only captures a snapshot of the conditions at the sampling time and does not allow for the time lag for a pulse of sediment (or nutrient) to pass through the wetland (residence time). However, most of the regular manual samples were collected under relatively steady state conditions (baseflow or latter stages of an event), when it was assumed that concentrations were only changing slowly. In addition, at Whinton Hill, the highest concentrations were recorded in baseflow conditions when the wastewater input was dominant.

The high temporal resolution data has been used to show the change in turbidity between the inlet and outlet for the duration of selected rainfall events.

Table A2.1 Summary of field wetlands. The wetland dimensions are measured at the base of the ponds. All wetlands have water level and turbidity measured at inlet and outlet (and middle if paired). Automatic water samplers and rain gauges are located at wetlands shown.

Site	No.	Soil type	Name (Abbreviation)	Design	Contrib. Area (ha)	Size	Approx. Area (m ²)	Dimensions (m) l x w x d	Runoff Source	Construct. Cost £	Land Use	Instruments	Monitoring period
Loddington, Leicestershire	1	Clay	Upper Ponds (LDUP Ditch)	SS	10	Large (0.1% area)	100	15 x 5 x 0.5 +	Ditch	1200	Arable	Autosamplers	Aug 2008 – Dec 2012
	2	Clay	Paradise (LDPD Drain)	DS	4	Medium (0.05% area)	20	5 x 7 x 0.5 ¹ +	Surface Runoff & Drain	1500	Arable	Rain gauge	Nov 2009 – Dec 2012
	3	Clay	Little Owl (LDLO Surface)	S	9	Small (0.025% area)	22	8 x 2 x 0.5 11 x 2 x 0.5	Surface Runoff	460	Arable		Jan 2010 – Dec 2012
Crake Trees Manor, Cumbria	4	Silty loam	Bill & Ted (CTBT Surface)	SS	20	Large (0.1% area)	200	17 x 6 x 0.5 + 17 x 6 x 0.5	Surface Runoff	1000	2009 Grass, 2010 Arable	Rain gauge Autosamplers	Oct 2009 – Dec 2012
	6	Silty loam	William (CTW Drain)	S	10	Medium (0.05% area)	50	17 x 3 x 0.5	Surface Runoff & Drain	1500	Grass		Nov 2009 – Dec 2012
	5	Silty loam	India (CTI Stream)	S	50	Small (0.025% area)	125	25 x 5 x 0.5	Stream	2700	2009 Grass, 2010 Arable	Autosamplers	Sep 2010 – Dec 2012
Whinton Hill, Cumbria	7	Sand	Shelduck (WHSD Drain)	DS	30	Large (0.1% area)	320	8 x 8 x 1.5 +	Drain	3100 ²	Grass	Rain gauge Autosamplers	Oct 2009 – Dec 2012
	8	Sand	Yellowhammer (WHYH Ditch)	S	20	Small (0.025% area)	50	17 x 3 x 0.5	Ditch	500	Arable		Aug 2010 – Dec 2012
	9	Sand	Gully Trap (WHGT Surface)	SS	1.5	Medium (0.05% area)	7.5	4 x 1 x 0.5 +	Surface Runoff	280	Arable		Nov 2010 – Dec 2012
Newton Rigg, Cumbria	10	Silt	Willow Coppice (NRWC Surface)	DS	1	Medium (0.05% area)	5	2.5 x 1 x 1.5 +	Surface Runoff	500	Arable	Rain gauge	Jan 2011 – Sep 2012

¹ This wetland is shaped to fit in a field corner. The aim is to have a wetland width-to-length ratio of greater than 1:4 to increase the effectiveness of the wetland area. In this wetland, wooden boards are being used to increase the flow path length. SS=Shallow paired ponds; DS=Deep and shallow paired ponds; S=Single shallow pond.

² Includes estimate of £1000 for fencing, as actual area fenced enclosed much wider area than wetland, at farmer's request