www.defra.gov.uk

Do on -farm natural, restored, managed and constructed wetlands mitigate agricultural pollution in Great Britain and Ireland?

A Systematic Review

Final report WT0989

Produced: January 2015

defra
Department for Environment Food and Rural Affairs

Do on-farm natural, restored, managed and constructed wetlands mitigate agricultural pollution in Great Britain and Ireland?

Final report WT0989

Produced: January 2015

A report of research carried out by Centre for Ecology and Hydrology on behalf of the Department for Environment, Farming and Rural Affairs, with support from Natural Environmental Research Council (NERC)

Research contractor: Centre for Ecology & Hydrology

Authors: Jonathan R. Newman[1*], (jone@ceh.ac.uk), Duenas-Lopez, Manuel A.[1], Mike C. Acreman[1] Elizabeth J. Palmer-Felgate[1], Jos T. A. Verhoeven[2], Miklas Scholz[3], Edward Maltby[4]

[1]Centre for Ecology and Hydrology, CEH Wallingford, Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire, OX10 8BB, UK
[2]Ecology and Biodiversity, Universiteit Utrecht, H.R. Kruytgebouw, N310 Padualaan 8, 3584 CH Utrecht, The Netherlands
[3]Civil Engineering Research Centre, School of Computing, Science & Engineering, The University of Salford, Salford, Greater Manchester, M5 4WT, UK
[4]Emeritus Professor, Wetland Science, Water & Ecosystem Management, University of Liverpool, Liverpool, L69 3BX, UK

Publishing organisation
Department for Environment, Food and Rural Affairs
Flood Risk Management Division,
Nobel House,
17 Smith Square
London SW1P 3JR

Executive Summary

Wetlands in agricultural landscapes offer a number of benefits to the landscape function in which they are set, reducing nutrient runoff, providing additional habitat mosaics and offering various ecosystem services. They require careful planning and maintenance in order to perform their optimum design function over a prolonged period of time. They should be treated as functional units of farm infrastructure rather than fit-and-forget systems.

A high priority topic within the Department for Environment, Food and Rural Affairs (DEFRA) water quality programme is the mitigation of pollution from agriculture. This programme was set up to meet the requirements of the European Water Framework Directive (WFD) EU (2000). Nutrient loss from agricultural land has been suggested as a major cause of elevated nutrient concentrations in surface waters in the UK. Nitrogen (N) and phosphorus (P) are of particular concern as an excess of either nutrient can lead to eutrophication of freshwater systems and coastal waters. Agriculture has also been identified as a significant source of suspended sediment (SS) concentrations in UK rivers and agriculturally derived sediment has been identified as a source of increased bed-sediment P concentrations in rivers. High bed sediments loads have other negative impacts, such as clogging river gravels reducing fish spawning.

There is considerable evidence in the published and grey literature that wetlands have the ability to remove nutrients and sediment and thus reduce the load on receiving waters. Wetlands have also been reported to perform other ecosystem services, such as reducing floods, supporting biodiversity and sequestering carbon. A policy to promote the conservation, management, restoration or construction of wetlands could help to mitigate the impacts of N, P and SS from agriculture delivering requirements of WFD through Catchment Sensitive Farming following an Ecosystem Approach and Catchment Based Approach promoted by Defra. It could also meet other commitments such as implementing the Ramsar and Biodiversity Conventions to which the UK is a signatory. However, the term wetlands covers a wide range of habitat types and it is important that policy makers are provided with accurate, robust and independently reviewed information on the degree to which different types of wetland perform these services under different circumstances, so that policy can most best targeted. This systematic review assesses the available evidence on the performance of various wetland types on farms to reduce nutrient

input and suspended sediments to receiving waters. It provides a defensible evidence base on which to base policy. The studies reviewed cover different input loads and the analysis compares performance of these wetland systems in respect of % reduction efficiency. In England and Wales, Defra, working closely with the Environment Agency and Natural England, has commissioned this systematic review on how effective, and what influences the effectiveness of wetlands at mitigating N, P and SS inputs from agriculture to receiving freshwater in the United Kingdom and Ireland.

SR process

The Systematic Review (SR) process followed the Centre for Environmental Evidence (CEE) approach and protocols. The process aimed to compile and describe available evidence on the effects of on-farm wetlands in the UK and Ireland on nitrogen (N), phosphorus (P) and suspended sediment loads (SS) to downstream receiving waters. Additional data on chemical oxygen demand (COD) and biological oxygen demand (BOD) were also used where available.

From an initial 111,555 potentially relevant articles found, 40 studies were found to contain adequate quantitative information to include in the analysis. Twenty-one studies were removed from this selected reference list because they used duplicate data from the same study site. The article first mentioning the study was usually used, unless better explanation or clarity of data was found in related articles. Nineteen relevant studies were collated into a searchable database of research and the findings summarised.

Key findings

General	**<u>The overall finding of the review was that all wetland types are very effective at reducing major nutrients and suspended sediments</u>**, with the exception of nitrate in integrated constructed wetland systems (open ponds). The data synthesis showed consistently high levels of removal were found for Total Nitrogen, ammonium / ammonia, nitrate and nitrite, Total Phosphorus (TP) and Soluble Reactive Phosphorus (SRP), Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD) and Suspended Sediments (SS). All these parameters were reduced by large amounts and therefore it can be concluded that agricultural wetland systems are good

	for reduction of all of these parameters.
Phosphorus	The mean reduction in SRP was 97 %, whilst the mean reduction in TP was 78 %**,** with a tendency for older (18 months) and larger wetlands (>30 m^2) reducing SRP and TP more than younger (4 months) and smaller (<1 m^2) ones.
Nitrogen	Nitrogen species are processed differently in wetland systems. We divided processing capacity into ammonia/ammonium, nitrite and nitrate. We also collected data on total nitrogen removal where available. Ammonia and ammonium are always reduced by passage through wetlands, with a mean of 94% removal. There is no significant effect on Nitrite in constructed wetland systems. Nitrate is only reduced when passing through overland buffer strips and through constructed wetlands with vegetation (after removal of significant outlier data points) with a total mean reduction of 29 %.
Suspended sediment	Suspended solids were generally reduced substantially by passage through all wetland types, except for the small pilot scale systems with mean reduction efficiency of 83 %. A minimum wetland area of 2,500 m^2 is recommended for removal of at least 80% of the input suspended sediment loads.
Biological Oxygen Demand	The average reduction in BOD was 91%. However, only four studies achieved output values of less than the discharge limit of 9 mg l^{-1}, with one study increasing the BOD but still achieving a value lower than the upper proposed limit. One study was just in excess of the proposed limit. It is clear that although BOD is reduced by on-farm wetland systems more must be done to effluent to achieve compliance with proposed discharge limits. The most effective system for BOD reduction was a five pond integrated constructed wetland system.
Chemical Oxygen Demand	The mean % reduction in COD was 90%. All of the studies exceeded the BOD / COD proposed limit, with the minimum output value of 13 mg/L being in excess of the upper limit by about 45%. Although reduction of COD is achieved in all studies, the lower limits are not below the upper limit for receiving waters in the UK of 9 mg/L.

Implications for policy and practice

- Conservation, restoration or construction of on-farm wetlands provides a very effective solution for reducing ammonium and ammonia, total nitrogen, soluble reactive phosphate, total phosphorus, suspended sediments and both chemical oxygen demand and biological oxygen demand.

- Integrated constructed wetlands consisting of linked open pond systems are less effective than constructed wetland systems using defined flow patterns, sediment porosity and flow control.

- Removal of nitrate may require additional processing by passage through an overland buffer strip with a degree of infiltration.

- The largest systems produced the most consistent and predictable results, it is advisable to construct as large a system as possible to ensure adequate nutrient removal capacity throughout the year. A minimum area of 2,500 m^2 is required for 80% removal of suspended solids.

- Data on the overall performance of each type of wetland system showed that the most effective systems are those with simple flow regimes, and when recirculation or additional flow patterns are introduced, the effectiveness declines (Figure 2). This emphasises the importance of construction of single function simple systems for effective water treatment for nutrient reduction.

Implications for research

- While we realise it is difficult to enforce statistically relevant experimental design on field wetland situations, some efforts should be made to ensure that when reporting data, the full data are reported in order that subsequent analysis can be made of *in situ* variability and variance. We found very few studies that had any meaningful replication of experimental treatments. Good experimental design is critical in elucidating the subtle effects of nutrient transformations in such systems and producing robust experimental data.

- Removal efficiency should be expressed on a mass balance per unit area basis, not on a percent reduction basis. This gives a figure that is comparable between wetland types of different sizes and structures.

- Tidal vertical flow wetland systems should be tested at field scale as this system at pilot scale showed the greatest total removal of nutrients by a factor of 10 over other wetland systems.

Contents

List of Tables

List of Figures

1. Background

A high priority topic within the Department for Environment, Food and Rural Affairs (Defra) water quality programme is the mitigation of pollution from agriculture. This programme was set up to meet the requirements of the European Water Framework Directive (WFD) EU (2000). 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 and coastal waters. Agriculture has also been identified as a significant source of suspended sediment concentrations in UK rivers (Edwards and Withers, 2008) and agriculturally derived sediment has been identified as a source of increased bed-sediment P concentrations in rivers. High bed sediments loads have other negative impacts, such as clogging river gravels reducing fish spawning.

Defra is seeking to address these issues through its agri-environment schemes and Catchment Sensitive Farming (CSF) that delivers practical solutions and targeted support to enable farmers and land managers to take action to reduce diffuse water pollution from agriculture to protect water bodies and the environment. They are supported by Catchment Partnerships ensuring engagement with stakeholders at the catchment and local level.

There is a large body of literature (books, journal articles and reports) stating that wetlands can perform many valuable functions and provide many benefits to people. In particular, wetlands have been called the 'kidneys of the landscape' (Mitsch and Gosselink, 2000) as they cleanse polluted water. Other functions and benefits include:

1. flood control, by reducing immediate runoff or acting as balancing ponds
2. groundwater recharge
3. sediment trapping
4. supporting biodiversity
5. storing carbon
6. maintaining cultural identity, tourism and recreation

Employing wetlands to remove agricultural pollutants would fulfil the above aspiration of Defra, meet other commitments such as implementing the Ramsar and Biodiversity Conventions, to which the UK is a signatory, and provide additional benefits as listed, The systematic review of wetland performance reported here concentrates on nutrient processing in inline wetland systems on farms to reduce nutrient input to receiving waters.

Wetland services

Wetland services result from a process or series of processes that take place within a wetland. These processes include the storage of water, transformation and assimilation of nutrients, sequestration of carbon, and they have value for surrounding ecosystems, and for people. The National Ecosystem Assessment (2011) grouped services into 4 classes:

1. Provisioning services: water resources, food, building material
2. Regulatory services: water purification, flood reduction, carbon storage, climate amelioration
3. Cultural services: recreation, tourism, cultural and social identify, spiritual well-being, education
4. Supporting services: soil formation, biodiversity

A policy to promote the conservation, management, restoration or construction of wetlands could help to mitigate the impacts of N, P and SS from agriculture delivering requirements of WFD. As added value these wetlands are likely to perform other services such as enhancing biodiversity and sequestering carbon. The exploitation of wetland services would be consistent with the Ecosystem Approach and Catchment Based Approach and would help deliver other commitments such as implementing the Ramsar and Biodiversity Conventions to which the UK is a signatory. However, the term wetlands covers a wide range of habitat types and it is important that policy makers are provided with accurate, robust and independently reviewed information on the degree to which different types of wetland perform these services under different circumstances, so that policy can be best targeted. Not all wetlands perform all services nor do they perform all services equally well. Previous reviews of wetland services (Bullock and Acreman, 2003; Fisher and Acreman, 2004) found that the location and size of a wetland may determine what functions it will perform. For example, the geographical location may determine its habitat functions, and the location of a wetland within a watershed may determine its hydrologic or water-quality functions. Many factors determine how well a wetland will perform these services: climatic conditions, quantity and quality of water entering the wetland, adjacent land use or the surrounding ecosystem and management of the wetland itself. Of particular importance is the hydrological functioning of the wetland including the quantity of water that enters, is stored in, or leaves a wetland and such factors as the reduction of flow velocity, the role of wetlands as ground-water recharge or discharge areas, and the influence of wetlands on atmospheric processes. Water-quality functions include the trapping of sediment, pollution control, and the biochemical processes that take place as water enters, is stored in, or leaves a wetland.

The placement of wetlands in agricultural landscapes may be related to existing wet or boggy areas left in their natural state or with enhanced management, or they may be constructed in strategic positions to intercept known sources of run-off. The aim of a constructed wetland should be to reduce the loading of any particular pollutant passing through, and in the case of this SR to reduce nutrient and/or suspended sediment inputs to surface waters.

There are also undoubtedly significant economic benefits from reducing nutrient input to river systems, as demonstrated by (Ockenden *et al.*, 2012c) who suggested net benefits of between €117 to €3100 Ha^{-1} for reduction of nitrogen loading in the Elbe river system.

Defra Need

Wetlands are cited as being effective at reducing nutrient and sediment loadings to receiving waters. However, the research in this area is inconsistent, and whilst most 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 length of time the wetland has been established for, seasonality, the hydrogeomorphic landscape setting, type, size, level and type of management, and the input concentrations/loads and historic loading of the wetland, (e.g. Maltby, 2009). For example, a constructed wetland system in South-west England switched from a net annual sink to a source of phosphorus over a 10 year period, and from being a sink to a source of soluble reactive phosphorus (SRP) and ammonium between spring and summer (Stratford *et al.*, 2010, Mackenzie and McIlwraith, 2013). Phosphorus removal has been shown to correlate positively with an increase in wetland area, and a minimum wetland to farmyard area ratio of 1.3 has been proposed for effective removal of molybdate reactive phosphorus (MRP) (Scholz *et al.*, 2010). When deciding on wetland size, other factors such as ecosystem services (Acreman *et al.*, 2011, Harrington *et al.*, 2011) should also be considered.

Agriculture is generally considered to be responsible for a large percentage of diffuse pollution inputs to surface waters. Two of the principal diffuse pollutants of water quality are sediment and phosphorus. Losses of phosphorus from agriculture are often high, as agricultural systems traditionally have high inputs of phosphorus applied in fertilisers and manures to enhance productivity. Phosphorus is an important diffuse agricultural pollutant, contributing to the risk of eutrophication of fresh waters. Phosphorus in surface runoff is largely transported in particulate form, bound to sediment particles, but also in solution (Haygarth *et al.* 2000). It is estimated that 82,000 t/year of phosphorus enters UK surface waters, of which around 25% comes from agriculture in England and 45% in Wales (Environment Agency, 2012).

To inform policy on whether to promote the conservation, management, restoration or construction of wetlands to mitigate the impacts of N, P and SS from agriculture, it is important that policy-makers are provided with accurate, robust and independently reviewed information. Whilst there is a great deal of published material on this subject, prior to this report a rigorous, independent systematic review had not been conducted. The current UK guidelines do not stipulate a target percent reduction of nutrient or SS concentrations required from wetlands and simply state that any reduction is sufficient. This obviously depends on when measurements are made, or how annual figures are weighted and prioritised. Hence Defra has commissioned a systematic review on how effective and what influences the effectiveness of wetlands at mitigating N, P and SS inputs from agriculture to receiving freshwater in England. It is also important to consider the potential multiple benefits or trade-off with other ecosystem services provided by wetlands, such as carbon sequestration and habitat provision (Acreman *et al.*, 2011, Harrington *et al.*, 2011) during the development of any policy, but these aspects are not the subjects of this SR.

2. The Systematic Review

Systematic review is a tool used to summarise, appraise and communicate the results and implications of a large quantity of research and information. It is particularly valuable as it can be used to synthesise results of many separate studies examining the same question, which may have conflicting findings. Meta-analysis is a statistical technique that may be used to integrate and summarise the results from individual studies within the systematic review, to generate a single summary estimate for the effect of an intervention on a subject.

The purpose of a systematic review is to provide the best available evidence on the likely outcomes of various actions and, if the evidence is unavailable, to highlight areas where further original research is required. It is, therefore, a tool to support decision-making by providing independent, unbiased and objective assessment of evidence; it is not designed to make decisions on behalf of the user-community.

There is an increasingly recognised need for evidence-based policies informed through objective review of evidence using systematic processes of evaluation. This has been accompanied by a growing acknowledgment within government and scientific organisations that despite significant research investment there is often insufficient consideration of what the available evidence presents when considered collectively and objectively. Literature reviews are the normal response to providing an informed and critical overview on a subject. However, traditional literature reviews can be liable to bias in representing a subjective view based upon selected sources and lack transparency of the review process. This has led to a growth of interest in the use of more systematic approaches to assessing evidence through Systematic Reviews.

The Centre for Evidence-Based Conservation (CEBC) at Bangor University has produced guidance on full Systematic Reviews (CEE, 2013) and provides facilities for peer review of various stages. The CEE process was followed in this review but is not describe fully in this report as it is extensive and the guidance is freely available. A key first step is to hold a meeting of experts who can formulate scientifically appropriate questions that can be answered by the literature and can address the overall policy question. The expert panel used for this review were:

Prof Jos Verhoeven: Utrecht University Specialist in diversity and functioning of wetland ecosystems.
Prof Ed Maltby: Liverpool University. Specialist in wetlands and the Ecosystem Approach
Prof Miklas Scholz: University of Salford, Specialist in constructed wetlands

Prof Mike Acreman: Centre for Ecology & Hydrology Specialist in hydrological functions of wetlands
Dr Mark Everard: Environment Agency and University of West of England. Specialist in ecosystem services and sustainable catchment management

The review was undertaken by Dr Liz Palmer-Felgate, Dr Jonathan Newman and Dr Manuel Duenas-Lopez. Project managers from Defra were Mr Stuart Kirk, Dr Debbie Coughlin and Dr Alexandra Collins.

The general objective of the review to assesses the available evidence on the performance of various wetland types on farms to reduce nutrient input and suspended sediments to receiving waters. The panel discussed the scope and extent of the issue and recommended a focus on assessing studies from the British Isles and on reduction of nitrogen and phosphorus as key nutrients plus suspended sediments. This focus was to keep the number of sources to be reviewed to a manageable size. The panel then formulated primary and secondary questions for the review to answer.

3. Objective of the Review

Primary Question

Using the policy needs guidance of Defra, the expert panel set the following primary question for the review.

How effective are restored and constructed wetlands such as reed beds and ponds, at retaining nitrogen, phosphorus and suspended sediment from agricultural pollution in Great Britain and Ireland?

In the next stage of analysis, the primary question was analysed to produce key components that would define the search strategy (Table 1). In addition to the focus of the review on nutrients and sediments, the need to assess added benefits for biodiversity, greenhouse gas reduction and flood management were recognised and this is included as a secondary outcome.

Table 1: Definition of components of the primary systematic review question.

Subject (Population)	**Intervention**	**Comparator**	**Outcome**
Water bodies receiving: Nitrogen (N) Phosphorus (P) Suspended solids/sediment (SS)	Wetland: Constructed / treatment Reedbeds Ponds Restored wetlands	Input vs output concentration to wetland No wetland vs with wetland present Before wetland vs with wetland present	1°: Percentage change in water quality measure 2°: Change in other parameters, including biodiversity measures and greenhouse gas emission; are there any synergies/trade-offs, e.g. flood risk?

Secondary question

What are the characteristics of the whole system that determine how effective an established reedbed/pond or restored or constructed wetland will be at reducing N, P & SS inputs from agricultural pollution in Great Britain and Ireland? This will be extracted at the synthesis stage. Table 2 describes the key search terms designed to retrieve publications relating to the primary questions and strategies set out in Table 1. (*used as wildcard symbol to indicate multiple endings).

Table 2: Search terms

Group 1 **Intervention elements**	**Group 2** **Population elements**	**Group 3** **Location elements**
• Wetland* • Pond* • Marsh* • Fen* • Floodplain • Bog* • Mire* • "Reed bed*" • Reedbed* • "Riparian zone" • Oxbow • "Riparian forest" • Scrape* • Berm*	• Nutrient* • P • Phos* • N • Nitr* • Amm* • Sediment • Suspended solid • Agricultural runoff • Farm*	• UK • United Kingdom • Brit* • Engl* • Scot* • Wales • Welsh • Ireland • Irish

4. Methods

Search strategy

The aim of the search strategy was to produce a set of references containing reports on agricultural wetland systems subject to direct or diffuse nutrient loading. It should capture an unbiased and comprehensive sample of the literature relevant to the question, whether published or unpublished. Different sources of information were searched in order to maximise the coverage of the search.

Electronic databases

The following electronic databases were searched:

1. ISI Web of Knowledge
2. Copac
3. Agricola
4. JSTOR
5. EThOS
6. DART – Europe E-theses Portal

No restrictions were applied regarding the year of publication. The search was refined by language (English) and country (UK, England, Scotland, Wales and Ireland) where this facility was available.

Conservation and statutory websites

The official websites for the following organisations were searched:

1. Department of Environment, Food and Rural Affairs (Defra)
2. Wildfowl and Wetlands Trust (WWT)
3. Ramsar
4. Environment Agency (EA)
5. English Nature
6. Countryside Council for Wales
7. Department of Agriculture and Rural Development (DARD)
8. Scottish Natural Heritage (SNH)

9. Water Framework Directive
10. Scottish Environment Protection Agency (SEPA)
11. Department of Agriculture, Food and the Marine
12. The Irish Agriculture and Food Development Agency (TEAGASC)
13. Constructed Wetland Association
14. Wetlands International

Websites

The following search engines were searched:

1. www.google.com
2. www.scholar.google.co.uk
3. www.dogpile.com

The first 50 returns from each search were examined for relevance, with any links present being followed only once from the original hit.

Questionnaire to authors, recognised experts and practitioners

Authors, recognised experts and practitioners (to include the Society of Wetland Scientists) were contacted for further recommendations and for the provision of any unpublished material or missing data that may be relevant. Unpublished data were not made available by authors from whom they were requested and articles with partial data were therefore excluded from the data analysis.

Search terms

Search terms were tested for the inclusion of known test papers containing data on agricultural wetland function (see Table 2). Two papers were selected as tests for the integrity of the search terms (Ockenden *et al.*, 2012b, Harrington *et al.*, 2012). If these papers did not appear in the list of papers retrieved by using the search terms at title and abstract level the terms were modified until both these papers appeared in the final list.

We ran a second search using all the online databases and websites in January 2014, in an attempt to collect the known papers using the different front end user interface of WoK. In undertaking this, we found that all relevant references were included in WoK with only one not being detected by WoK that was in Agricola, and on examination at full text level the Agricola reference was excluded based on the selection criteria.

Study Inclusion Criteria

Study inclusion criteria were applied to identify relevant articles. The articles were filtered at three levels; by title, then abstract (or introduction section if abstract was not available), and finally by full text.

- **Relevant subjects:** Water bodies receiving N, P and SS from agricultural waste in GB and Ireland. All forms of N and P, and all types of agricultural waste were included.

- **Type of intervention:** Freshwater constructed or restored wetlands, to include ponds, marshes, fens, floodplains, bogs, mires and reed beds.

- **Types of comparator:** Studies with the following comparators will be included:
  - Input concentration/load of N, P, or SS to wetland versus output concentration/load of N, P or SS from wetland;

  - Concentration/load of N, P, or SS from agricultural pollution entering receiving water with no wetland versus with a wetland (provided input and geography are comparable);

  - Concentration/load of N, P, or SS entering receiving water before installation of a wetland versus after installation of a wetland (provided input and geography are comparable).

  - Upstream concentration of N, P or SS in receiving water versus downstream concentration of N, P or SS in receiving water were not included due to the possibility of in-stream processing/additional inputs.

- **Types of outcome:** The primary outcome is a quantitative change in N, P or SS concentration or load. Quantitative changes in different species of N (e.g. nitrate and ammonium) and P were included. The secondary outcome is a change in other water quality parameters, biodiversity, or greenhouse gas production. The secondary outcome will not be used as an inclusion criterion.

Types of study: Studies on both full scale wetlands and pilot scale wetlands were included. Studies on laboratory mesocosms and modelling studies were not included.

ISI Web of Knowledge (WoK)

The iterative selection was a process run using WoK in January 2013, December 2013, and January 2014. Articles were selected on the basis of relevance to the primary and secondary questions of the SR and the selection criteria listed above. Papers were selected for assessment at full text on the basis of the abstract or summary.

The search terms used were

> Title=((wetland OR pond OR marsh OR fen OR floodplain OR bog OR mire OR "reed bed" OR reedbed OR "riparian zone" OR oxbow OR "riparian forest" OR scrapes OR berms) AND (N OR nitr* OR amm* OR sediment OR nutrient OR P OR phos* OR "suspended solid" OR "agricultural runoff" OR farm)) AND Topic=(UK OR Britain OR England OR Ireland OR Wales OR British OR Irish OR English AND (SCOTLAND OR NORTH IRELAND OR IRELAND OR ENGLAND OR UK OR WALES)) AND Language=(English)
> Timespan=All years. Databases=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH.

407 papers identified by title and exported with abstracts into Endnote library, my groups: Wetlands SR.WOK

Agricola

The iterative selection was process run using Agricola in January 2013 and December 2013. Articles were selected on the basis of perceived relevance to the primary and secondary questions of the SR. Papers were selected for assessment at full text on the basis of the abstract or summary. It is important to note that Agricola does not enable a wild card facility (i.e. no *) was available and the search was limited to a maximum of 383 characters.

> (wetland OR pond OR marsh OR fen OR floodplain OR bog OR mire OR reedbed OR "reed bed "OR" riparian zone "OR oxbow OR "riparian forest" OR scrapes OR berms) AND (nutrient OR phosphorus OR phosphate OR nitrate OR nitrogen OR ammonium OR ammonia OR sediment OR "suspended solid "OR" agricultural runoff "OR farm) AND ("United Kingdom" OR Scotland OR Scottish OR Welsh).
> Refined by: Language = English.
> Article citation database searched.

46 papers identified were identified by title, 20 of which had already been retrieved by WOK search (my groups: Wetlands SR.AgricolaWOK), the remaining 26 imported with abstracts into Endnote library from WOS (my groups: Wetlands SR.Agricola).

JSTOR

The iterative selection was process run using JStor in January 2013 and December 2013. Articles were selected on the basis of perceived relevance to the primary and secondary questions of the SR. Papers were selected for assessment at full text on the basis of the abstract or summary. It is important to note that Agricola does not enable a wild card facility (i.e. no *) was available and the search was limited to a maximum of 383 characters.

Special notes: In order to pluralise the search term it is necessary to add '&' at end of word to pluralise. Only approximately 10% of JSTOR articles have abstracts and this could affect the number of results returned.

The search terms used were:

> ((ab:(wetland& OR pond& OR marsh& OR fen& OR floodplain& OR bog& OR mire& OR "reed bed&" OR reedbed& OR "riparian zone&" OR oxbow& OR "riparian forest&" OR scrapes OR berms) AND ab:(N OR nitr* OR amm* OR sediment& OR nutrient& OR P OR phos* OR "suspended solid&" OR "agricultural runoff" OR farm&)) AND (UK OR "United Kingdom" OR Britain OR British OR ENgland OR Scotland OR English OR Scottish OR Wales OR Welsh OR Ireland OR Irish)). Refined by: Language = English. Abstract only search for group 1 and 2 elements, full text for group 3 terms.

73 papers were identified by title, 2 of which already retrieved by WOK search (my groups: Wetlands SR.JSTORWOK), remaining 71 imported with abstracts into Endnote library from WOK (my groups: Wetlands SR.JSTOR). None of these were selected by full text.

Authors, recognised experts and practitioners:

Contact produced data on Irish wetland systems that were already included in published papers harvested by WoK.

Dogpile

Search terms : agricultural, wetland, nutrient, farm, united kingdom, sediment
No additional papers, reports, or other literature were retrieved using Dogpile to those already harvested by WoK

Repeat Search Strategy

The search was repeated in January and March 2014 to collect references published in the intervening time period.

ISI Web of Knowledge March 2014 – Final search

Only ISI web of Knowledge (WoK) was used as previous searches had shown that all published papers captured by other search engines all appeared in WoK.

The search produced the following results after removal of duplicates and obviously irrelevant articles. Topic searches were used instead of title (TS) in this search as we found that this included a wider base of published articles and did not preselect on the basis of title alone.

6,668
TS=(wetland* or pond* or marsh* or fen* or floodplain* or bog* or reedbed* or "reed bed*" or "riparian zone" or oxbow or "riparian forest" or scrape* or berm*) and TS=(N or nitr* or amm* or sediment* or nutrient* or P or phosph* or "suspended solid*" or "agricultural runoff" or farm* or agricultu*) and COUNTRY=(SCOTLAND or "British Isles" or "NORTH IRELAND" or "Northern Ireland" or "United Kingdom" or "Great Britain" or "Britain" or IRELAND OR ENGLAND OR UK OR U.K. OR WALES)) *AND* LANGUAGE**:** *(English) Indexes=SCI-EXPANDED, CPCI-S Timespan=1970-2014*

6,575

(TS=(wetland* or pond* or marsh* or fen* or floodplain* or bog* or reedbed* or "reed bed*" or "riparian zone" or oxbow or "riparian forest" or scrape* or berm*) and TS=(N or nitr* or amm* or sediment* or nutrient* or P or phosph* or "suspended solid*" or "agricultural runoff" or farm* or agricultu*) and COUNTRY=(SCOTLAND or "British Isles" or "NORTH IRELAND" or "Northern Ireland" or "United Kingdom" or "Great Britain" or "Britain" or IRELAND OR ENGLAND OR UK OR U.K. OR WALES)) *AND* **LANGUAGE:** *(English)* Refined by: [excluding] DOCUMENT TYPES=(NOTE OR BOOK REVIEW OR ITEM ABOUT AN INDIVIDUAL OR MEETING ABSTRACT OR CORRECTION OR DISCUSSION OR LETTER OR CORRECTION ADDITION OR REPRINT OR EDITORIAL MATERIAL) *Indexes=SCI-EXPANDED, CPCI-S Timespan=1970-2014*

This starting set was used as the basis for further selection resulting in a total of 158 that were read at full text level. 115 of these were excluded due to laboratory scale and model components, being not relevant, having no data and being unobtainable. Of these 40 were selected for data extraction; 21 contained data duplicated from the same experiment as papers selected in the original 40; two contained no data on hydraulic loads, leaving 17 for data extraction and synthesis.

Theses

Online databases relating to published Theses were searched again in January and March 2014 using two electronic databases.

Electronic databases:

- *DART*
- *Ethos*

Search string

(wetland OR pond OR marsh OR fen OR floodplain OR bog OR mire OR "reed bed" OR reedbed OR "riparian zone" OR oxbow OR "riparian forest" OR scrapes OR berms) AND (N OR nitr* OR amm* OR sediment OR nutrient OR P OR phos* OR "suspended solid" OR "agricultural runoff" OR farm)

Total hits
DART 135
Ethos 20

Selected by title and abstract 18
Relevant 1
Duplicate data + paper 3
No able to obtain 2

Reports

Reports from all organisations identified were searched and selected for data containing publications

Total Selected by title and abstract 7
Relevant 1
Duplicate data + paper 1
No able to obtain 2
Not relevant 5

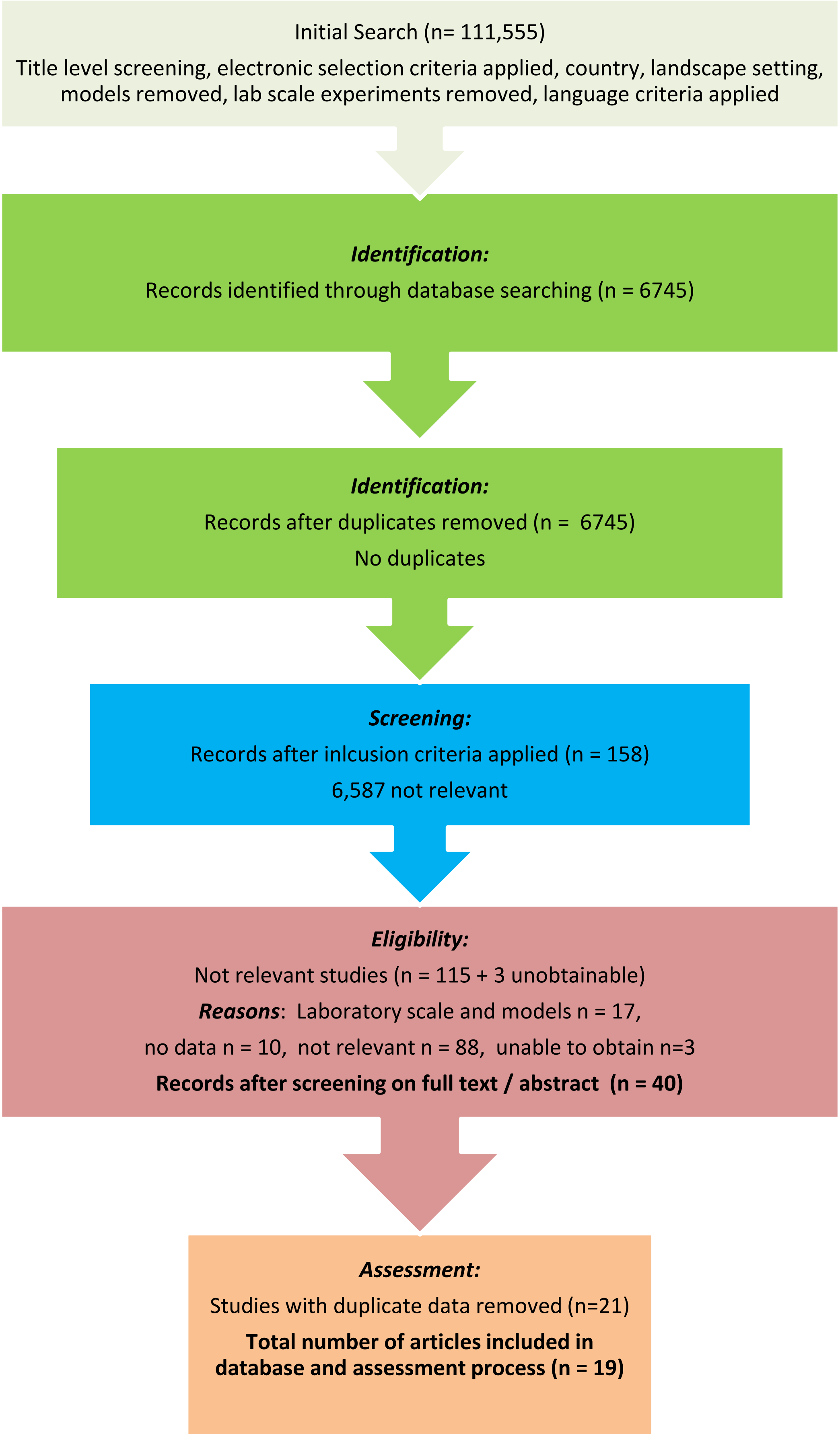
The total number of articles used in the review process was nineteen. Seventeen refereed papers in scientific Journals, one research report and one thesis.

Evidence Refinement

The first stage of evidence refinement involved the application of the inclusion criteria to each article using the title and abstract. Articles meeting at least one of the inclusion criteria were selected for full text review. Where there was ambiguity or uncertainty as to the relevance or value of the data the article was selected for full text review.

The refined list of references was used for the SR. The number of references used and the number excluded were recorded. The list was assessed by two reviewers independently, Dr Manuel Duenas and Dr Jonathan Newman (CEH). Both the selected articles and those articles not included by either author were confirmed by assessment by a third reviewer, Charlie Stratford (CEH). The process is described in Figure 1.

Figure 1: Assessment and selection criteria


Initial Search (n= 111,555)
Title level screening, electronic selection criteria applied, country, landscape setting, models removed, lab scale experiments removed, language criteria applied
Identification:
Records identified through database searching (n = 6745)
Identification:
Records after duplicates removed (n = 6745)
No duplicates
Screening:
Records after inlcusion criteria applied (n = 158)
6,587 not relevant
Eligibility:
Not relevant studies (n = 115 + 3 unobtainable)
Reasons: Laboratory scale and models n = 17,
no data n = 10, not relevant n = 88, unable to obtain n=3
Records after screening on full text / abstract (n = 40)
Assessment:
Studies with duplicate data removed (n=21)
Total number of articles included in database and assessment process (n = 19)

SR Quality Assessment Screening

The quality assessment of papers was part of the review of articles selected for assessment at full text. Papers were rejected if the following criteria were met:

- they only contained data from laboratory scale studies;
- they were the results of modelling;
- they reported data on microbial reductions (which were strongly correlated with reduction of suspended sediment but this value was not reported, or was not measured as input and output concentrations); and
- they reported data that had been reported in other previous publications.

Table 3: Study quality assessment criteria scoring system

Category	Score	Hierarchy of Evidence
Randomised	1	Randomised
	0	Not randomised
Control	3	Controlled
	2	Control
	1	Comparison
	0	None
Replicates	2	Replicated in time and space
	1	Replicated either in time or space
	0	No replicates
Assessment Time	2	More than five years
	1	More than one year
	0	Less than one year
Study Type	3	Field scale with unaltered inputs
	2	Field scale with managed inputs
	1	Small scale
	0	Pilot scale
Inclusion Criteria	2	All criteria matched

1	≥ 3 criteria matched
0	≥ 1 criteria matched (nutrient input output values must be quoted)

Articles were assessed for the robustness of the study design in order to provide an indication of the quality of the data produced. The inclusion criteria were also used as an indicator of the appropriateness of the studies. No studies were excluded on the basis of the quality assessment. The assessment criteria are set out in Table 3.

Data Synthesis

The full text of each of the selected articles in the list was read and data for each of the nutrient criteria were collated and entered into an Excel spreadsheet database. In addition, data for hydraulic retention time were used to calculate a mass load value. The mass load can be used to more easily and directly compare studies with widely varying input and output concentrations, and provide a fair measure of wetland effectiveness for all nutrient parameters. These data were log transformed. This also allows for comparison across scales of wetland sizes, as it directly measures the removal efficiency of each wetland, regardless of surface area or input load.

Statistically significant outlying data points were excluded from the analysis.

The following data were recorded on a specially designed data extraction form in the Excel database to include the following information where available:

General location;
Hydro geomorphic landscape setting;
Type of wetland;
sub type of wetland (flow);
Type of vegetation;
Area of wetland;
Type of management;
Hydro period;
Hydraulic loading;
Hydraulic retention time;
Size of the area generating the pollution;
Ratio of area generating waste to area of wetland;
Type of waste;
Agricultural intensity of upstream area;
length of time wetland has been established;

frequency of monitoring; length of time monitored;
seasons monitored;
Analytes measured;
Control type;
Input and output (without/with; before/after) concentrations/loads/populations of any analytes measured;
Reduction/increase/no change;
% reduction.

The data synthesis process resulted in a spreadsheet of 19 articles, with 186 rows of data. Data from each article were extracted for each wetland and each analyte was recorded on a separate row. This allowed for differentiation between measurements made at different time intervals during the study and for different flow rates and hydraulic retention times. This also allowed for analysis of analyte processing in different wetland types and sub-types.

The following data were extracted from the selected papers

Study type

Full scale	FS
Pilot scale	PS

Wetland Type

Constructed wetland (CW)
Integrated constructed wetland (ICW)
Wetland: Restoration peatland
Floodplain-buffer zone

Wetland sub-type

(HF) Horizontal flow
(HSSF) Horizontal sub surface flow
HF-recirculation
(VF) Vertical flow
VF-recirculation
VF-tidal flow
VF-tidal flow with recirculation
Sequencing batch reactor (SBR)
Hybrids systems-(VF + HF + lagoon)
high rate algal ponds (HRAP)

Horizontal flow biofilm system (HFBR)
Woodchip filters

Vegetation type
No vegetation
Free floating plant
Floating leaved plant
Emergent plant
Submerged plant
Reed beds
Helophytes

Types of treatment
Agriculture runoff
Field run-off (conservation area)
diluted farmyard run-off
Pre-treated dairy
diluted treated piggery slurry
Farmyard runoff
farmyard and field runoff
Pre-treated dairy
Pre-treated dairy and farm run-off
aquaculture wastewaters from biofilter

Comparator type
Inflow vs. Outflow.

Analytes

Table 4 lists the analytes available for analysis. Not all analytes were recorded in all articles. The number of relevant sites from which analyte data were recorded was used to list as a separate entry in the spreadsheet table. The analytes in Bold were used for statistical meta analysis of agricultural wetland function.

Table 4: Analytes recorded from selected articles

Total organic nitrogen	TON

Dissolved organic nitrogen	DON
T inorganic dissolved nitrogen	TIDN
Total nitrogen	TN
Reactive P	The total orthophosphate
Soluble reactive phosphorus	SRP (= orthophosphate)
Total phosphorus	TP
Nitrate	NO_3
Nitrite	NO_2
Ammonium	NH_4
Ammonia	NH_3
Biological oxygen demand	BOD
Chemical oxygen demand	COD
Suspended solids	SS
Total solids	TS

Selected references

The final list of used in the data extraction and synthesis process to provide the basis for the SR contained the following 19 publications

BIDDLESTONE, A. J., GRAY, K. R. & JOB, G. D. 1991. TREATMENT OF DAIRY FARM WASTEWATERS IN ENGINEERED REED BED SYSTEMS. *Process Biochemistry,* 26**,** 265-268.

BIDDLESTONE, A. J., GRAY, K. R. & THURAIRAJAN, K. 1991. A BOTANICAL APPROACH TO THE TREATMENT OF WASTEWATERS. *Journal of Biotechnology,* 17**,** 209-220.

BLACKWELL, M. S. A., HOGAN, D. V. & MALTBY, E. 1999. The use of conventionally and alternatively located buffer zones for the removal of nitrate from diffuse agricultural run-off. *Water Science and Technology,* 39**,** 157-164.

DUNNE, E. J., CULLETON, N., O'DONOVAN, G., HARRINGTON, R. & OLSEN, A. E. 2005. An integrated constructed wetland to treat contaminants and nutrients from dairy farmyard dirty water. *Ecological Engineering,* 24**,** 221-234.

FORBES, E. G. A., FOY, R. H., MULHOLLAND, M. V. & BRETTELL, J. L. 2011. Performance of a constructed wetland for treating farm-yard dirty water. *Water Science and Technology,* 64**,** 22-28.

FORBES, E. G. A., FOY, R. H., MULHOLLAND, M. V. & WOODS, V. B. 2009. The performance of a five pond Constructed Wetland for the bioremediation of farm effluent. Preliminary findings on the performance, efficiency and sustainability of the CAFRE constructed wetland system. *Occasional Publication No. 9.* Agri-food and Biosciences Institute.

GOURIVEAU, F. 2009. *Constructed farm wetlands designed for remediation of farmyard runoff: an evaluation of their water treatment efficiency, ecological value costs and benefits.* The University of, Edinburgh.

HARRINGTON, C., SCHOLZ, M., CULLETON, N. & LAWLOR, P. G. 2012. The use of integrated constructed wetlands (ICW) for the treatment of separated swine wastewaters. *Hydrobiologia,* 692**,** 111-119.

HU, Y. S., KUMAR, J. L. G., AKINTUNDE, A. O., ZHAO, X. H. & ZHAO, Y. Q. 2011. Effects of livestock wastewater variety and disinfectants on the performance of constructed wetlands in organic matters and nitrogen removal. *Environmental Science and Pollution Research,* 18**,** 1414-1421.

McCARTNEY, M. P., STRATFORD, C., NEAL, C., BRADFORD, R., MILLS, S. & JOHNSON, M. 2003. Seasonality and water quality trends in a maturing recreated reed bed. *Science of the Total Environment,* 314**,** 233-254.

MOIR, S. E., SVOBODA, I., SYM, G., CLARK, J., MCGECHAN, M. B. & CASTLE, K. 2005. An experimental plant for testing methods of treating dilute farm effluents and dirty water. *Biosystems Engineering,* 90**,** 349-355.

OCKENDEN, M. C., DEASY, C., QUINTON, J. N., BAILEY, A. P., SURRIDGE, B. & STOATE, C. 2012. Evaluation of field wetlands for mitigation of diffuse pollution from agriculture: Sediment retention, cost and effectiveness. *Environmental Science & Policy,* 24**,** 110-119.

PARKES, M. E., MCBRIDE, A. D. & WAALKENS, A. 1998. Treatment of dilute piggery effluent with vertical flow reed beds. *Journal of Environmental Quality,* 27**,** 783-788.

REDDING, T., TODD, S. & MIDLEN, A. 1997. The treatment of aquaculture wastewaters - A botanical approach. *Journal of Environmental Management,* 50**,** 283-299.

RUANE, E. M., MURPHY, P. N. C., HEALY, M. G., FRENCH, P. & RODGERS, M. 2011. On-farm treatment of dairy soiled water using aerobic woodchip filters. *Water Research,* 45**,** 6668-6676.

SCHOLZ, M., HARRINGTON, R., CARROLL, P. & MUSTAFA, A. 2007. The Integrated Constructed Wetlands (ICW) concept. *Wetlands,* 27**,** 337-354.

SUN, G., GRAY, K. R., BIDDLESTONE, A. J., ALLEN, S. J. & COOPER, D. J. 2003. Effect of effluent recirculation on the performance of a reed bed system treating agricultural wastewater. *Process Biochemistry,* 39**,** 351-357.

SUN, G., ZHAO, Y., ALLEN, S. & COOPER, D. 2006. Generating "tide" in pilot-scale constructed wetlands to enhance agricultural wastewater treatment. *Engineering in Life Sciences,* 6**,** 560-565.

WOOD, J., FERNANDEZ, G., BARKER, A., GREGORY, J. & CUMBY, T. 2007. Efficiency of reed beds in treating dairy wastewater. *Biosystems Engineering,* 98**,** 455-469.

4.1. Study Quality Assessment Results

The results of the study quality assessment are given in Table 5. We allocated a good (green), medium (orange) or low (blue) rating to each study. The totals were calculated according to the assessment criteria set out in Table 3, with the addition of another score, the number of analytes reported in each article. This gave a maximum possible score of 21. The highest score achieved was 16. The loss of points was often due to no randomised experimental design, even in pilot scale studies; no real control experiments, just comparisons between input and outputs and a lack of replicates mainly due to the difficulties of field scale experiments not using suitable pond systems. However, replications were counted if measurements were taken in different seasons.

None of the studies included sufficient data on implications for greenhouse gas emissions, or on ecosystem service provision. It has been assumed that all wetlands provide a high level of ecosystem services and therefore, combined with nutrient processing capabilities, they should all be considered a positive landscape element.

Table 5: Study Quality Assessment scores

Study No.	Study	Randomised	Control	Replicates	Assessment Time	Study Type	Inclusion Criteria Matched	# Analytes	Total (21)
1	GOURIVEAU, F. 2009. Constructed Farm Wetlands (CFWs) designed for remediation of farmyard runoff: an evaluation of their water treatment efficiency, ecological value, costs and benefits. University of Edinburgh.	0	1	2	2	3	2	6	**16**
2	SCHOLZ, M., HARRINGTON, R., CARROLL, P. & MUSTAFA, A. 2007. *Wetlands,* 27**,** 337-354.	0	1	1	2	3	2	7	**16**
3	RUANE, E. M., MURPHY, P. N. C., HEALY, M. G., FRENCH, P. & RODGERS, M. 2011. *Water Research,* 45**,** 6668-6676.	0	0	1	1	2	2	8	**14**
4	SUN, G., GRAY, K. R., BIDDLESTONE, A. J., ALLEN, S. J. & COOPER, D. J. 2003. *Process Biochemistry,* 39**,** 351-357.	0	1	1	1	2	2	7	**14**
5	FORBES, E. G. A., FOY, R. H., MULHOLLAND, M. V. & BRETTELL, J. L. 2011. *Water Science and Technology,* 64**,** 22-28.	0	0	1	1	3	2	4	**11**

6	FORBES, E. G. A., FOY, R. H., MULHOLLAND, M. V. & WOODS, V. B. 2009. *Occasional Publication No. 9.* Agri-food and Biosciences Institute.	0	0	1	1	3	2	4	**11**
7	HARRINGTON, C., SCHOLZ, M., CULLETON, N. & LAWLOR, P. G. 2012. *Hydrobiologia,* 692**,** 111-119.	0	1	2	1	0	2	5	**11**
8	MOIR, S. E., SVOBODA, I., SYM, G., CLARK, J., MCGECHAN, M. B. & CASTLE, K. 2005.*Biosystems Engineering,* 90**,** 349-355.	0	1	1	0	2	2	5	**11**
9	OCKENDEN, M. C., DEASY, C., QUINTON, J. N., BAILEY, A. P., SURRIDGE, B. & STOATE, C. 2012.. *Environmental Science & Policy,* 24**,** 110-119.	0	0	0	0	3	3	5	**11**
10	SUN, G., ZHAO, Y., ALLEN, S. & COOPER, D. 2006. *Engineering in Life Sciences,* 6**,** 560-565.	0	1	0	0	1	2	7	**11**
11	BIDDLESTONE, A. J., GRAY, K. R. & JOB, G. D. 1991. *Process Biochemistry,* 26**,** 265-268.	0	1	0	1	3	2	3	**10**
12	BIDDLESTONE, A. J., GRAY, K. R. & THURAIRAJAN, K. 1991. *Journal of Biotechnology,* 17**,** 209-220.	0	1	1	1	3	2	2	**10**

13	REDDING, T., TODD, S. & MIDLEN, A. 1997. The treatment of aquaculture wastewaters - A botanical approach. *Journal of Environmental Management,* 50**,** 283-299.	0	1	2	0	2	2	3	**10**
14	DUNNE, E. J., CULLETON, N., O'DONOVAN, G., HARRINGTON, R. & DALY, K. 2005. *Water Research,* 39**,** 4355-4362.	0	0	0	1	2	2	4	**9**
15	PARKES, M. E., MCBRIDE, A. D. & WAALKENS, A. 1998. Treatment of dilute piggery effluent with vertical flow reed beds. *Journal of Environmental Quality,* 27**,** 783-788.	0	0	1	0	2	2	4	**9**
16	BLACKWELL, M. S. A., HOGAN, D. V. & MALTBY, E. 1999. *Water Science and Technology,* 39**,** 157-164.	0	1	1	1	3	1	1	**8**
17	HU, Y. S., KUMAR, J. L. G., AKINTUNDE, A. O., ZHAO, X. H. & ZHAO, Y. Q. 2011. *Environmental Science and Pollution Research,* 18**,** 1414-1421.	0	1	1	0	0	2	4	**8**
18	MCCARTNEY, M. P., STRATFORD, C., NEAL, C., BRADFORD, R., MILLS, S. & JOHNSON, M. 2003.*Science of the Total Environment,* 314**,** 233-254.	0	0	0	1	2	2	2	**7**
19	WOOD, J., FERNANDEZ, G., BARKER, A., GREGORY, J. & CUMBY, T. 2007. *Biosystems Engineering,* 98, 455-469.	0	0	0	1	2	2	2	**7**

4.2. Meta analysis

Meta analysis of the data was required to normalise comparisons between wetlands of different areas, input loadings, vegetation, flow pattern and other variables. The methods used are widely used in medical assessments of drug treatments and in medical systematic reviews.

In order to estimate the effect of wetland type on reduction of nutrients the ln-transformed (natural log) response ratio as the effect size metric was calculated for each type of wetland and analyte combination as, $\ln(R) = \ln(X_{out}/X_{in})$, where X_{out} is the mean concentration for the wetland outlet and X_{in} is the mean for inlet of wetland. Bias-corrected 95% confidence intervals (CI) around the effect size were generated based on 5,000 bootstrap iterations carried out by using the R statistical program.

Negative values of the log response ratio indicate that, for a given response variable, the output decreased relative to the input, as would be expected if the wetland had some positive effects in retention or reduction of nutrients. Positive values indicate no-reduction. The effect sizes were considered significantly different from zero when the 95% confidence intervals did not include or overlap zero (Gurevitch and Hedges 2001).

The log response ratio is one of the most frequently used effect metrics in ecological meta-analysis (Hedges et al. 1999; Lajeunesse & Forbes 2003). Unlike Hedges, the natural log (ln)-response ratio does not require a measure of sample variability (e.g. standard deviation) which is particularly useful for this specific study, as nearly half of the articles selected for data extraction just report the mean of nutrient in the input and output without any other variability measure associated with the mean.

This system has been used in other ecological meta-analyses (e.g. Stirling and Cornelissen, 2005; Shurin et al. 2002). This effect size metric seemed appropriate, making comparing output and input values as a ratio more appropriate than comparing the values as percent change. For more details see Hedges *et al*. (1999) for a comprehensive overview of the log response ratio.

For each study, we used a unique study identifier linked to the citation of the publication and obtained the following information wherever possible. We categorized the system as wetland, CW, ICW, and within each system by subcategories depending of flow type (HF, VF, etc).

To make the effect size results more meaningful and ease of interpretation the effect size was back-transformed as $100-(e^{\ln(r)} \times 100)$ and reported in the text, tables and figures as the normalised percentage change at the outlet.

5. Data Synthesis

The systematic review question was "Do on-farm natural, restored, managed and constructed wetlands mitigate agricultural pollution in Great Britain and Ireland?" The answers are set out below according to which analyte is being compared with a wetland type and wetland subtype.

The data in the following sections show reductions in all analytes across most wetland types. Ammonium, Biological Oxygen Demand, Chemical Oxygen Demand and Suspended Solids. Parameters that showed consistently high levels of removal were Total Nitrogen, Total Phosphorus and Soluble Reactive Phosphorus.

5.1. Wetland Types

There were three main wetland types, of the total of 187 studies included in 19 articles, these were distributed as follows:

- Constructed wetland (CW), consisting of a man made infrastructure, either planted or without plants, with some control of flow direction, with either concrete or lined construction. Flow direction can be horizontal surface, horizontal sub-surface, vertical or tidal, or a combination of any of these, with or without recirculation. There were 94 of these systems included in the data synthesis
- Integrated constructed wetland (ICW), consisting of one or a series of natural ponds used for the passage and treatment of run-off, without liners or significant man made infrastructure. They can include systems with water level control structures. All the flow type is horizontal flow in these systems. There were 90 of these systems included in the data synthesis.
- Wetland, this category included wetland buffer zones and restoration peat land areas, and other wetlands that did not fall easily into either of the above categories. There were only 3 of this category in the data synthesis.

The data in Figure 2 show the overall performance of each type of wetland system, including vertical flow systems. The data are based on very high input loads in pilot scale systems, which reduced the output loads by about 50%, but the output loads were still exceptionally high. No data were available for normally loaded vertical flow systems. Figure 3 shows the same data without vertical flow systems that compares horizontal and hybrid flow systems.

Figure 2: The removal efficiency of wetland types against all observed analytes expressed as % reduction.

(HF: Horizontal flow, HSSF: Horizontal sub surface flow, VF: Vertical flow)

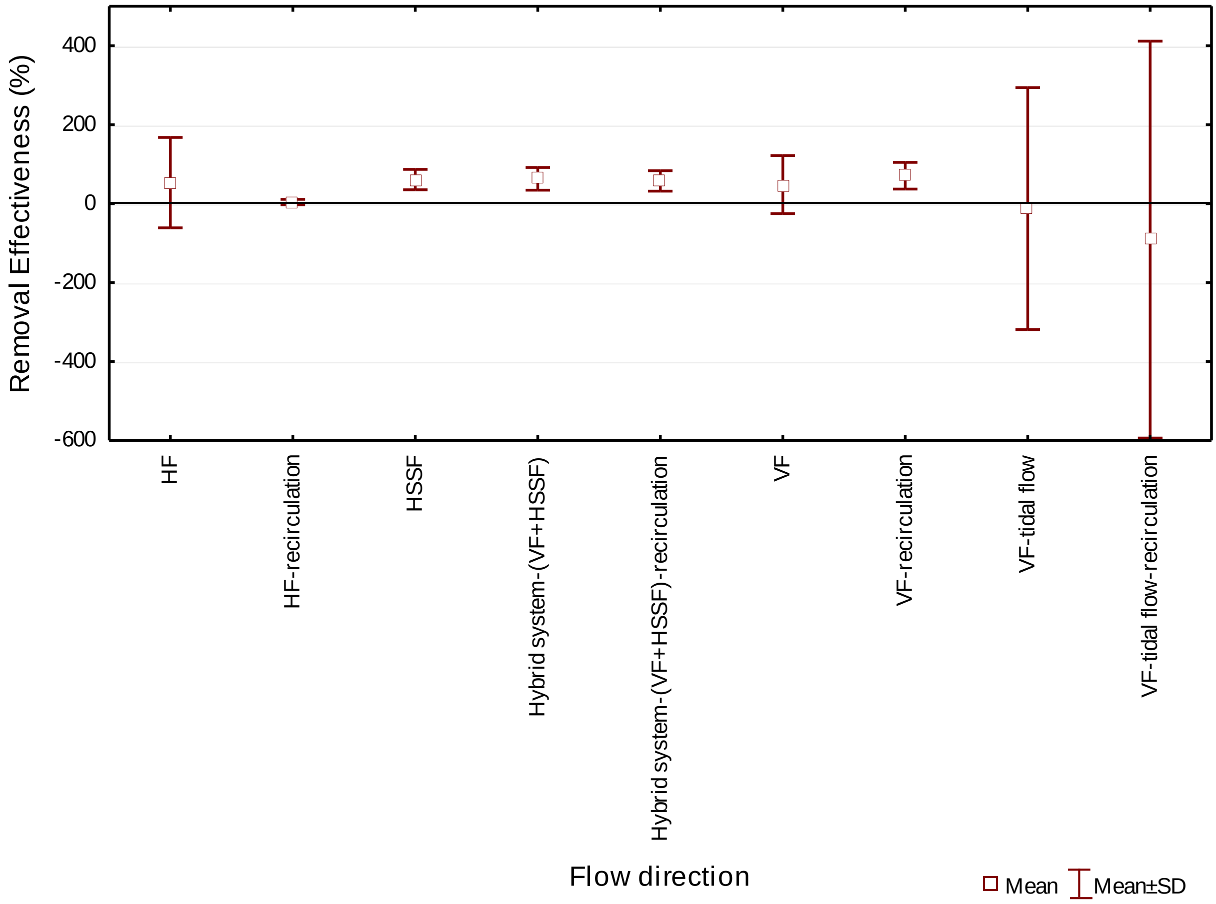


Figure 2 gives the overall removal efficiency of wetland types (given as flow type). A positive value indicates a removal of all analytes combined by each wetland type. The X axis categories are defined in the text above Table 4; they represent the major flow types and are used as definitions of wetland systems in this context.

Figure 2 shows that most, with the exception of tidal flow and recirculation systems, wetland systems are effective for the removal of all analytes on a percent reduction basis. Using this measurement vertical tidal flow wetland systems show relatively poor performance, this is entirely due to a very high increase of 1200 and 1761 % increase in NO_2 and NO_3 respectively in these systems. The data for these percent changes show a very small output concentration derived from an even smaller input concentration. This indicates that expression of data on a percent reduction value can be very misleading in terms of the actual function of a wetland system.

However, in Figure 3, the data for removal expressed as $gm^{-2}d^{-1}$ of analytes is much more effective in vertical tidal flow systems, this is due to a cumulatively higher removal rate of all analytes (other than NO_3) in these systems. The expression of function on a mass removal rate (R_{mass}) gives a much better indication of complete nutrient removal efficiency than just percent reduction values.

Figure 3: Removal efficiency of wetland types expressed as g $m^{-2}d^{-1}$.

(HF: Horizontal flow, HSSF: Horizontal sub surface flow, VF: Vertical flow)

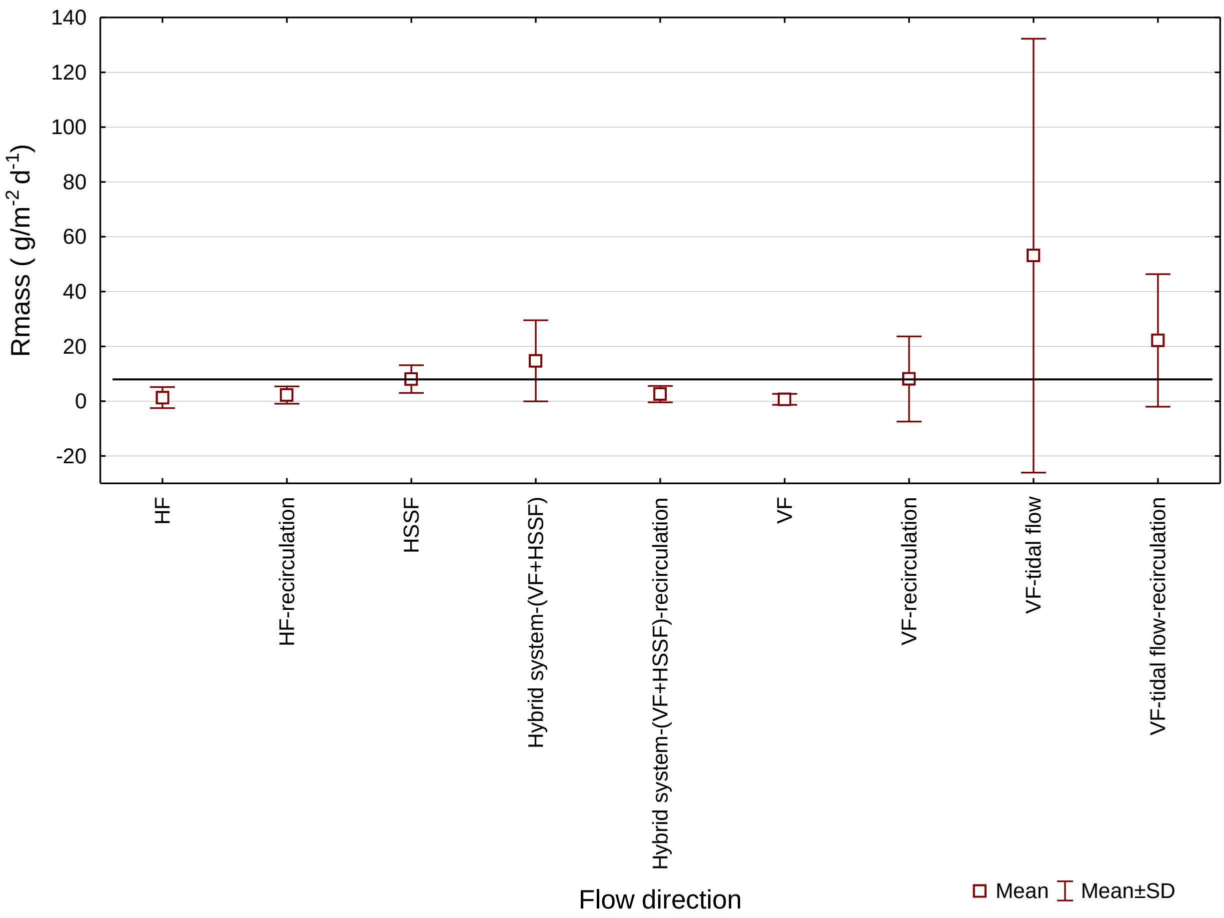
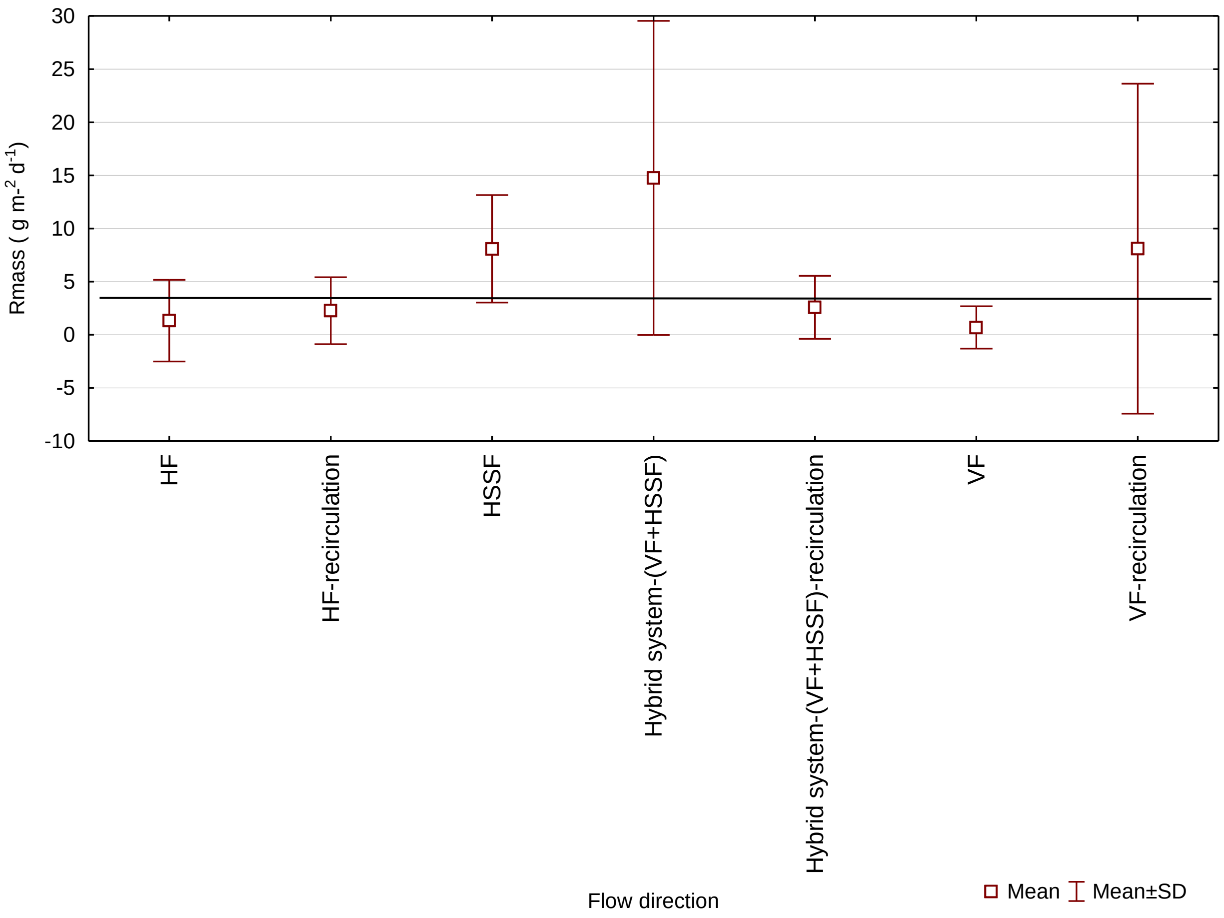


Figure 4: Removal efficiency of wetland types (not including vertical tidal flow systems) expressed as g $m^{-2}d^{-1}$

(HF: Horizontal flow, HSSF: Horizontal sub surface flow, VF: Vertical flow)



If we remove the data for vertical tidal flow systems in order to allow better comparison, Figure 4 shows that Hybrid Systems are the most effective type of the remaining types of wetland, with values of a total of 15 $gm^{-2}d^{-12}$ removal capacity. The tidal flow systems were pilot scale systems and there were no data for field scale systems using this type of tidal vertical flow pattern. The data indicate that this may be a much more effective method of nutrient removal and we recommend that this type of flow is tested at field scale level.

5.2. Data Analysis

To answer the SR question "Do on-farm natural, restored, managed and constructed wetlands mitigate agricultural pollution in Great Britain and Ireland?" we assessed the performance of the wetland system on a linear percent reduction of analyte basis. This provided data on a simple assessment basis, and although it allows comparisons, percent reduction values are not a very good indicator of the actual intensity of the chemical process. To assess performance of different wetland types (irrespective of flow direction) we used natural log transformed data on input and output loads (which were available by calculation of data in all selected articles). These data were analysed by using meta analysis techniques and plotted using a forest plot. A forest plot is a graphical display designed to illustrate the relative strength of treatment effects in multiple quantitative scientific studies addressing the same question. It was developed for use in medical research as a means of graphically representing a meta-analysis of the results of randomized controlled trials, but similar meta-analytical techniques have been applied in observational studies, such as those data used in this SR.

The graphs were plotted on a natural logarithmic scale so that the confidence intervals are symmetrical about the mean from each study and to ensure undue emphasis is not given to odds ratios greater than 1 when compared to those less than 1. The area of each square is proportional to the study's weight in the meta-analysis. The overall meta-analysed measure of effect is often represented on the plot as a dashed vertical line. This meta-analysed measure of effect is commonly plotted as a diamond, the lateral points of which indicate confidence intervals for this estimate.

A vertical line representing no effect is also plotted. If the confidence intervals for individual studies overlap with this line, it demonstrates that at the given level of confidence their effect sizes do not differ from no effect for the individual study. The same applies for the meta-analysed measure of effect: if the points of the diamond overlap the line of no effect the overall meta-analysed result cannot be said to differ from no effect at the given level of confidence.

In our graphs, if the confidence limits overlap the zero vertical axis, this indicates that there is no significant reduction of the analyte by the wetland type category analyte combination.

The results for each analyte are set out below with percent reduction, distribution of percent reduction and a forest plot to indicate significance of the process.

5.3. Phosphorus Compounds

Soluble Reactive Phosphorus (orthophosphate) (SRP) and Reactive Phosphorus (RP)

SRP is data obtained from filtered samples and RP is data obtained from unfiltered water samples. Both forms were all undigested. It was not possible to compare data for SRP and RP as no articles used both methods.

Data were available from 15 articles for a total of 11 wetland sites with 36 possible combinations of analyte. The mean reduction in SRP was 58.3 ± 40.7 %. The input mass load values ranged from a minimum of 17.67 kg Ha^{-1} to 1,406 kg Ha^{-1}, with output loads ranging from 0.0007 to 0.018 kg Ha^{-1}. The wetland receiving a total of 1,406 kg Ha^{-1} (Dunne *et al.*, 2005), showed a 90.8% reduction, but the output load was still 12.9 kg Ha^{-1}. Clearly this is in excess of desired nutrient loading rates for good surface water quality where SRP concentrations should not normally[1] exceed 120 µg l^{-1} (equivalent to a loading rate on our scale of 1.2 kg Ha^{-1} in water 1 m deep over a hectare, or a length of river 100 m long by 10 m wide). 27 studies out of 36 achieved output mass loads of less than 1 kg Ha^{-1}, while the maximum mass load at the output was 528 kg Ha^{-1} in an un-vegetated recirculating horizontal flow system (Redding *et al.*, 1997).

Total phosphorus (TP)

Data were available from 4 articles, with a total of 5 wetland sites. The mean reduction in TP was 81.7 ± 22.7%. The input mass load values ranged from 1.56 to 2.36 kg Ha^{-1}, with the output values ranging from 0.001 to 0.054 kg Ha^{-1} (Ockenden *et al.*, 2012c, Fallowfield *et al.*, 1999, Forbes *et al.*, 2009, Forbes *et al.*, 2011).

Wetland Type

Horizontal flow

Horizontal flow systems were classified as systems where the inflow and outflow were either at the same level (e.g. pond), or where flow was directed across the surface of a substrate before leaving the wetland.

We found 7 papers, one report and one thesis citing robust data for SRP and TP changes in horizontal flow constructed wetlands (Clifford *et al.*, 2008, Dunne *et al.*,

[1] Table 5 in http://archive.defra.gov.uk/environment/quality/water/wfd/documents/2010directions.pdf

2005, Forbes *et al.*, 2009, Forbes *et al.*, 2011, Gouriveau, 2009, McCartney *et al.*, 2003, Ockenden *et al.*, 2012a, Redding *et al.*, 1997, Scholz *et al.*, 2007b). The mean value for SRP or TP reduction was 65.32%, the median value was 92.88% and the minimum and maximum values were -16.67 to 99.74%.

Vertical flow

Vertical flow systems were classified as systems where the inlet was at the surface of the substrate and the outlet was at the bottom of the substrate. These were invariably constructed systems

We found 7 papers (Moir *et al.*, 2005, Sun *et al.*, 2006, Sun *et al.*, 2003, Ruane *et al.*, 2011, Hu *et al.*, 2011, Harrington *et al.*, 2012). The mean reduction was 70.68%. The median reduction was 77.98% and the minimum and maximum values were 30.95 and 98.44%.

Tidal flow

Tidal flow systems are characterised by intermittent flooding and drying the surface of the wetland. The principle is to enable intermittent periods of aerobic and anaerobic conditions at the surface of the wetland to stimulate nutrient removal processes.

We found two papers (Sun *et al.*, 2003, Sun *et al.*, 2006). The mean value for reduction was 40.39%, with the median value of 45% and a minimum and maximum of 30.95 and 45.21

Re-circulating

Re-circulating systems were either HF or VF or tidal, but with the addition of the outlet being returned to the inlet to re-circulate the effluent through the wetland.

Three papers showed contrasting results for re-circulating systems. A horizontal flow re-circulating system established for only 4 months and of only 0.9 m^2 surface area did not perform well (Redding *et al.*, 1997) showed a mean slight increase in SRP of 6.01%, with a median value of -6.41%, a maximum value of -2.6 and a minimum of -2.6%. Sun *et al.*, 2003 and Harrington *et al.*, 2012 showed decreases of 37.93% and 97.53 5 respectively in wetlands of about 18 months old and of areas of 33.28 and

3,152 m^{-2} respectively, indicating both the importance of age and size for this type of system.

The distribution of % reduction values for all P species is shown in Figure 5. This shows that the majority of studies showed a % reduction of P (SRP, RP and TP) when comparing output vs input values.

Figure 5: Distribution of % reduction of all Phosphorus (P) species in all studies

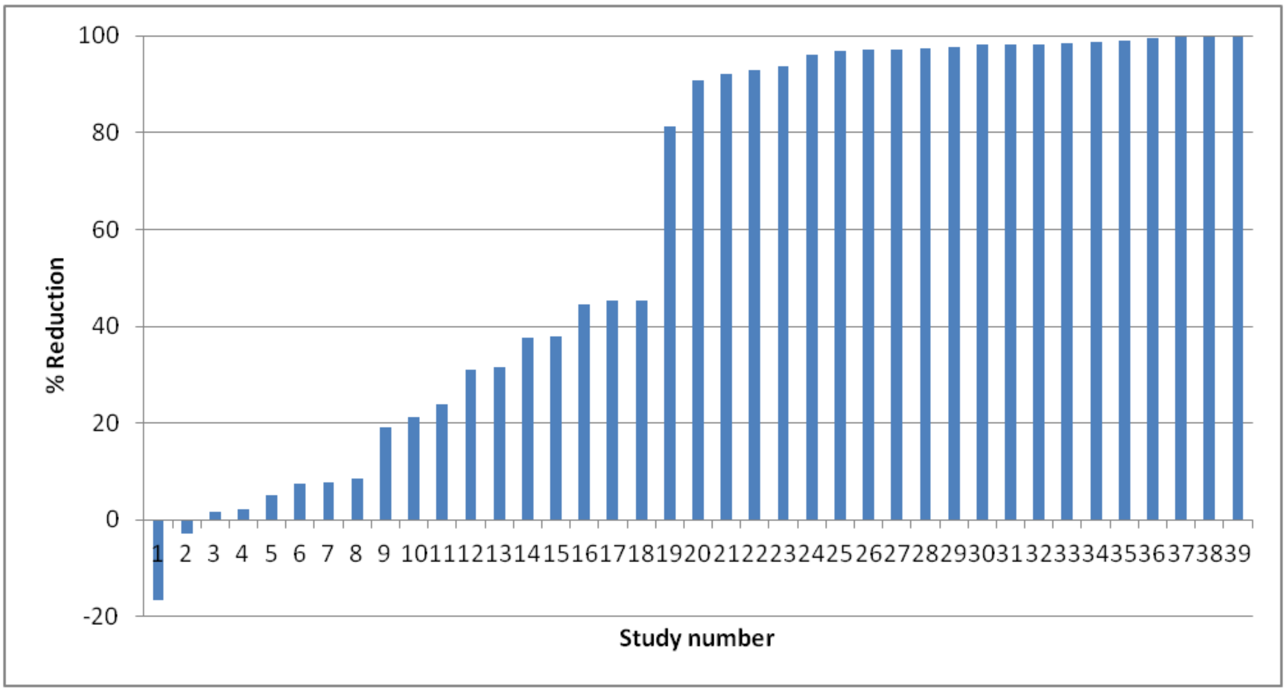


Figure 6: Response ratio effect size (ES) for phosphorus species in different type of wetlands (data points: mean) and the bars represent 95% confidence intervals (CIs).

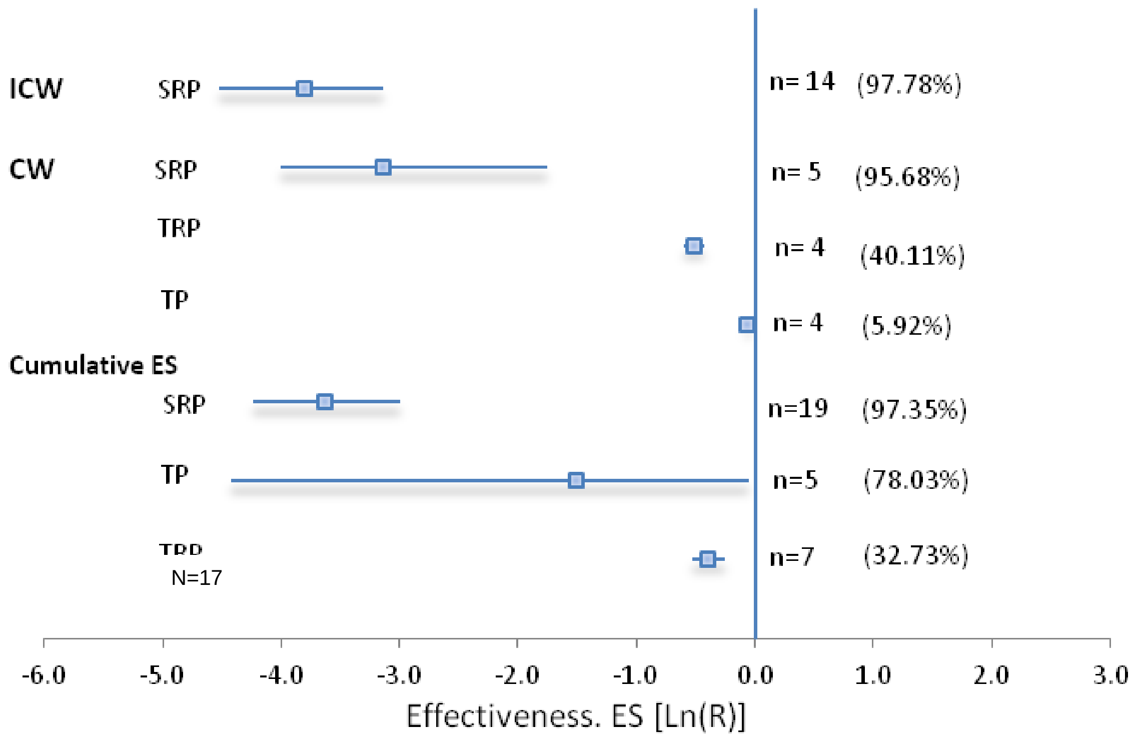


Figure 6 shows the relative effects of wetland type on reduction of phosphorus compounds. The data are means of all wetland types with 95% confidence intervals. The number in parentheses represents the percentage reduction. In order to make the effect size results easier to interpret, the sample size of different groups is given next to the percentage of phosphorus species (n). Means (data points) are significantly different when their CIs do not overlap and negative ES indicates reduction and positive represents an increase. Sample size < 2 are excluded from this analysis. Type of wetlands: constructed wetland (CW), integrated constructed wetland (ICW). Phosphorus species: total phosphorus (TP), soluble reactive phosphorus (SRP), total reactive phosphorus (TRP). The cumulative ES are the total sample mean values across all wetland types.

Figure 6 shows that with the exception of TP in CW systems, all P species are significantly reduced by passage through all wetland systems

5.4. Nitrogen Compounds

5.4.1. Ammonia / Ammonium ions

Data were available from 17 articles for a total of 17 wetland sites with 43 possible combinations of analyte. The percentage reduction in all studies is shown in Figure 8. The mean reduction in NH_3/NH_4 was 66.9 ± 35.9 %. The input mass load values ranged from a minimum of .04 kg Ha^{-1} to 3,648 kg Ha^{-1}, with output loads ranging from .00068 to 214.8 kg Ha^{-1}. The wetland receiving a total of 3,648 kg Ha^{-1} (Dunne *et al.*, 2005) showed a 96.4 % reduction, but the output load was still 144 kg Ha^{-1}. There are no recommended target values set for Ammonia in drinking water, but an output load rate of 144 kg Ha^{-1} would result in a concentration of 14.4 mg l^{-1} in a hectare of water). Given the ease with which this is converted to nitrate (a nutrient better suited to algal and plant growth stimulation) in open aerated systems, a target output value of less than 12.9 mg l^{-1} (Drinking Water Directive Limit) would be advisable, and should preferably be about 20% of this value. The highest output mass load value was 214.8 kg Ha^{-1} (Redding *et al.*, 1997) in an un-vegetated horizontal flow recirculating system. The aim of this paper was to demonstrate the value of vegetation in a biologically orientated approach to waste water management, so it is perhaps not surprising that un-vegetated plots showed the least capacity to transform input nutrients. Only one wetland site did not reduce Ammonium ions (Gouriveau, 2009), but this was from a measurement made in autumn and winter. The same wetland achieved a reduction of 50% when measured in spring and summer.

Horizontal flow

Horizontal flow wetlands are the most frequent type of wetland included in this Systematic Review. HF wetlands calculated by the data analysis showed an average % reduction of NH_4 /NH_3 of 84.42. Papers by (Surridge, 2004, Mustafa, 2010, Scholz *et al.*, 2007a, Mustafa *et al.*, 2009, Pangala *et al.*, 2010, Clifford *et al.*, 2008, Forbes *et al.*, 2011, Forbes *et al.*, 2009, Dunne *et al.*, 2005, Fallowfield *et al.*, 1999, McCartney *et al.*, 2003) were used in this section

Vertical flow

One paper provided data for removal of NH_4/NH_3 in vertical flow wetlands, with a mean reduction percentage of 87.03% (Harrington and Scholz, 2010)

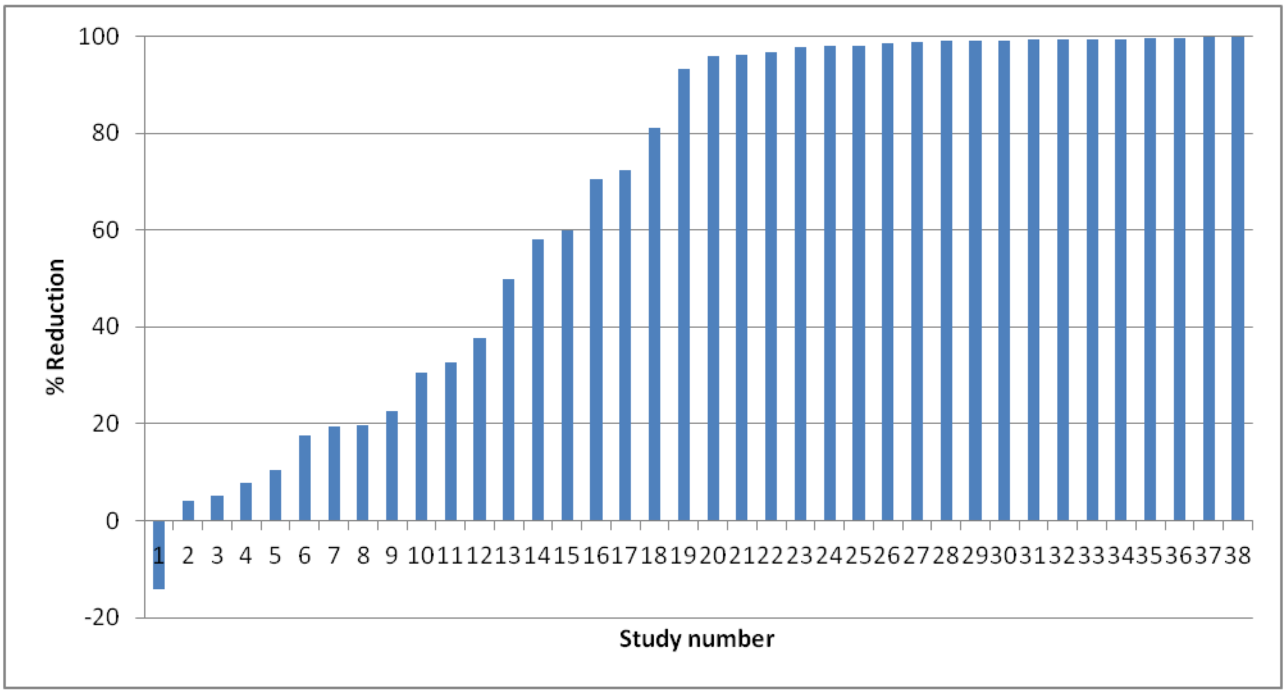
Tidal flow

Sun *et al.*, (2006) showed a 58.21 % reduction in NH_4 in an experimental tidal flow system

Recirulating

Two papers showed contrasting results for recirculating systems. A horizontal flow recirculating system (Redding *et al.*, 1997) showed an increase in NH3 of 7.1 ± 2.88 %, while (Harrington and Scholz, 2010) showed decreases of between 92.36 ± 8.83 % in a vertical flow system of much larger area.

Figure 7: Distribution of % Reduction values for Ammonia (NH_3) and Ammonium (NH_4) in all wetland types



5.4.2. Nitrite

Five articles contained data to enable calculation of mass loading values for NO_2 (Sun *et al.*, 2003, Sun *et al.*, 2006, Ruane *et al.*, 2011, Redding *et al.*, 1997, Harrington *et al.*, 2012) with data for 12 monitoring intervals and replicates. The data for percent reduction are given in Figure 8. The wetlands studied were vertical flow, tidal vertical flow, with and without recirculation, and horizontal flow with recirculation, with areas ranging from 1.08 m^2 to 0.315 Ha.

The mean value for nitrite reduction was an increase of 96.9% for all wetland types, with a median value of 4.17% increase and a minimum and maximum value of 1200% increase and 96.76 % decrease. The 120% increase was disregarded in statistical analysis because it was a significant outlier value, the actual data for this percent increase was a 0.01 mg/L input to a 1.3 mg/L output

The highest input load was 187.2 kg Ha^{-1} with a corresponding output load of 193.2 kg Ha^{-1}. Reductions in NO_2 were only achieved in two studies using vertical flow systems (one with tidal flow (Sun *et al.*, 2006) with an input load value of 11.4 and an output load of 1.44 kg Ha^{-1} and one with recirculation (Harrington *et al.*, 2012) with very low input loadings of less than 0.07 kg Ha^{-1}.

Horizontal flow

(Redding *et al.*, 1997) showed a mean reduction of nitrite of 4.22 % in a pilot study wetland 0f 0.9 m^2 with a short retention time and only established for four months.

Vertical flow

Ruane *et al.* (2011) observed a 182% increase in nitrite, while Sun *et al. (*2003) observed a 73% decrease and Sun *et al* (2006) observed an 90 % decrease.

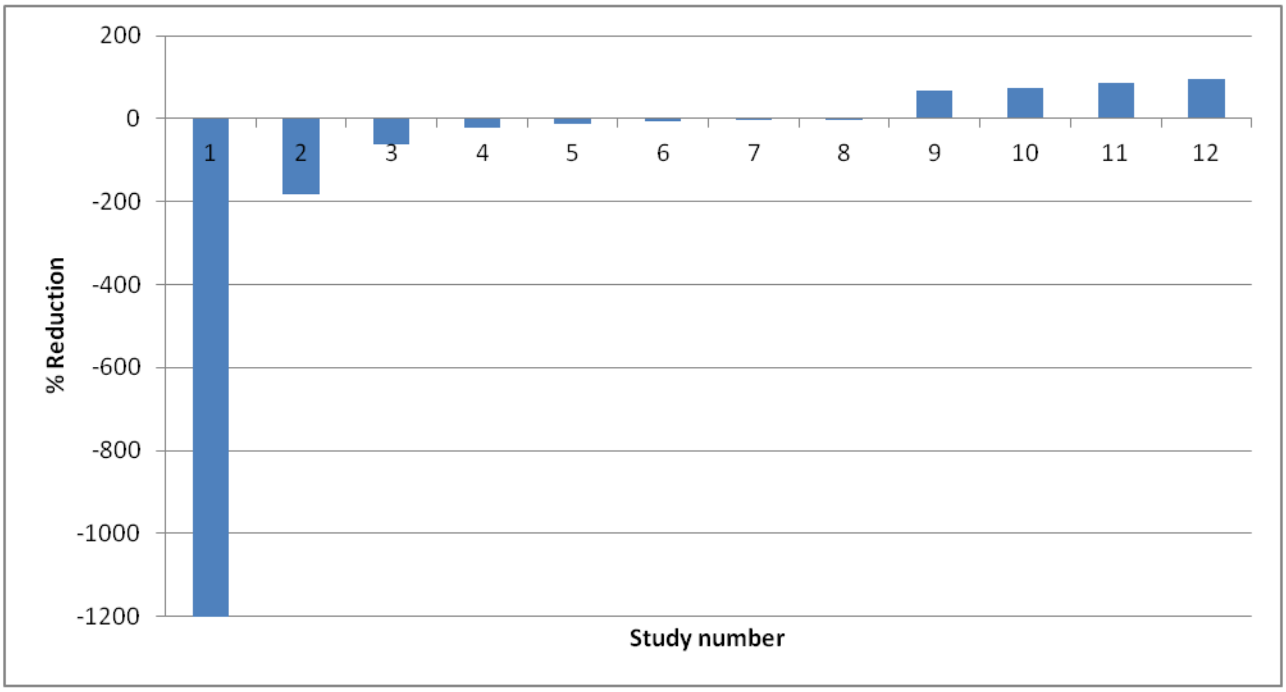
Tidal flow

Sun *et al.* (2006) showed a 87.37% reduction in a vertical flow recirculating system and Sun *et al* 2003 showed a 90% reduction.

Recirulating

Horizontal flow recirculation studies by Redding *et al.* (1997) showed low reduction rates of NO_2, with a mean value of 5.45 %. Vertical flow recirculation systems are much more effective for the removal of NO_2, with Sun *et al.* (2003) obtaining mean reduction values of 84.51 %.

Figure 8: Distribution of % reduction of nitrite (NO_2) in all wetland types



5.4.3. Nitrate

Data were available from 11 papers for 37 sites or replicates or time intervals for reduction of NO_3. The average increase in NO_3 was 76.9% with a median value of 15.37% decrease for all wetland types. The data are summarised in Figure 10.

The maximum input load of 648 kg Ha^{-1} (Redding *et al.*, 1997) was reduced to 578.4 kg Ha^{-1}. Most studies citing input loads of less than 1 kg Ha^{-1} cited output loads of similar concentrations, but because concentrations were small the percentage changes were usually high. Data from studies where input loads were between 1 and 20 kg Ha^{-1} showed an average removal of nitrate of 39.7%.

This SR suggests that NO_3 is better removed by buffer strips consisting of overland flow systems where denitrification can occur in the soil, rather than by treatment in a wetland system (Blackwell *et al.*, 1999).

Horizontal flow

Increases of between 29.51% and 548.84% were observed by Scholz *et al.* (2007a). Redding *et al.* (1997) observed effects between a 3.3 % increase and a 15.3 % increase. McCartney *et al.* (2003) observed reductions of 15.28% and (Blackwell *et al.*, 1999) showed reductions of 99.39% in an overland flow buffer zone system. While Gouriveau (2009) and Moir *et al.* (2005) found that nitrate was reduced. The mean value for nitrate increase in horizontal flow systems was 198.49%, with a median value of 9.77% and a minimum and maximum of 1200 % increase (Sun *et al.*, 2003) and a maximum of 99.39% removal (Blackwell *et al.*, 1999).

Vertical flow

The mean increase in NO_3 was -187.64%, the median value was 39.74 % removal and the minimum and maximum values were -1,861.4% (increase) and a 79.31% decrease (Harrington *et al.*, 2012, Moir *et al.*, 2005, Parkes *et al.*, 1998, Sun *et al.*, 2003, Sun *et al.*, 2006)

Tidal flow

Sun *et al.* (2006) showed reductions of 63.89 – 65% in a vertical flow tidal wetland system

Recirulating

Harrington *et al.* (2012) observed a reduction of 79.31%, while Redding *et al.* (1997) and (Sun *et al.* (2006) both observed increases in nitrate after passing through their wetlands.

Figure 9: Distribution of % reduction of Nitrate (NO_3) by all wetlands

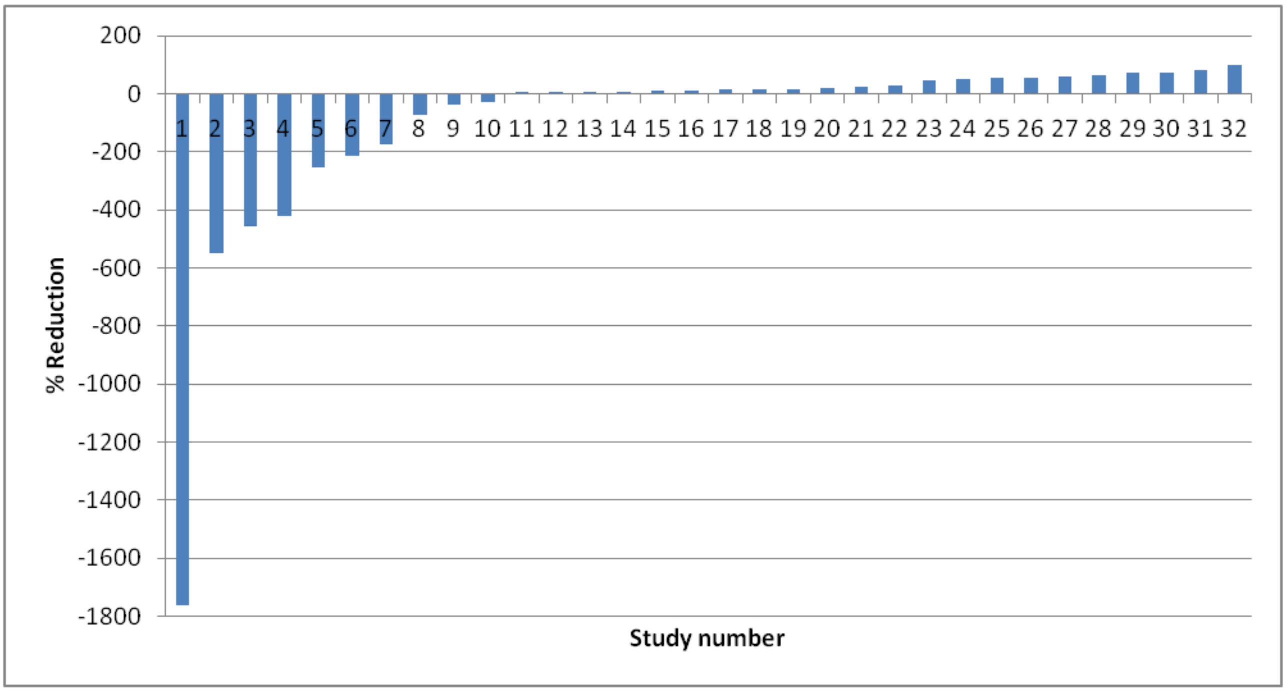


Figure 9 shows the distribution of the % reduction of NO_3 for all wetland types. The range is very large, due to changes where input loads are very small, resulting in small increases in output loads becoming very large % increases. For the majority of studies there was a small decrease in NO_3, but this was mainly due to the presence of vegetated wetland systems measure in spring and summer and by overland flow buffer strips.

Figure 10 Response ratio effect size (ES) for nitrogen species in different type of wetlands (data points: mean) and the bars are 95% confidence intervals (CIs)

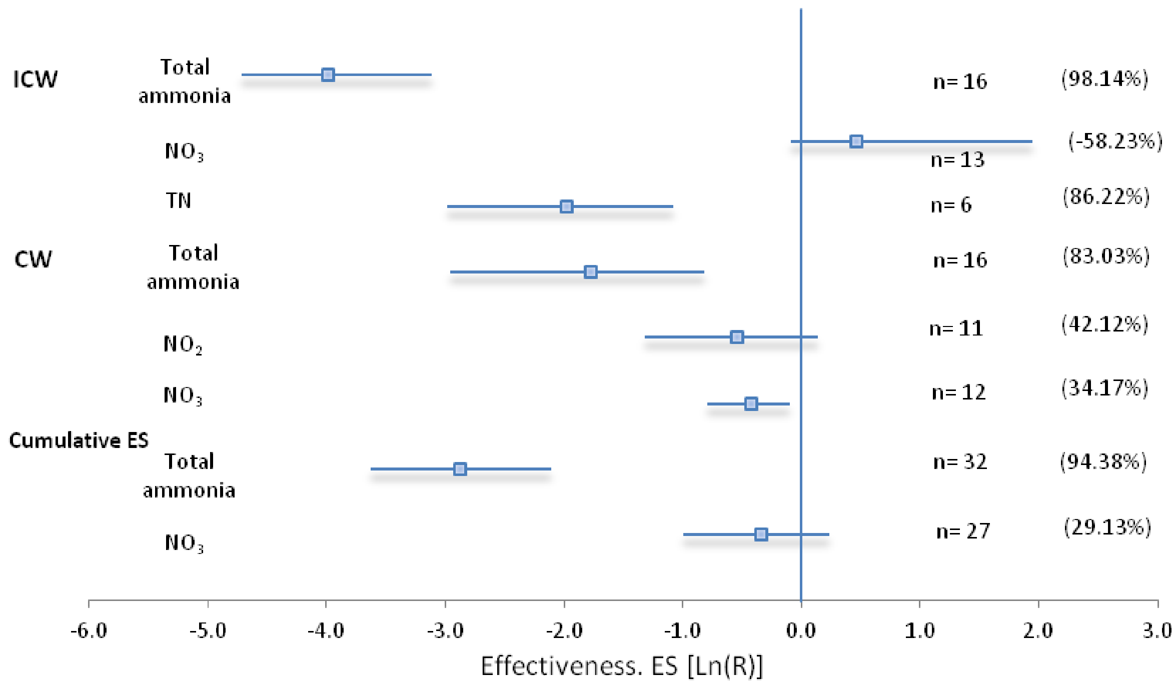


Figure 10 shows the response ratio effect size (ES) for nitrogen species in different type of wetlands (data points: mean) and the bars are 95% confidence intervals (CIs). The number in parentheses represents the percentage of reduction. In order to make the effect size results easier to interpret the sample size of different groups is given next to the percentage of nitrogen species (n). Means (data points) are significantly different when their CIs do not overlap and negative ES means reduction and positive increase. Sample size < 2 are excluded from this analysis. Type of wetlands: constructed wetland (CW), integrated constructed wetland (ICW). Nitrogen species: total nitrogen (TN), total ammonia (NH_3+NH_4), nitrite (NO_2), nitrate (NO_3).

Figure 10 clearly shows that total ammonia is reduced significantly in both CW and ICWs. Nitrate is only reduced in CW systems when significant outlier data points were removed from the analysis. The data show that **nitrate is not significantly altered by passage through ICW systems**. Nitrite is not significantly reduced in any wetland system because the CIs overlap the zero axis. The cumulative means show that **ammonia species are always reduced very significantly by wetlands,** while nitrate is reduced but not significantly so.

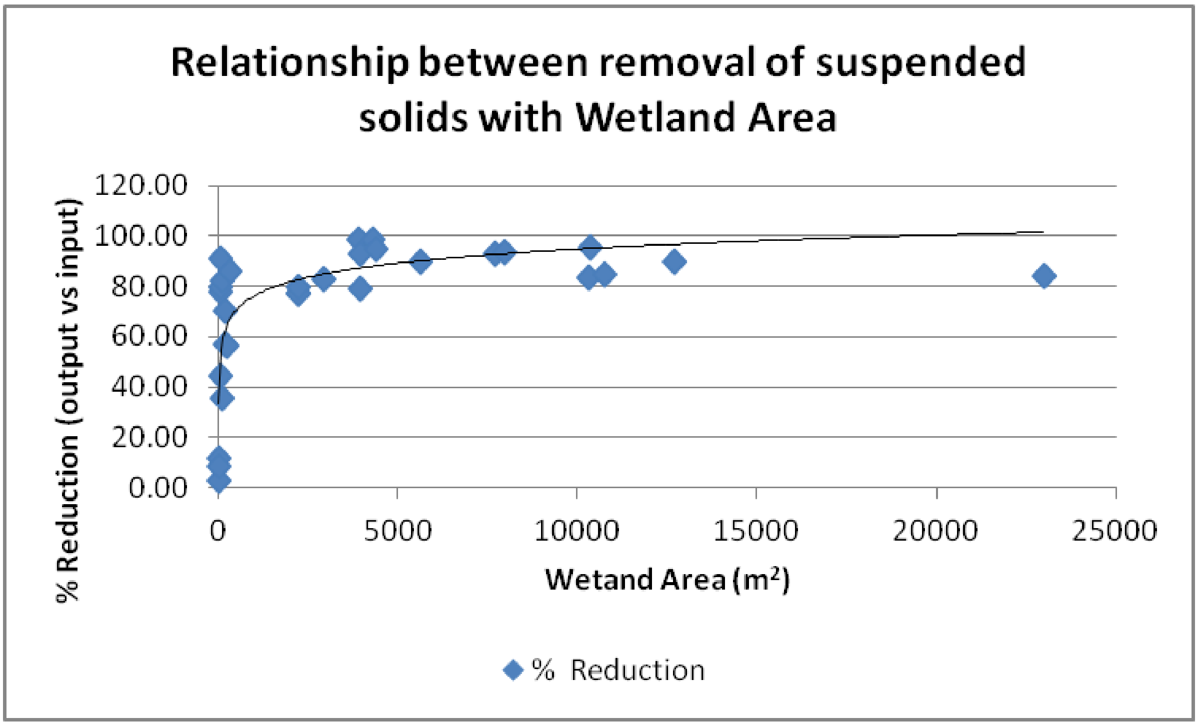
5.5. Suspended Solids

A total of 9 articles provided data for analysis of suspended solids (SS) removal by wetland systems with 30 sites, replicates and time intervals. All were constructed wetland systems, with hybrid systems, vertical tidal flow, vertical re-circulating flow, horizontal surface flow and horizontal flow systems represented. All were vegetated except for one system (Ruane *et al.*, 2011). Most were field scale plots with areas between 33 m^2 and 22 Ha. There were three pilot scale vertical flow re-circulating plots included each of and area of 5 m^2 (Wood *et al.*, 2007).

Suspended solids were generally reduced substantially by passage through all wetland types, except for the small pilot scale systems of Wood *et al.* (2007). Excluding the high values of this paper and those quoted in Dunne *et al.* (2005), the mean input and output loads for all wetlands were 95.47 and 27.18 kg Ha^{-1}, a reduction efficiency of 73.31%. The range of input loads varied from 0.69 to 74,442 kg Ha^{-1}.

We made the assumption that the area of the wetland would be related to removal of suspended solids, due to increase in water retention time and slower flow through larger wetlands allowing for settlement of solids. This relationship is shown in Figure 11, where increasing the area of the wetland is related to improved removal of suspended solids. Although some smaller wetlands have high removal rates, it appears that in order to achieve removal efficiencies of over 80% an area of wetland of at least 2,500 m^2 should be used.

Figure 11: Relationship between wetland area and suspended solids removal efficiency. The trend line is a log transformed fit.



Horizontal flow

The mean reduction in SS for horizontal flow wetland systems (including hybrid systems) is 73.31 %, with a median value of 82.64 % and a minimum and maximum value of 2.71 % to 98.88% (Biddlestone *et al.*, 1991b, Biddlestone *et al.*, 1991a, Dunne *et al.*, 2005, Gouriveau, 2009, Moir *et al.*, 2005, Scholz *et al.*, 2007a). The biofilm reactor system cited in (Clifford *et al.*, 2008) was not used for analysis, but data are used in Figure 12 for comparison.

Vertical flow

The mean reduction for SS in vertical flow systems was 53.63%, with a median value of 67.23, and a minimum and maximum value of 2.271 to 91.2% (Biddlestone *et al.*, 1991a, Moir *et al.*, 2005, Sun *et al.*, 2003, Sun *et al.*, 2006, Wood *et al.*, 2007)

Tidal flow

The mean value for SS reduction in tidal flow systems is 37.15%, with a median value of 27.90% and a minimum and maximum value of 2.71% to 78% (Sun *et al,* 2003, Sun *et al*. 2006, *Wood et al.*, 2007).

Re-circulating

Wood *et al*. (2007) showed reductions of between 2.71 and 11.39 % in re-circulating systems.

Figure 12: Distribution of % reduction in suspended solids across all wetland types.

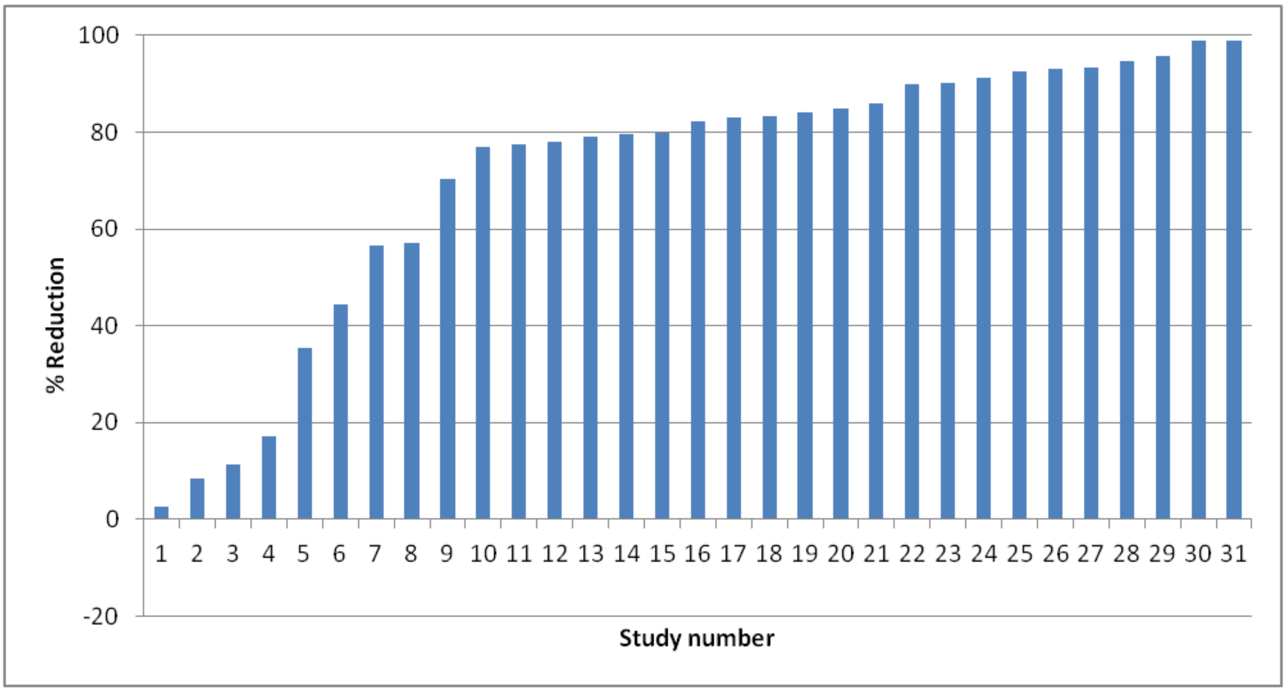


Figure 12 shows the distribution of reduction of SS across all wetland types. In all cases the reduction was positive, meaning all wetlands reduced suspended solids. Low removal efficiencies were reported in pilot scale systems with high suspended solid loads.

5.6. Chemical Oxygen Demand (COD)

Data for Chemical Oxygen Demand (COD) cannot be scaled to a single unit area value. Therefore only studies with reported input and output measurements were used for analysis. There were eight articles with 23 replicates over time and space for analysis.

The wetlands consisted of hybrid systems with recirculation, vertical flow systems with tidal flow, or recirculation of just VF, and HF systems. One system used an algal biofilm system, but data were not used in the analysis for this paper as hydraulic loading rates could not be calculated. The majority of studies were field scale (18) with 4 pilot scale studies included. All were constructed wetland systems.

The mean % reduction in COD was 80.88%, with a median value of 84.92%. The range for removal was between 23.33 and 99.64%. Actual values for input COD values ranged from
77 to 8,342 mg l^{-1}. The highest input value was reduced to 30.4 mg l^{-1} by passage through a HF system (Scholz *et al.*, 2007a). Given that proposed limits for Biological Oxygen Demand[2] set an upper limit of 9 mg/L for poor quality lowland high alkalinity rivers, this value is still 3.5 times higher than the limits would allow. Assuming no dilution this would exceed the proposed limits. All of the studies exceeded the BOD / COD proposed limit, with the minimum output value of 13 mg/L being in excess of the upper limit by about 45%. Although reduction of COD is achieved in all studies, the lower limits are not below the upper limit for receiving waters in the UK[2]. **Recirculation of the effluent or additional treatment may be required to reduce COD to below current discharge limits**

Horizontal flow

Fallowfield *et al.* (1999), Moir *et al.* (2005), Scholz *et al.* (2007a) provide data on horizontal flow systems for COD reduction. The mean reduction is 87.96% the median 92.56% and the min and max values are 69.37 to 99.64%. All of the studies exceeded the BOD / COD proposed limit.

Vertical flow

---

2 http://www.wfduk.org/sites/default/files/Media/Environmental%20standards/Environmental%20standards%20phase%201_Finalv2_010408.pdf

The mean value was 68.3% reduction, the median 77.60% with min and max values of 43 and 83.12% (Moir, *et al.*, 2005, Parkes *et al.*, 1998, Sun *et al.* 2003, and Sun *et al.*, 2006). All of the studies exceeded the BOD / COD proposed limit

Tidal flow

Sun *et al.*, 2003, Sun *et al.*, 2006 provide data showing between 50% and 80% reduction. All of the studies exceeded the BOD / COD proposed limit

Re-circulating

Sun *et al.*, 2003 observed a 77.6% reduction in a vertical flow re-circulating system.

5.7. Biological Oxygen Demand (BOD)

Oxygen in rivers is affected by complex interactions between ecological processes, and by anthropogenic pressures. Additions of organic matter such as discharges from sewage treatment works and storm overflows, and agricultural sources such as slurry and silage liquor, reduce dissolved oxygen due to the enhanced microbial respiration. The UK TAG proposed limits for BOD are a maximum of 9 mg l^{-1} for poor quality lowland high alkalinity rivers[3].

Data were available from 11 articles on 38 sites across replicates and time intervals. All wetland types were represented, including recirculation systems, HF and VF systems with and without tidal flow in the analysis. The areas ranged from 2.93 m^2 (Hu *et al.*, 2011) to nearly 23 Ha (Scholz *et al.*, 2007a).

The average reduction in BOD was 74.96% with a median value of 82.95% and a range of between -46.15% (Gouriveau, 2009) and 99.89% (Forbes *et al.*, 2009). However, only four study numbers achieved output values of less than 9 mg l^{-1}, with one study increasing the BOD but still achieving a value lower than the upper proposed limit (Gouriveau, 2009). One study was just in excess of the proposed limit (Forbes *et al.*, 2011). It is clear that although BOD is reduced by on-farm wetland systems more must be done to effluent to achieve compliance with proposed discharge limits. The most effective system for BOD reduction was a five pond integrated constructed wetland system reported in Forbes *et al.*, 2009.

Horizontal flow

---

[3] http://www.wfduk.org/sites/default/files/Media/Environmental%20standards/Environmental%20standards%20phase%201_Finalv2_010408.pdf

The mean reduction of BOD in HF systems was 84.4%, with a median value of 95.25% and a min and max value of -100 to +99.98% removal (Biddlestone *et al.*, 1991a, Biddlestone *et al.*, 1991b, Dunne *et al.*, 2005, Forbes *et al.*, 2011, Gouriveau, 2009, Parkes *et al.*, 1998, Scholz *et al.*, 2007a).

Vertical flow

The mean reduction of BOD in VF systems was 69.37%, with a median value of 73 % and a min and max value of 26.05 to +96.7 % removal (Biddlestone *et al.*, 1991a, Hu et al, 2011, Parkes *et al.*, 1998, Sun *et al.*, 2003, Sun *et al.*, 2006, Wood *et al.*, 2007).

Tidal flow

Tidal flow systems had a mean value for reduction of BOD of 62.21%, with a median value of 68.4% and a min and max value of 26.05 to 82.2% (Hu *et al.*, 2011, Sun *et al.*, 2003, Sun *et al.*, 2006, Wood *et al.*, 2007)

Re-circulating

Re-circulating systems reduced BOD by an average value of 50.71%, with a median value of 40.04, and a min and max value of 26.05 to 96.70% (Sun *et al.*, 2003, Wood *et al.*, 2007).

Figure 13: Response ratio effect size (ES) for BOD (biological oxygen demand), COD (chemical oxygen demand) and SS (suspend solids) in different types of wetland (data points: mean) and the bars represent 95% confidence intervals (CIs).

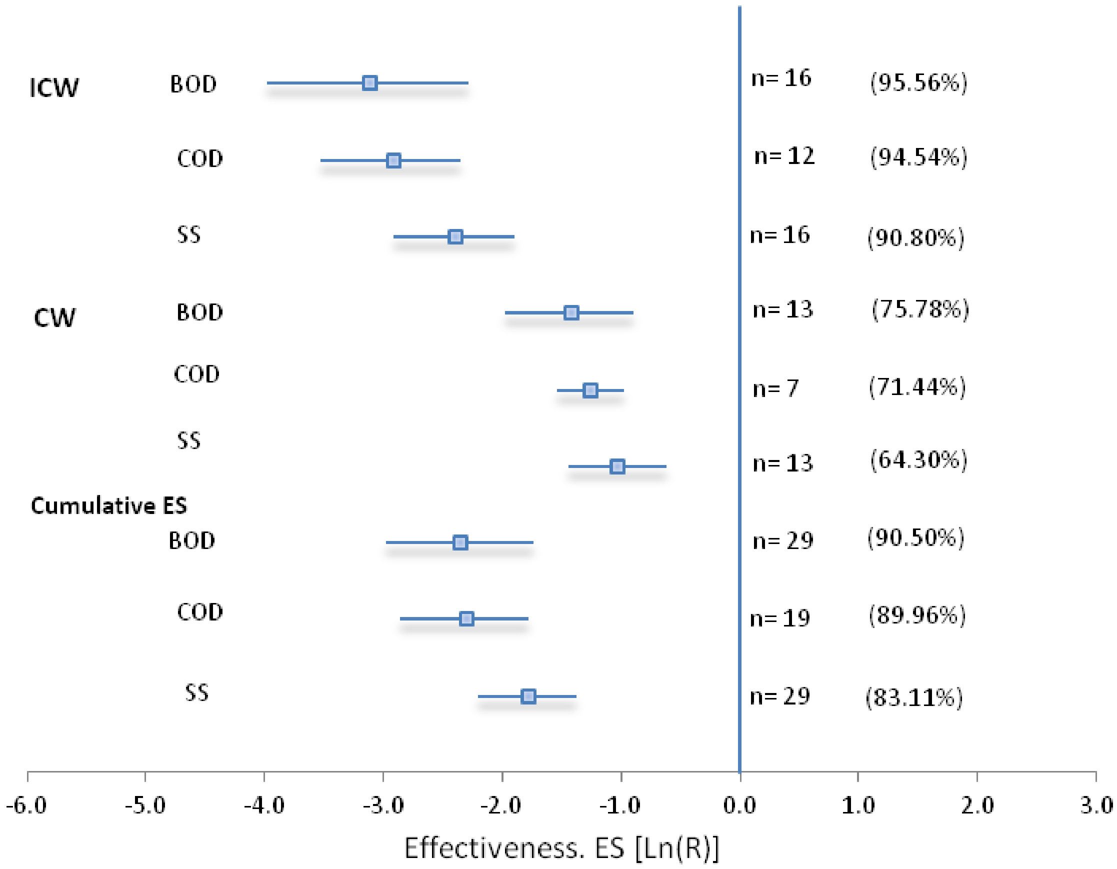


Figure 13 is a summary of the data for BOD, COD and SS. It shows the response ratio effect size (ES) for BOD (biological oxygen demand), COD (chemical oxygen demand) and SS (suspend solid) in different types of wetland system (data points: mean) and the bars are 95% confidence intervals (CIs). The numbers in parentheses represent the percentage of reduction. In order to make the effect size results easier to interpret the sample size of different groups is given next to the percentage of nitrogen species (n). Means (data points) are significantly different when their CIs do not overlap and negative ES means reduction and positive increase. Sample size < 2 are excluded from this analysis. Type of wetlands: constructed wetland (CW), integrated constructed wetland (ICW).

Figure 13 shows that ICWs are more effective at removing BOD, COD and SS than CW systems, by an order of 15 – 20 % more effective

6. Additional Benefits

None of the studies included sufficient data on implications for greenhouse gas emissions, or on other ecosystem service provision, such as biodiversity, recreation or flood control. It has been assumed that all wetlands are likely to provide some other ecosystem services and therefore, combined with nutrient processing capabilities, they should all be considered a positive landscape element.

7. Discussion

The data synthesised in this SR suggest that on farm wetlands do have a very positive impact in terms of reducing nutrients, SS, COD and BOD. On farm wetlands reduce ammonium and ammonia, total nitrogen, soluble reactive phosphate, total phosphorus and both chemical oxygen demand and biological oxygen demand.

There were clear relationships between wetland types and removal efficiencies as expressed on forest plots associated with each analyte. Constructed on farm wetlands with horizontal sub surface flow are the most effective type of systems in this landscape setting.

On farm wetlands in this SR have little or no effect on nitrite, but some wetlands systems do have a slight positive benefit for nitrate, in most studies used in the SR, input loads were very small for nitrate, and even quite small increases due to nitrification process leads to very large percentage differences. The most effective method of removing nitrate found in this SR was that of an overland flow and soil drainage system described in Blackwell *et al.* (1999). Consideration should be given to incorporating a section of overland flow before discharge to receiving waters, in order to allow soil denitrification processes to reduce nitrate loading.

Suspended solids are reduced, and the efficiency of removal of suspended solids is related to wetland area, and consequently flow rate, allowing for increase time for suspended solids to settle out. Small areas with high loadings are not very efficient at removal of suspended solids, and there appears to be a minimum size at which 80% removal rates are always achieved of approximately 2,500 m^2. Suspended solids removal is related to removal of total P as most P is sediment bound.

Biological oxygen demand and chemical oxygen demand are both always reduced by passage through on-farm wetlands. However, the discharge limits of a maximum of 9 mg l^{-1} proposed by the UK TAG is exceed in all studies in the SR for COD and reached by only four studies in the case of BOD. It is clear that further storage or oxygenation of effluent is required to reduce both BOD and COD from on farm wetland systems before they comply with discharge consent limits. This is compounded by the type of watercourse into which most farm wetland systems discharge, often being small, slow flowing or temporarily stagnant ditch systems, which would be adversely affected by this type of discharge.

Reductions in other nutrients often resulted in compliance with discharge limits, e.g. mass loads of less than 1 kg P Ha^{-1} were achieved in about half of the studies selected for analysis in the SR. There are no limits in place for ammonium at the moment, but the proposed maximum limit set by the UK Theme Advisory Group[4] of 2.5 mg l^{-1} was exceeded by only 10 of 36 studies. These were in single pass systems (no recirculation) with very high input loads and the mean reduction in these systems was only 43% when compared with an average reduction value for ammonium of 79% in the other studies that resulted in compliant outputs of less than 2.5 mg $^{-1}$.

To compare the results from the different studies, we used articles that reported hydraulic loading rates to calculate mass load values for individual analytes. We then log transformed the data to further reduce the scaling issues presented by variable input loads. This allowed a comparison of treatment efficiencies on an area performance basis. However, as most observers understand percentage values we used percentage reduction values to express the performance of each wetland study number to give a percentage reduction value. This worked well for most analytes, but as previously stated, the very low input values for nitrate caused some problems for percentage reductions. We recommend that as much data as possible are reported for future studies, especially input and output loads as these are valuable for calculating mass transport and potential concentrations in receiving waters. Where hydraulic measurements were reported in papers and article, there was no method of assigning a quality score to these, as most were expressed as daily mean values, without any reference to storm surge events or prolonged periods of low flow.

In cases where the hydraulic retention time was insufficient to achieve good reduction of nutrients, there might be a case for either installing recirculation systems or having a bypass system increase the total volume of the wetland in periods of high flow, a sort of summer / winter variable state. Higher flows in winter would be re-circulated or diverted to additional treatment wetlands to increase the time exposed to the treatment area. The additional area would have residual habitat value and would provide additional ecosystem services both when in operation and when unused (e.g. bird besting, buffer strip).

4 http://www.wfduk.org/sites/default/files/Media/Environmental%20standards/Environmental%20standards%20phase%201_Finalv2_010408.pdf

In order to understand the functioning of wetland systems continuous monitoring is required. Monitoring of input loads (concentrations and flow rates) is very important, as is monitoring of these at the outlet. This is required to optimise the functioning of the wetland system. Each system has a design capacity for treatment of various nutrient types, and if these are not monitored, then the performance of the wetland cannot be expected to be optimised. They are not "fit and forget" options. They are delicate machines and should be maintained with similar care and attention. This SR has shown that on-farm wetlands function well in terms of removal of most target nutrient inputs, but a clear understanding of the input material is required at the design stage to ensure optimum treatment capacity is maintained. The key message from this SR is that on-farm wetlands should be as large as possible to reduce hydraulic loading rates, which increase treatment efficiencies.

For future SRs, it is important to consider how the restriction criteria will determine the number of papers reviewed and the implications for statistical analysis. In this study the Steering Group recommended reviewing only studies in GB and Ireland. In transpired that many of the studies used data from the same wetland, with several groups of papers using exactly the same data. Excluding duplicates had the effect of limiting significantly the number of studies available to the systematic review process. The reason for limiting the geographical area in the protocol was a concern that there would be an unacceptably high number of relevant papers, this has not been the case. The value of increasing the data pool for the SR would have made statistical analysis more robust, and more relevant conclusions could have been drawn. A larger database would have allowed for additional assessment criteria to refine available material for the exact requirements of the SR. However, the limited amount of data available to us did not prevent an assessment of the majority of wetland types, a comparison between field scale and pilot scale systems and there were sufficient studies with good experimental design and sufficient replicates to make the data analysis robust and reliable.

8. Lessons Learnt

A complication arose during the Systematic Review process when the ISI Web of Knowledge changed the interface and the way references were presented and prioritised. On running the search terms in Table 3, originally run in January 2013 again in December 2013, a different number of references were retrieved. This was not accounted for by additional papers published in the intervening time period. In addition to this, the Ockenden *et al.* paper was not included in the search terms, even at the first level when run again in December 2013.

The majority of articles were retrieved by only one search engine. It may be possible to reduced the search effort to a single search engine if accepted by the expert panel. Additional references could be provided by the expert panel if they think that there is a significant contribution to be made from this source.

It does not appear to make a lot of difference as to how many studies are included in the SR as long as they comply with the inclusion and exclusion criteria. We would recommend that a minimum number of studies should be included in order to undertake robust statistical meta – analysis of the data available, perhaps a minimum of three representative scenarios for each analyte or factor should be recommended. Single data points or observations are likely to lead to a misunderstanding of the processes involved, and a loss of context of the range of responses.

9. References

ACREMAN, M. C., HARDING, R. J., LLOYD, C., MCNAMARA, N. P., MOUNTFORD, J. O., MOULD, D. J., PURSE, B. V., HEARD, M. S., STRATFORD, C. J. & DURY, S. J. 2011. Trade-off in ecosystem services of the Somerset Levels and Moors wetlands. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques,* 56**,** 1543-1565.

BIDDLESTONE, A. J., GRAY, K. R. & JOB, G. D. 1991a. TREATMENT OF DAIRY FARM WASTEWATERS IN ENGINEERED REED BED SYSTEMS. *Process Biochemistry,* 26**,** 265-268.

BIDDLESTONE, A. J., GRAY, K. R. & THURAIRAJAN, K. 1991b. A BOTANICAL APPROACH TO THE TREATMENT OF WASTEWATERS. *Journal of Biotechnology,* 17**,** 209-220.

BLACKWELL, M. S. A., HOGAN, D. V. & MALTBY, E. 1999. The use of conventionally and alternatively located buffer zones for the removal of nitrate from diffuse agricultural run-off. *Water Science and Technology,* 39**,** 157-164.

BRASKERUD, B. C., TONDERSKI, K. S., WEDDING, B., BAKKE, R., BLANKENBERG, A. G. B., ULEN, B. & KOSKIAHO, J. 2005. Can constructed wetlands reduce the diffuse phosphorus loads to eutrophic water in cold temperate regions? *Journal of Environmental Quality,* 34**,** 2145-2155.

BULLOCK, A. & ACREMAN, M. 2003. The role of wetlands in the hydrological cycle. *Hydrology and Earth System Sciences,* 7**,** 358-389.

COLLABORATION FOR ENVIRONMENTAL EVIDENCE 2013 *Guidelines for Systematic Review and Evidence Synthesis in Environmental Management*. Version 4.2. Environmental Evidence: www.environmentalevidence.org/Authors.htm/Guidelines 4.2.pdf

CLIFFORD, E., RODGERS, M. & DE PAOR, D. 2008. Dairy washwater treatment using a horizontal flow biofilm system. *Water Science and Technology,* 58**,** 1879-1888.

DUNNE, E. J., CULLETON, N., O'DONOVAN, G., HARRINGTON, R. & OLSEN, A. E. 2005. An integrated constructed wetland to treat contaminants and nutrients from dairy farmyard dirty water. *Ecological Engineering,* 24**,** 221-234.

EDWARDS, A. C. & WITHERS, P. J. A. 2008. Transport and delivery of suspended solids, nitrogen and phosphorus from various sources to freshwaters in the UK. *Journal of Hydrology,* 350**,** 144-153.

ENVIRONMENT AGENCY (2012) Freshwater Eutrophication: A nationally significant water management issue. http://www.geostore.com/environmentagency/Freshwater_Eutrophication_Briefing_Note_December_2012.pdf

EU 2000 European Parliament and the Council of the European Union. Directive 2000/60/EC. Establishing a framework for community action in the field of water policy.

FALLOWFIELD, H. J., MARTIN, N. J. & CROMAR, N. J. 1999. Performance of a batch-fed High Rate Algal Pond for animal waste treatment. *European Journal of Phycology,* 34**,** 231-237.

FISHER, J. & ACREMAN, M. C. 2004. Wetland nutrient removal: a review of the evidence. *Hydrology and Earth System Sciences,* 8**,** 673-685.

FORBES, E. G. A., FOY, R. H., MULHOLLAND, M. V. & BRETTELL, J. L. 2011. Performance of a constructed wetland for treating farm-yard dirty water. *Water Science and Technology,* 64**,** 22-28.

FORBES, E. G. A., FOY, R. H., MULHOLLAND, M. V. & WOODS, V. B. 2009. The performance of a five pond Constructed Wetland for the bioremediation of farm effluent. Preliminary findings on the performance, efficiency and sustainability of the CAFRE constructed wetland system. *Occasional Publication No. 9.* Agri-food and Biosciences Institute.

GOURIVEAU, F. 2009. *Constructed farm wetlands designed for remediation of farmyard runoff: an evaluation of their water treatment efficiency, ecological value costs and benefits.* The University of, Edinburgh.

GUREVITCH J, HEDGES LV (2001) Meta-analysis: combining the results of independent experiments. In: Scheiner SM, Gurevitch J (eds) *Design and analysis of ecological experiments*. Oxford University Press, NY, pp 347–369

HARRINGTON, C. & SCHOLZ, M. 2010. Assessment of pre-digested piggery wastewater treatment operations with surface flow integrated constructed wetland systems. *Bioresource Technology,* 101**,** 7713-7723.

HARRINGTON, C., SCHOLZ, M., CULLETON, N. & LAWLOR, P. G. 2012. The use of integrated constructed wetlands (ICW) for the treatment of separated swine wastewaters. *Hydrobiologia,* 692**,** 111-119.

HARRINGTON, R., CARROLL, P., COOK, S., HARRINGTON, C., SCHOLZ, M. & MCINNES, R. J. 2011. Integrated constructed wetlands: water management as a land-use issue, implementing the 'Ecosystem Approach'. *Water Science and Technology,* 63**,** 2929-2937.

HAYGARTH, PM, HEATHWAITE, AL, JARVIS, SC AND HARROD, TR (2000) ‘Hydrological factors for phosphorus transfer from agricultural soils’, *Advances in Agronomy*, 69, 153-178. 33

HEATHWAITE, A. L., JOHNES, P. J. & PETERS, N. E. 1996. Trends in nutrients. *Hydrological Processes,* 10**,** 263-293.

HEDGES LV, GUREVITCH J, CURTIS PS (1999) The meta-analysis of response ratios in experimental ecology. *Ecology* 80:1150–1156

HU, Y. S., KUMAR, J. L. G., AKINTUNDE, A. O., ZHAO, X. H. & ZHAO, Y. Q. 2011. Effects of livestock wastewater variety and disinfectants on the performance of constructed wetlands in organic matters and nitrogen removal. *Environmental Science and Pollution Research,* 18**,** 1414-1421.

LAJEUNESSE, M. & FORBES, M. (2003). Variable reporting and quantitative reviews: a comparison of three meta-analytical techniques. *Ecological Letters*, 6, 448–454.

MACKENZIE, S. M. & MCILWRAITH, C. I. 2013. Constructed farm wetlands - treating agricultural water pollution and enhancing biodiversity. WWT.

MALTBY, E. 2009. *Functional assessment of wetlands: Towards evaluation of ecosystem services*, Elsevier.

MCCARTNEY, M. P., STRATFORD, C., NEAL, C., BRADFORD, R., MILLS, S. & JOHNSON, M. 2003. Seasonality and water quality trends in a maturing recreated reed bed. *Science of the Total Environment,* 314**,** 233-254.

MILLER, J., COUGHLIN, D., KIRK, S. 2013 Guidance document for production of Quick Scoping Reviews and Rapid Evidence Assessments. Joint Water Evidence Group, Defra, London

MITSCH, W.J., GOSSELINK, J.G. 2000 Wetlands, 4th Edition, Wiley 600 pp

MOIR, S. E., SVOBODA, I., SYM, G., CLARK, J., MCGECHAN, M. B. & CASTLE, K. 2005. An experimental plant for testing methods of treating dilute farm effluents and dirty water. *Biosystems Engineering,* 90**,** 349-355.

MORSE, G. K., LASTER, J. N., AND PERRY, R. (1993) The economic and environmental impact of phosphorus removal from wastewater in the European Community. Selper Publications, London

MUSTAFA, A. 2010. *Nutrient removal with integrated constructed wetlands : microbial ecology and treatment performance evaluation of full-scale integrated constructed wetlands.* The University of Edinburgh.

MUSTAFA, A., SCHOLZ, M., HARRINGTON, R. & CARROLL, P. 2009. Long-term performance of a representative integrated constructed wetland treating farmyard runoff. *Ecological Engineering,* 35**,** 779-790.

NATIONAL ECOSYSTEM ASSESSMENT 2011 The UK National Ecosystem Assessment. Technical Report. UNEP-WCMC Cambridge.

OCKENDEN, M. C., DEARY, M., QUINTON, J. N., FAVARETTO, N. & STOATE, C. 2012a. Reducing diffuse pollution in agricultural catchments: retention of sediment and nutrients in field wetlands. *British Hydrological Society Eleventh National Symposium proceedings.***,** 1-5.

OCKENDEN, M. C., DEASY, C., QUINTON, J. N., BAILEY, A. P., SURRIDGE, B. & STOATE, C. 2012b. Evaluation of field wetlands for mitigation of diffuse pollution from agriculture: Sediment retention, cost and effectiveness. *Environmental Science & Policy,* 24**,** 110-119.

OCKENDEN, M. C., DEASY, C., QUINTON, J. N., FAVARETTO, N. & STOATE, C. Reducing diffuse pollution in agricultural catchments: retention of sediment and nutrients in field wetlands. *In:* SOCIETY, B. H., ed. BHS Eleventh National Symposium, Hydrology for a changing world, 2012c Dundee.

PANGALA, S. R., REAY, D. S. & HEAL, K. V. 2010. Mitigation of methane emissions from constructed farm wetlands. *Chemosphere,* 78**,** 493-499.

PARKES, M. E., MCBRIDE, A. D. & WAALKENS, A. 1998. Treatment of dilute piggery effluent with vertical flow reed beds. *Journal of Environmental Quality,* 27**,** 783-788.

REDDING, T., TODD, S. & MIDLEN, A. 1997. The treatment of aquaculture wastewaters - A botanical approach. *Journal of Environmental Management,* 50**,** 283-299.

REYNOLDS, C. AND DAVIES, P. (2001) Sources and bioavailability of phosphorus fractions in freshwaters: a British perspective. *Biological Reviews of the Cambridge Philosophical Society*, 76, 27-64.

RUANE, E. M., MURPHY, P. N. C., HEALY, M. G., FRENCH, P. & RODGERS, M. 2011. On-farm treatment of dairy soiled water using aerobic woodchip filters. *Water Research,* 45**,** 6668-6676.

SCHOLZ, M., HARRINGTON, R., CARROLL, P. & MUSTAFA, A. 2007a. The Integrated Constructed Wetlands (ICW) concept. *Wetlands,* 27**,** 337-354.

SCHOLZ, M., HARRINGTON, R., CARROLL, P. & MUSTAFA, A. 2010. Monitoring of nutrient removal within integrated constructed wetlands (ICW). *Desalination,* 250**,** 356-360.

SCHOLZ, M., SADOWSKI, A. J., HARRINGTON, R. & CARROLL, P. 2007b. Integrated Constructed Wetlands assessment and design for phosphate removal. *Biosystems Engineering,* 97**,** 415-423.

SHURIN JB, BORER ET, SEABLOOM EW, ANDERSON K, BLANCHETTE CA, COOPER SD, HALPERN BS (2002) A cross-ecosystem comparison of the strength of trophic cascades. *Ecological Letters* 5:785–791.

STIRLING P, CORNELISSEN T (2005) What makes a successful biological control agent? A meta-analysis of biological control agent performance. *Biological Control* 34:236–246

STRATFORD, C. J., DUENAS, M., BOWES, M., PALMER-FELGATE, E. J. & MACKENZIE, S. 2010. 10 years on: How the nutrient removal performance of a treatment reed bed changes with time. *2nd Irish International Conference on Constructed Wetlands for Wastewater Treatment and Environmental Pollution Control.* Dublin, Ireland: Conference Proceedings

SUN, G., GRAY, K. R., BIDDLESTONE, A. J., ALLEN, S. J. & COOPER, D. J. 2003. Effect of effluent recirculation on the performance of a reed bed system treating agricultural wastewater. *Process Biochemistry,* 39**,** 351-357.

SUN, G., ZHAO, Y., ALLEN, S. & COOPER, D. 2006. Generating "tide" in pilot-scale constructed wetlands to enhance agricultural wastewater treatment. *Engineering in Life Sciences,* 6**,** 560-565.

SURRIDGE, B. W. J. 2004. *Biogeochemical and hydrological controls on phosphorus transport in a floodplain fen*. University of Sheffield.

VERHOEVEN, J. T. A., ARHEIMER, B., YIN, C. & HEFTING, M. M. 2006. Regional and global concerns over wetlands and water quality. *Trends in Ecology & Evolution,* 21**,** 96-103.

WITHERS, PJA, EDWARDS, AC AND FOY, RH (2001) 'Phosphorus cycling in UK agriculture and implications for phosphorus loss from soil', *Soil Use and Management,* 17, 139-149.

WOOD, J., FERNANDEZ, G., BARKER, A., GREGORY, J. & CUMBY, T. 2007. Efficiency of reed beds in treating dairy wastewater. *Biosystems Engineering,* 98**,** 455-469.