DOES THE PRESENCE OF A WETLAND REDUCE NUTRIENT AND SEDIMENT POLLUTION FROM AGRICULTURE TO RECEIVING FRESHWATERS IN THE UK AND IRELAND?

Authors: Elizabeth Palmer-Felgate, Mike Bowes, Mike Acreman
Research Institute: Centre for Ecology and Hydrology, Wallingford

1. BACKGROUND

Nutrient loss from agricultural land has been suggested as a major cause of elevated nutrient concentrations in surface waters in the UK (Heathwaite *et al.*, 1996). Nitrogen (N) and phosphorus (P) are of particular concern as an excess of either nutrient can lead to eutrophication of freshwater systems. Agriculture has also been identified as a significant source of suspended sediment concentrations in UK rivers (Edwards and Withers, 2008). Suspended sediment (SS) can lead to loss of ecological integrity (Schwartz *et al.*, 2011) and agriculturally derived sediment has been identified as a source of increased bed-sediment P concentrations in rivers (Palmer-Felgate *et al.*, 2009).

Wetlands are often cited as being effective at reducing nutrient and sediment loadings to receiving waters. However, the research in this area is inconsistent, and whilst some studies have shown that both natural and constructed wetlands retain nutrients and sediments, others have shown that they have little effect, or even increase nutrient and sediment loads to receiving water bodies (Fisher and Acreman, 2004; Braskerud *et al.*, 2005; Verhoeven *et al.*, 2006). Many factors may have contributed to these disparate results, including the type and size of wetland, the length of time the wetland has been established for, the hydro-landscape location, the level and type of management, and the input concentrations/loads and historic loading of the wetland.

This report was commissioned by the RSPB who requested a mini-systematic-type review on the use of wetlands to mitigate nutrient and sediment pollution from agriculture to receiving freshwater in England.

2. REVIEW QUESTION

Does the presence of a wetland reduce nutrient and sediment pollution from agriculture to receiving freshwaters?

Table 1: Definition of components of the review question.

Subject (Population)	Intervention	Comparator	Outcome
Water quality measures: • Nitrogen (N) • Phosphorus (P) • Suspended solids/sediment (SS)	Wetland: • Constructed/ treatment • Natural • Ponds • Reedbed	• Input concentration to wetland	Change in water quality measure

3. METHODS

3.1 Search strategy

ISI Web if Knowledge was used to conduct the search. No restrictions were applied regarding the year of publication. The search was refined by: Languages = (ENGLISH) AND Countries/Territories = (UK OR NORTHERN IRELAND OR IRELAND OR UK OR WALES OR ENGLAND OR SCOTLAND).

3.1.1. Search terms

Table 2: Search terms

Group 1 **Intervention elements**	**Group 2** **Population elements**
• Wetland • Pond • "Reed bed" • Reedbed	• Nutrient • P • Phos* • N • Nitr* • Amm* • Sediment • Suspended solid

Combinations of the above search terms were used (where * denotes a wildcard term) to search ISI Web if Knowledge. Search terms within each group were combined using the Boolean OR operator, and between groups using the Boolean AND operator.

3.2. Study inclusion criteria

Once the search had been conducted, inclusion criteria were crudely applied in order to identify relevant articles. Primary studies and review papers were included in the study. The articles were filtered at three levels; by title, then abstract and finally by full text. Citations were stored in Endnote.

- **Relevant subjects:** N, P and SS from agricultural in the UK and Ireland.
- **Type of intervention:** Freshwater wetlands (both constructed and natural), ponds and reedbeds. Although not included in the search terms, any papers retrieved on marshes, fens, floodplains, bogs, mires were also included.
- **Types of comparator:** Input concentration/load of N, P, or SS to wetland versus output concentration/load of N, P or SS from wetland.
- **Types of outcome:** Any change in N, P or SS concentration or load. Changes in different species of N (e.g. nitrate and ammonium) and P were included.
- **Types of study:** Studies on both full scale wetlands and pilot scale wetlands were included. Studies on laboratory mesocosms were not included.

3.3. Data extraction

A range of factors will contribute to the potential for a wetland to remove nutrients and SS, and hence it is important to capture this data where it is available within the literature to aid in the interpretation of the results. Where possible, the following data was extracted from each paper:

Location (e.g.: SW England); Annual rainfall; Soil drainage (e.g.: poor); Hydroperiod; Hydrogeomorphic lanscape setting (e.g.: river margin); Wetland type (e.g.: reedbed); Size; Hydraulic loading; Hydraulic retention time; Management (e.g.: gravity fed); Input (e.g.: piggery waste); Time established; Monitoring frequency; Monitoring time (months); Seasons monitored; Analytes; Percentage reduction.

Where percentage reduction was not directly reported, it was calculated from data supplied within the paper if possible.

4. RESULTS

4.1. Study selection

The initial search retrieved approximately 2000 articles. These were filtered using the specified inclusion criteria at title level to 256, and then at abstract level to 89. A final selection of 31 of the most relevant articles based on the abstract was made from this list, which included a mixture of reviews and primary studies (Table 3). Out of these final 32 articles, the full text of only 23 could be retrieved through the NERC library service due to time and budget constraints. After evaluation of these 23 articles at full text level, 16 met the full inclusion criteria and were included in the review. These included 15 peer reviewed journal papers (consisting of 3 review papers and 12 primary studies), and one book chapter.

4.2. Summary statistics

4.2.1. Dataset

The quality and type of data retrieved from the articles was variable. A complete dataset of all the parameters listed in Section 3.3. was not provided in any of the articles. A summary table containing the key parameters has been included within the body of this report (Table 3), and the full dataset has been included as an appendix.

Within the 16 articles meeting the full inclusion criteria, data on a minimum of 40 different wetland systems was retrieved (one dataset comprised of averaged results from a number of constructed wetland systems (Babatunde *et al.*, 2008), hence why 40 is a minimum number). In addition, one paper contained data on using varying flow rates and input concentrations at one site (Harrington and Scholz), giving data from a minimum of 43 sites or experimental set ups. This figure comprises of a minimum of 33 constructed wetland systems and 10 natural wetlands, with size and length of time established ranging from 0.788 m^2 to 40000 m^2 and 0 to 15 years respectively.

The range of analytes reported were: TP (total P), nitrate, TSS (total suspended solids), SRP (soluble reactive P), ammonium, N, P, TDN (total dissolved N), TDP (total dissolved P), SS (suspended solids), phosphate, TON (total organic N), nitrite, and MRP (molybdate reactive P). Many studies reported on several different N or P species. In total there were 35 results for P-species (including 26 for 'reactive' P species (i.e. SRP, MRP and phosphate, widely considered to be the bioavailable-P fraction)), 70 results for N-species (including 27 for nitrate and 31 for ammonium) and 7 results for suspended solids (Table 4).

Studies were conducted over varying time-periods and percentage reductions in nutrient or sediment load were often averaged across the entire sampling period. Ranges of percentage reductions are given where the results have been separated out according to season (Table 3).

Table 3: Summary of key parameters and results extracted from the final selection of articles.

Paper	Inclusion?	Site No.	Location	Wetland Type	Size (m^2)	Time Established (years)	Analyte	Reduction?	% Reduction
(Babatunde *et al.*, 2008)	Y	1	Ireland	Constructed	N/A	N/A	TP	Y	90
		2	Denmark & UK	Constructed	N/A	N/A	TP	Y	25
(Blackwell *et al.*, 1999)	Y	1	SW England	Floodplain	40000	Long term	NO_3	Y	N/A
		2		Humid grassland, heath & mire	N/A	Long term	NO_3	Y	60 – 100
(Blackwell and Pilgrim, 2011)	N, insufficient information								
(Carroll *et al.*, 2005)	Could not retrieve article								
(Cooper, 2001)	Could not retrieve article								
(Dunne *et al.*, 2005)	Y		SE Ireland	Constructed (reedbed and pond)	4755	1 – 3	TSS	Y	N/A
							SRP	Y	5 – 80
							NH_4	Y	N/A
(Fisher and Acreman, 2004)	Y	1	W England	Floodplain	N/A	N/A	NO_3	Y	N/A
		2	W England	Floodplain	N/A	N/A	NO_3	Y	N/A
		3	S England	Floodplain	N/A	N/A	N	Y	N/A
							P	Y	N/A
							TDN	N	N/A
							TDP	N	N/A
		4	W England	Riparian	N/A	N/A	NO_3	Y	N/A
		5	SW England	Floodplain	N/A	N/A	N	Y	N/A
(Forbes *et al.*, 2011)	Y		Northern Ireland	Constructed (reedbed and pond)	12510	1 – 6	TP	Y	90
							NH_4	Y	75 – 100
(Gill *et al.*, 2011)	Could not retrieve article								
(Healy and O'Flynn, 2011)	Y	1	Ireland	Constructed (free-water surface flow)	N/A	N/A	SS	Y	N/A
							NH_4	Y	N/A
							PO_4	N	N/A
		2			N/A	N/A	SS	N	N/A
							NH_4	N	N/A
		3			N/A	N/A	SS	Y	N/A
							NH_4	N	N/A
							PO_4	N	N/A
		4			N/A	N/A	SS	Y	N/A
							NH_4	Y	N/A
							PO_4	Y	N/A
		5			N/A	N/A	NH_4	Y	N/A
							PO_4	Y	N/A
		6			N/A	N/A	NH_4	Y	N/A
							PO_4	Y	N/A
		7			N/A	N/A	NH_4	Y	N/A
							PO_4	Y	N/A

Paper	Inclusion?	Site No.	Location	Wetland Type	Size (m^2)	Time Established (years)	Analyte	Reduction?	% Reduction
(Harrington *et al.*, 2011)	N, insufficient information								
(Harrington and Scholz)	Y	Exp. 1	SW Ireland	Constructed (reedbed)	0.788	0	TON	Y	90
							NH_4	Y	75
							NO_2	Y	95
							NO_3	Y	85
							MRP	Y	85
		Exp. 2					TON	Y	50
							NH_4	Y	65
							NO_2	Y	65
							NO_3	Y	45
							MRP	Y	85
		Exp. 3					TON	Y	80
							NH_4	Y	85
							NO_2	Y	80
							NO_3	Y	80
							MRP	Y	70
		Exp. 4					TON	Y	80
							NH_4	Y	95
							NO_2	Y	80
							NO_3	Y	80
							MRP	Y	85
(Harrington and McInnes, 2009)	Could not retrieve article								
(Hiley, 2003)	Could not retrieve article								
(Job *et al.*, 1991)	Could not retrieve article								
(Magmedov *et al.*, 1996)	Could not retrieve article								
(McCartney *et al.*, 2003)	N, no comparable input and output data								
(Moir *et al.*, 2005)	Y		SW Scotland	Constructed (horizontal and vertical flow reedbeds)	56	N/A	NH_4	Y	60
							NO_3	Y	20
							PO_4	Y	45
(Mustafa *et al.*, 2009)	Y		SE Ireland	Constructed (horizontal surface flow)	7600	0 – 7	NH_4	Y	100
							NO_3	Y	75
							MRP	Y	90
(O'Neill *et al.*, 2011)	N, data same as Forbes et al., 2011								
(Owens *et al.*, 2007)	N, no control								

Paper	**Inclusion?**	**Site No.**	**Location**	**Wetland Type**	**Size (m^2)**	**Time Established (years)**	**Analyte**	**Reduction?**	**% Reduction**
(Palmer-Felgate *et al.*, 2011)	Y		W England	Constructed (pond)	2100	15	NH_4	Y &N	-140 – 95
							NO_3	Y	5 – 100
							TP	Y & N	-115 – 70
							SRP	Y &N	-185 – 80
(Sabater *et al.*, 2003)	Y	1	NE England	Forested riparian buffer	N/A	N/A	NO_3	Y & N	N/A
		2		Herbaceous riparian buffer	N/A	N/A	NO_3	Y & N	N/A
		3		Herbaceious riparian buffer	N/A	N/A	NO_3	Y & N	N/A
(Scholz *et al.*, 2010)	Y	1	SE Ireland	Constructed (reedbeds and pond)	3906	1 – 7	MRP	Y	100
		2			22966	1 – 7	MRP	Y	100
		3			10288	1 – 7	MRP	Y	80
		4			10327	1 – 7	MRP	Y	95
		5			3940	1 – 7	MRP	Y	100
		6			12691	1 – 7	MRP	Y	100
		7			3940	1 – 7	MRP	Y	95
		8			7964	1 – 7	MRP	Y	95
		9			4375	1 – 7	MRP	Y	100
		10			10748	1 – 7	MRP	Y	100
		11			5610	1 – 7	MRP	Y	95
(Scholz *et al.*, 2007a)	Y	1	SE Ireland	Constructed (reedbeds and pond)	3906	1 – 7	NH_4	Y	100
							NO_3	N	-175
		2			22966	1 – 7	NH_4	Y	100
							NO_3	N	-215
		3			10288	1 – 7	NH_4	Y	100
							NO_3	N	-420
		4			10327	1 – 7	NH_4	Y	100
							NO_3	N	-255
		5			3940	1 – 7	NH_4	Y	100
							NO_3	N	-550
		6			12691	1 – 7	NH_4	Y	100
							NO_3	N	-30
		7			3940	1 – 7	NH_4	Y	100
							NO_3	Y	55
		8			7964	1 – 7	NH_4	Y	100
							NO_3	N	-455
		9			4375	1 – 7	NH_4	Y	100
							NO_3	N	-5
		10			10748	1 – 7	NH_4	Y	100
							NO_3	N/A	N/A
		11			5610	1 – 7	NH_4	Y	100
							NO_3	Y	30
(Scholz *et al.*, 2007b)	N, Same dataset as (Scholz *et al.*, 2010)								
(Stutter *et al.*, 2009)	N, soil samples								

Paper	Inclusion?	Site No.	Location	Wetland Type	Size (m^2)	Time Established (years)	Analyte	Reduction?	% Reduction
(Sun *et al.*, 2006)	Y		N England	Constructed (vertical flow reedbeds)	40	0	NH_4	Y	60
							NO_2	Y	90
							NO_3	Y	65
							PO_4	Y	45
(Surridge *et al.*, 2007)	N, sediment and pore-water P								
(Wood *et al.*, 2007)	Y	1	UK	Constructed (reedbeds)	6	0 – 2	NH_4	Y	50
							TP	Y	70
							TSS	Y	50
		2		Constructed (percolation soil plot)	49	0 – 2	NH_4	Y	40
							TP	Y	50
		3		Constructed (overland flow plot)	70	0 – 2	NH_4	Y	30
							TP	Y	40
							TSS	Y	20 – 30
(Zhao *et al.*, 2008)	N, laboratory mesocosm								

N/A = data not available

4.2.2. Summary statistics

Due to the range of P and N species reported, results have been grouped for analysis as follows:

1) All P-species
2) All N-species
3) Reactive P-species (SRP, MRP and phosphate)
4) Less-reactive P-species (TP, P, TDP)
5) Ammonium
6) Nitrate
7) Nitrite
8) Total and organic N (N, TDN, TON)
9) Suspended solids (TSS and SS)

The mean percentage reduction (Table 4) has been calculated using the percentage reductions either quoted in the articles or calculated from the data provided within the paper. Where ranges of percentage reductions were reported in Table 3, a mean was calculated using primary data from the original article.

Table 4: Summary of results for different analytes.

Analyte	Number of sites[1]	% of sites showing a reduction[2]	% of sites showing an increase[2]	Mean % reduction (n^3, sd)
All P-species	35	91	14	73 (26, 34)
All N-species	70	83	20	24 (52, 146)
Reactive P-species	26	92	12	80 (20, 30)
Less-reactive P-species	9	89	22	51 (7, 36)
Ammonium	31	90	10	81 (23, 28)
Nitrate	27	67	37	-67 (20, 205)
Nitrite	5	100	0	82 (5, 12)
Total and organic N	7	86	14	75 (4, 17)
Suspended solids	7	100	0	38 (2, 18)

[1]or experimental set ups; [2]% of sites showing and reduction and % of sites showing an increase may not equal 100%, as some sites showed both. [3]number of sites with % reduction calculated.

The majority of sites for all nutrient species and SS showed a reduction in concentration or load between the input and output to the wetland. However, with the exception of nitrite and SS, there was an increase in concentration or load between input and output to the wetland at some sites for all nutrient species. The mean reduction of P-species was substantial at 73 %, and was greater for reactive (and potentially more bio-available) P than the less-reactive P species. The results for the N-species were more diverse, with ammonium showing a substantial mean reduction of 81 %, compared to nitrate which showed a mean increase of 67 %. SS showed a moderate mean reduction of 38 %, although these results should be treated with caution as there were only two data points for SS.

Only 6 of the 16 papers reviewed clearly detailed whether the removal efficiency of wetlands varied over different seasons. No seasonal variability was reported by both Forbes et al., and Mustafa et al. in constructed wetland systems in Ireland. However Blackwell et al. observed that removal efficiencies of nitrate in a natural wetland increased from 60 % to near 100 % between May and June-Sept. Sabater et al., 2003, observed that nitrate removal efficiency varied inconsistently with season. Dunne et al. reported that SRP removal in a constructed wetland increased from only 5 % in winter to 80 % between spring and autumn. Palmer-Felgate et al. reported that a wetland pond actually switched from being a sink to a source of both SRP and ammonium between spring and summer.

5. DISCUSION

The data collated from over 42 sites/experimental set ups within this review report shows that both constructed and natural wetlands *can* be effective at reducing nutrient and SS inputs from agriculture to receiving freshwaters, and the majority of the literature surveyed supports this finding. However, the results also show that both constructed and natural wetlands are not effective in reducing nutrient inputs in all cases, and can actually increase nutrient inputs substantially. If wetlands are to be used successfully to remediate agricultural waste it is therefore important to establish why there is this difference in performance. Unfortunately, despite the large number of wetlands included in this review, the number of potential co-variants (e.g. wetland type; size; management; time established etc) is too numerous, and the data on them too sparse, to be able to perform a rigorous analysis of the data. The following discussion is therefore based on expert opinion and interpretation of the available data.

The analyte which stands out as having the most variable results is nitrate, with results ranging from a reduction of 100% to an increase of over 500%. Out of the 8 papers (encompassing 27 sites/experimental set ups) that reported nitrate concentrations, it was only the sites within Scholz et al., 2007a and Sabater et al., 2003, where wetlands resulted in an increase in nitrate concentrations. The wetlands reported in Scholz et al., 2007a were large constructed reedbed and pond systems in South East Ireland. The data from these sites had been collected over a six year period, with the wetlands being 7 years old during the final year of data collection. Only 2 out of 10 wetlands within this paper reduced nitrate concentrations. The wetlands reported in Sabater et al., 2003, were natural riparian buffer systems, and showed that wetlands both increased and decreased nitrate. The removal efficiency of nitrate varied with season at all three sites, with two out of the three sites showing that wetlands acted as a source of nitrate during spring. Out of the total of 27 sites reporting nitrate concentrations, a range of locations, wetland types, sizes and establishment time were covered, including similar systems to those reported in the Scholz and Sabater papers. Evaluation of the full dataset (Appendix 2) did not elucidate any consistent distinction between the wetlands that increased nitrate and those that decreased it. Hence, it is difficult to discern from the extracted data why the sites studied within these two papers behaved differently in terms of nitrate removal. No reasons for the increase in nitrate concentration are provided within the source papers.

5.1. Sources of bias and other considerations

There are several potential sources of bias within the results of this review, and these are considered below.

Only 10 of the 16 papers reviewed reported the length of time that the studied wetlands had been established for. Of those reported, only 3 sites had been established for more than 7 years. The processing of nutrients within wetlands will change as a wetland matures, and their continuing capacity for nutrient (especially P) and sediment retention may well be limited (Kadlec and Wallace, 2009). A newly established wetland may initially appear to perform well, but may change from a sink to a source of nutrients over time (Stratford *et al.*, 2010). Indeed, the only study that reported P concentrations on an established wetland (15 years), showed that wetlands could result in a increase in both TP and SRP concentrations (Palmer-Felgate *et al.*, 2011). The only other study that reported P concentrations and could reasonably be assumed to be an established system, was a natural floodplain system and showed a decrease in TDP, but not TP (Fisher and Acreman, 2004).

The majority of studies did not report upon any seasonality in the wetlands performance, and so it is possible that whilst the study reported a reduction in nutrient or SS outputs due to the presence of a wetland, periods in which the wetland acted as a source of nutrients of SS may have not been reported due to averaging. In addition to this, sampling frequency was typically weekly to monthly and hence storm events, which have the potential to re-suspend nutrient-rich sediment that has settled within the wetland or inflowing stream may not have been captured within the data set.

The concentrations of all the different nutrient species and SS were not measured or reported for every site. It is of course possible that the unmeasured or unreported analytes exhibited different behaviour than those that were reported upon. Further to this, there is little information within the retrieved literature on whether wetlands reduce or increase other types of agricultural pollution, such as faecal coliforms or greenhouse gas production.

Finally, publication bias must be considered when interpreting the results from this review. One problematic form of publication bias is that positive results (i.e. showing a significant finding) are more widely published than negative (i.e. supporting the null hypothesis) or inconclusive results. This leads to a misleading bias in the overall published literature, and in the case of wetlands, may have led to a disproportionate representation within the literature of studies where wetlands were effective at reducing nutrients and SS. As the 'perceived wisdom' is that wetlands reduce nutrient and sediment loadings, studies that observe an increase could well be discounted or repeated, and ultimately are less likely to be submitted for publication, and less likely to get through the peer-reviewing process.

6. CONCLUSIONS

This mini-systematic-type review has captured data from a large range of wetland systems treating P, N and SS from agriculture, in the UK and Ireland. The majority of these systems were effective at reducing both nutrient and SS pollution. However, there were exceptions, where wetlands resulted in an increase in nutrient concentrations to the receiving water body. How well a wetland functions at removing nutrient and SS pollution from agriculture is likely to be due to a combination of factors. From the data extracted within this review, seasonality and length of time that the wetland has been established have been highlighted as factors that may affect how effectively a wetland retains nutrients and sediment. However, this review has highlighted that there is still some uncertainty, particularly with regards to nitrate, in predicting whether a wetland will reduce or increase nutrient inputs to receiving freshwater from agricultural pollution.

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