A Review of the Role of Agricultural Ponds in England

Climate change and biodiversity risks and opportunities

September 2023

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Foreword

This report was commissioned to strengthen Natural England's evidence base on the contribution of habitats towards tackling the climate and biodiversity crises. The requirement was to further explore the available evidence surrounding agricultural ponds, their importance for biodiversity and their potential to mitigate against and adapt to a changing climate. The risks and opportunities of each were assessed, including where management may jointly benefit biodiversity and climate change and where conflicts may arise. This research will further be used to build a robust set of recommendations for the management of new and existing ponds, with both climate change and biodiversity in mind.

Natural England commission a range of reports from external contractors to provide evidence and advice to assist us in delivering our duties. The views in this report are those of the authors and do not necessarily represent those of Natural England.

Executive summary

This report reviews the evidence base surrounding agricultural ponds and the opportunities they can provide for enhancing biodiversity and their potential for carbon sequestration to mitigate against climate change. The report highlights:

- Current number of agricultural ponds (latest estimates are between 400,000 – 500,000 ponds across UK, with 5% as seasonal, 25% as semi permeant and 70% as permanent ponds) across England and the UK and estimates of ponds lost over the last century (50% decline since 1900).
- The type and extent of ecosystem services provided by agricultural ponds including carbon sequestration, biodiversity, and hydrological management.
- The role that ponds play in the carbon cycle, including their capacity for long-term storage of carbon and the drivers behind this.
- Climate change risks that agricultural ponds will face. This includes an increased occurrence of long dry periods causing ponds to dry out, increased sediment flow into ponds through intense summer storms, increased maximum air temperatures, increased frequency of invasive species and general species migration
- Current best practice guidance for restoration and general management.
- Case studies of successful pond management and restoration projects.

After reviewing a range of published academic literature, it can be summarised that ponds within an agricultural landscape can be of great benefit to supporting and enhancing the species abundance and diversity of both flora and fauna. The carbon sequestration potential of ponds is highly variable and is dependent on many factors including depth of water column, presence or absence of aquatic vegetation, water temperature and size of waterbody. All ponds tend to undergo carbon fluxes over time and net storage may only be evident after several years. Management practices for biodiversity enhancement purposes may not always be compatible with management for maximum carbon storage.

When assessing a pond's need for management, it is important to consider the unique characteristics of the pond within the context of the wider landscape. If the pond is situated

within the vicinity of other ponds, then it forms part of a “pondscape,” and individual pond management options should be considered within the context of the condition of neighbouring ponds. It is more beneficial for a pondscape to contain ponds at differing successional stages in order to meet the requirements of the greatest diversity of species.

Terrestrialised (ponds that are fully terrestrialised) and temporary ponds are overlooked and undervalued in terms of their biodiversity provision, and more research is needed on their role in the carbon cycle. The impact of climate change on ponds needs further research as this is an area that is lacking in evidence, although impacts are likely to include changes in species assemblages and more frequent drying-out.

To summarise, the presence of ponds in an agricultural landscape can be of great benefit to enhancing local biodiversity. Ponds undergo a carbon flux of storage and emission, and more long-term research is required to fully understand their role in carbon sequestration for climate mitigation purposes. Prior to management, a pond should be surveyed and its role within the wider pondscape considered.

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1 Introduction

Natural England have commissioned an up-to-date literature review on agricultural ponds and their role in the wider landscape. The report will focus on the following key areas:

- Review of latest estimates of agricultural ponds across England and UK and numbers lost over the past 50 – 100 years.
- Review of existing evidence-base of the type and extent of ecosystem services provided by agricultural ponds including carbon sequestration, biodiversity, and hydrological management.
- Review of the role that ponds play in the carbon cycle, including their capacity for long-term storage of carbon and the drivers behind this.
- Highlight climate change risks that agricultural ponds will face, and what management practices can be used to help mitigate against these impacts.
- Review best practice guidance for restoration and general agricultural pond management.
- Case studies of successful pond management and restoration projects

The report will summarise findings from peer-reviewed journal articles as well as grey guidance literature. This report will be used by Natural England to make further decisions on best practice guidance in the context of biodiversity and climate change and inform decisions on the inclusion of agricultural ponds to future government agri-environmental initiatives.

1.1 Methodology

1.1.1 Academic Literature

To assess the scope of the available academic literature, a systematic literature review approach was conducted using Google Scholar. The search terms used in this search are given in table 1. Multiple search terms were used to find appropriate literature. When it was found that returned papers were being repeated, the search was terminated.

The timeframe over which literature was to be considered in the review was left open ended, any data considered relevant to the research questions posed was considered.

Table 1: Search terms used in Google Scholar.

Row	1	2	3	4	Total Results	Page number reached	Title number reached on page	Number of titles scanned	Complete?	Comment
1	England	Agricultural	Ponds	Carbon	48,500	8	10	80	Yes	
2	England	Agricultural	Ponds	Biodiversity	42,200	6	10	60	Yes	
3	England	Agricultural	Ponds	Water	172,000	6	10	60	Yes	Similar/less relevant. One new paper found
4	England	Agricultural	Ponds	Climate Change	111,000	9	10	90	Yes	
5	England	Agricultural	Ponds	Restoration	48,600	10	10	100	Yes	Similar/less relevant. Only a few papers found
6	England	Agricultural	Ponds	Management	140,000	7	10	70	Yes	Similar/less relevant. Only a few papers found
7	England	Agriculture	Ponds	Carbon	50,100	10	10	100	Yes	Similar/less relevant. No new papers found

Row	1	2	3	4	Total Results	Page number reached	Title number reached on page	Number of titles scanned	Complete?	Comment
8	England	Agriculture	Ponds	Biodiversity	42,400	11	10	110	Yes	Similar/less relevant. Only a few papers found
9	England	Agriculture	Ponds	Water	183,000	6	10	60	Yes	Similar/less relevant. No new papers found
10	England	Agriculture	Ponds	Climate Change	112,000	10	10	100	Yes	Similar. One new paper found
11	England	Agriculture	Ponds	Restoration	49,600	5	10	50	Yes	Similar/less relevant. No new papers found
12	England	Agriculture	Ponds	Management	156,000	6	10	60	Yes	Repeated papers
13	England	Agricultural	Ponds		48,500	10	10	100	Yes	Similar/less relevant. No new papers found
14	England	Agriculture	Ponds		173,000	13	10	130	Yes	

Row	1	2	3	4	Total Results	Page number reached	Title number reached on page	Number of titles scanned	Complete?	Comment
15	England	Farm	Ponds		132,000	9	10	90	Yes	Similar/less relevant. Heavy focus on fish ponds
16	England	Farm	Ponds	Carbon	36,200	10	10	100	Yes	Similar/less relevant. No new papers found. Heavy focus on fish ponds
17	England	Farm	Ponds	Biodiversity	29,200	6	10	60	Yes	Similar/less relevant
18	England	Farm	Ponds	Water	113,000	5	10	50	Yes	Similar/less relevant. One new paper.
19	England	Farm	Ponds	Climate Change	80,300	11	10	110	Yes	Similar. One new paper found

Row	1	2	3	4	Total Results	Page number reached	Title number reached on page	Number of titles scanned	Complete?	Comment
20	England	Farm	Ponds	Restoration	37,600	7	10	70	Yes	Similar/less relevant. No new papers found
21	England	Farm	Ponds	Management	83,100	5	10	50	Yes	Similar/less relevant. No new papers found

In total, 159 academic papers were identified as being relevant to this review. These were spilt into three relevance categories (highly, somewhat, and maybe relevant). In total, 73 academic papers were read in full for the purposes of this review and summaries of these papers were produced. Additional papers were skim read for relevant data.

1.1.2 Grey literature

Grey literature was also reviewed, with a total of 19 articles being included in the database. Many other sources were scanned but showed a high degree of similarity with the reviewed articles and so the decision was taken to focus on the key sources.

1.1.3 Database

A database was created with all relevant information to track academic and grey literature. This database will be provided to Natural England in Attachment 1 and contains the list of search terms used. Academic literature summaries are provided in Attachments 2 and 3.

1.1.4 Ecosystem Services

Ecosystem Services were defined by the Millennium Ecosystem Assessment (MA) in their framework for assessment (Millennium Ecosystem Assessment, 2003) as “the benefits people derive from ecosystems” and cover a wide range of goods and services. The MA further delineated these goods and services into 4 broad categories.

Supporting Services: Services necessary for the production of all other ecosystem services such as soil formation, nutrient cycling, primary production.

Provisioning Services: Products obtained from ecosystems such as food, fresh water, fuelwood, fibre, biochemicals and genetic resources.

Regulating Services: Benefits obtained from regulation of ecosystem processes such as climate regulation, disease regulation, water regulation, and water purification.

Cultural Services: Nonmaterial benefits obtained from ecosystems such as spiritual and religious fulfilment, recreation and ecotourism, aesthetics, inspiration, education, sense of place and heritage.

Agricultural ponds provide a number of ecosystem services for the wider landscape (Biggs, von Fumetti and Kelly-Quinn, 2017a) which can include:

- Providing a water source for livestock (**provisioning**)
- Providing a habitat for a wide variety of species, and habitat diversity (**supporting**)
- Increasing landscape-scale biodiversity (**supporting**)
- Acting as pollutant and sediment traps (**regulating**)
- Forming part of Natural Flood Management schemes within a landscape (**regulating**)

- Providing visual enjoyment for people (**cultural**)
- Providing fish stocks for recreational use (**provisioning**)
- Playing an important role in carbon cycling (**regulating**)

This literature review focuses on a subset of these ecosystem services and examines the evidence concerning the capacity of agricultural ponds to offer them; to increase biodiversity (**supporting**), influence the carbon cycle (**regulating**), and manage flooding, silt and nutrient loads (**regulating**). Often the provision of one ecosystem service has the potential to be at the expense of the availability of another. Therefore, careful consideration must be given to what services a pond is expected to provide when considering its role and management within a wider landscape.

1.2 Definition and importance of agricultural ponds

There is no single universal definition of an agricultural pond or even for what size of waterbody constitutes a "pond." One of the most used definitions of a pond is:

"a small body of water, between 1m^2 and 2ha in area, which usually holds water for at least four months of the year" (Pond Conservation Group 1993).

The UK Biodiversity Action Plan Priority Habitat Descriptions (2011) describes ponds as:

"Permanent and seasonal standing water bodies up to 2ha in extent".

Other definitions of ponds exist. For example, the lower boundary has been increased to a minimum area of 25m^2 (Williams et al., 2010; Hill et al., 2016) and in other cases, the upper boundary increased to 5ha (Richardson et al., 2022). This variation in the definition of a "pond" is one of the reasons why it is difficult to compare data and estimate the total number of ponds present across a large area. For the purposes of this report, the standard Pond Conservation Group definition will be used.

Agricultural ponds, are by definition, located on agricultural land. There are many types of agricultural pond often created for a variety of different reasons. Some can be also natural depressions or scours created on flood plains, with temporary or ephemeral characteristics. Table 2 provides a summary of common agricultural pond types in the UK.

Table 2: Provides a summary of common agricultural pond types in the UK.

Type of pond	Characteristics	Common locations
Old excavations (e.g., marl pits, historical and recreation areas)	Usually, historical removal of clay for building or fertiliser. Location picked due to proximity to the destination or supply of clay.	Norfolk and Cheshire (marl pits), historical features widespread

Type of pond	Characteristics	Common locations
Dewponds – livestock watering	Small ponds created on high ground to provide drinking supply to livestock. Ponds often lined with clay or stone with an insulating layer of straw to retain water.	Downlands of Yorkshire, Derbyshire, and Southern England
Natural depressions	Shallow depressions within landscape. Often within floodplains or glacial in origin.	Previously widespread – infilled as agricultural practices intensified, and as land use changed
Recreation and biodiversity	Created for specific aims e.g., conservation, shooting, stocking fish, boating or aesthetic	Widespread

Ponds have the potential to be biodiversity hotspots and are an important component of a diverse agricultural landscape (Jeffries, 2016). However, they are historically under-surveyed, overlooked and misunderstood by both researchers and policy makers (Biggs et al., 2005a; Downing, 2008). This includes being overlooked by the EU Water Framework Directive which only applies to waterbodies larger than 50ha (Miracle et al., 2010)

2 Current situation

2.1 Decline of agricultural ponds

Despite often being created for agricultural purposes, ponds have been and continue to be lost due to agricultural intensification and arable land reclamation, lack of management and urban development (Hassall, 2014; Sayer, 2014; Quigley, 2017). There is also no specific legislation in place to prevent infilling of ponds (Sayer, 2014). Within England there are no restrictions on pond infilling within the Cross Compliance rules attached to agricultural support payments, as there are in Wales, though such actions may be covered by the EIA (Agriculture) Regulations. Certain engineering operations including the importation of waste would fall within the scope of requiring planning permission.

It is difficult to quantify the number of agricultural ponds that have been lost in England due to infilling and removal. There are many reasons for this, including that there is not a globally accepted definition on what size of waterbody constitutes a “pond,” variations in study method and timeframe, and reasons for loss not being known or recorded.

Additionally, the majority of ponds are very small (less than one hectare) which can make them difficult to map and identify from satellite images (Lehner and Doell, 2004; Verpoorter et al., 2014), and seasonality of ponds may mean that many are missed if recording occurs during dry periods. However, recent estimates place agricultural pond loss at around 50% since 1900, with most of this loss caused by infilling due to agricultural consolidation (Hassall, 2014).

Table 3 provides a summary of recent estimates of pond loss (or gain) in selected English counties, England, and the UK since the 1800s.

Table 3: Pond numbers over time in the selected counties, England, and the UK

Time period	Location	Percentage loss/gain	Pond numbers	Reference
1800s – 1980s	UK	**Loss:** c.75%	c.800,000 – c.200,000	(Jeffries, 2012)
1984 – 1990	UK	**Loss:** 4% - 11.5%	[none]	(Barr, Howard and Benefield, 1994)
1880 – 2000	UK	**Loss:** 67.9%	1,200,000 – 385,769	(Biggs et al., 2005a)
1948 – 2000	UK	**Loss:** 18.4%	473,000 – 385,769	(Biggs et al., 2005a)
1998 – 2007	UK	**Gain:** +12.5%	425,000 – 478,000	(Williams et al., 2010)
1998 – 2007	England	**Gain:** +18.3%	197,000 – 234,000	(Williams et al., 2010)
1860 – 2008	Southeast Northumberland	**Gain:** +15.7% But 199 original ponds lost	222 – 257 Only 23 original ponds remained	(Jeffries, 2012)
1870 – 1990	Cheshire	**Loss:** 61%	41,564 – 16,210	(Boothby and Hull, 1997)
1900 – 2019	Severn Vale catchment	**Loss:** 57.7% Accounting for	10,833 – 6,628	(Smith et al., 2022)

Time period	Location	Percentage loss/gain	Pond numbers	Reference
		pond creation: 38.8% loss	(2,048 newly created)	

The figures in Table 3 show that in addition to considering pond loss and pond gain, it may also be necessary to consider pond turnover (overall gain due to pond creation, but a loss of historical ponds) and the process of natural succession of ponds.

Regional estimates of pond loss have varied between 47% and 85% depending on the location studied and timescale analysed (Smith et al., 2022). Loss of individual ponds contributes to the loss of wider pond “clusters” (Gibbs, 2000), impacting species colonisation, population resilience and genetic diversity, which can lead to further decline.

2.2 Estimations of pond numbers

The 2007 Countryside Survey report estimated that there are 478,000 “contemporary” ponds in Great Britain, with 234,000 of these being in England (Williams et al., 2010). It is important to note that this figure includes ponds from a range of landscapes, including woodlands and golf courses, not just from agriculture. This figure represents an increase of 12.5% from 1998 to 2007 across Great Britain, and a 18.3% increase across England.

There was a loss of 18,000 ponds in Great Britain over the same period, but a gain of 70,600, resulting in an overall increase. Most of these losses were from England (14,900 lost, 48,300 gained). The majority (70%) of ponds recorded were small, between 25m^2 to 400m^2. The 2007 Countryside Survey report does not include ponds smaller than 25m^2 so an additional significant number of ponds may be missing from the data. It is likely that there are more ponds present on the ground than can be identified on maps and using satellite technology (Jeffries, 2016).

Pond estimates using Natural England’s ‘Living Pond Layer’ which uses Ordnance Survey (OS) data, estimates the number of water bodies between 0 – 10,000m^2 between 409,082 – 444,717 on land classified as ‘Agricultural’ or between 297,943 – 323,343 on land classified as UK Centre for Ecology and Hydrology Arable & Horticulture and Improved Grassland. Note upper limits include ponds that were previously on OS maps but were not present on the latest map.

Pond numbers also depend on whether temporary ponds are present at the time of counting. For example, during 2011 and 2012, a survey by Jeffries, M. J., (2016) counted 105 ponds in an area following heavy rainfall, with only 12 of these ponds being present during the time of a drought. The 2007 Countryside Survey calculated that at least 5% of ponds are “seasonal” (drying every year), with around 25% being semi-permanent (drying out in dry years), and the remaining 70% being permanent ponds. Additionally, some ponds across Britain are likely to be heavily “terrestrialised” and therefore may not function as a typical pond.

The recorded increase in ponds can be attributed to a concerted effort to halt the decline of ponds over the last 30 years. Examples of this includes The Million Ponds Project, which has created over 1,000 new ponds across England and Wales between 2008 and 2012 (Pond Conservation, 2012), and the Norfolk Ponds Project, which has restored over 200 ponds since 2014 (Sayer, Hawkins and Greaves, 2022). The agri-environment schemes operational in England in the preceding 20 years up until 2009 restored and maintained 3,440 ponds and created 2,265 new ones (Natural England, 2009).

We have investigated a novel approach to estimating pond numbers in the landscape using nationwide LiDAR data within a terrain modelling software tool called SCALGO. The results of this initial trial method are presented in Appendix 1. Accuracy of pond identification ranged from 53 – 80% and required significant manual analysis. It is therefore recommended to develop this method further and employ the use of artificial intelligence to refine pond identification techniques.

Despite this increase in pond number, the quality of ponds (at least in nature reserves) declined between 1990 and 2016, with 66% of ponds in England having lost plant species and all ponds in England losing, on average, 17% of their wetland plant diversity (Williams, 2018). The 2007 Countryside Survey identified that 58% of ponds in England had phosphorus and/or nitrogen concentrations at levels that were likely to be causing negative pollution impacts (Williams et al., 2010).

3 Academic literature review of ecosystem service provision of agricultural ponds

3.1 Supporting services: Biodiversity

Agricultural ponds play an important role in supporting a large number of species, providing refuges in agricultural landscapes, hosting migratory species and supporting rare aquatic species (Bilton et al., 2009).

3.1.1 General biodiversity benefits of ponds

Agricultural ponds are recognised as biodiversity hotspots and unpolluted ponds have been shown to increase biodiversity in an area by 26% (Williams et al., 2020). Unpolluted, or “clean water” ponds are “offline” – not connected to ditches or streams. This type of pond has been shown to hold a greater species richness and diversity than “online” (connected), and therefore possibly polluted ponds (Williams et al., 2020) reinforcing the importance of good water quality on aquatic biodiversity.

On an individual scale, farmland ponds may support a lower diversity of macroinvertebrates than UK rivers, but when considered on a landscape scale, the “pondscape” across the UK has greater diversity than many other types of aquatic habitats such as rivers, lakes, and ditches. Pondscapes also support more uncommon species (Biggs et al., 2005a; Gilbert et al., 2017). In general, ponds support a wide variety of species, and act as key habitats in a fragmented agricultural landscape (Davies et al., 2008). In one study in Hampshire and Cornwall, most plant and macroinvertebrate species found in agricultural ponds were locally rare, with over 50% occurring in less than 10% of ponds. More than 50% of ponds supported at least one nationally rare plant and 75% at least one nationally rare macroinvertebrate (Bilton et al., 2009).

Table 4 provides an overview of the benefits of agricultural ponds on individual taxa.

Table 4: Benefits of ponds on taxa.

Taxa	Benefits of ponds on taxa	References
Birds	Source of food, water, nesting material and habitat. Provides aquatic invertebrates as a food source which contain higher levels of essential omega-3s than terrestrial invertebrates. Open and closed - canopy ponds support bird species of conservation concern. 55 breeding bird species identified across 22 ponds (managed and unmanaged). Increases the population and diversity of bird species compared to farmed landscapes with no ponds.	(Gee et al., 1997; Davies et al., 2016; Twining et al., 2016; Lewis-Phillips et al., 2020)
Mammals	Used by bats, otter (*Lutra lutra*), water vole (*Arvicola amphibius*), shrews and others for habitat provision, food, and water.	(Riley et al., 2018)
Amphibians	Provides breeding habitat and a food source through the provision of invertebrates. Act as “steppingstones,” aiding in species distribution for local metapopulations	(Knutson et al., 2004; Biggs et al., 2005a)
Invertebrates	Source of food, refuge from predators, and egg-laying sites. Provision of materials for case-building. Submerged and floating aquatic plants used for ovipositing.	(Biggs et al., 1994; E. M. Raebel et al., 2012; Lewis-Phillips et al., 2020; R. E. Walton et al., 2021)
Vegetation	Open-canopy ponds promote flowering species. Increases species diversity including submerged, floating, and emergent plants	(Biggs et al., 1994; Walton, 2019)

Taxa	Benefits of ponds on taxa	References
Molluscs	Greatest population in unmanaged ponds. Provides refuge, food source, habitat.	(Biggs et al., 1994; Davies et al., 2016)
Overall	Provides a habitat refuge and can act as a source of “species colonists” to the wider area	(Chester and Robson, 2013)

3.1.2 Temporary ponds

Agricultural ponds often support specific conditions which are beneficial for certain species or lifecycles. One of the most important characteristics is the ephemeral nature of some ponds, with regular wetting and drying cycles. Known as ‘temporary’ ponds, the chemical and physical variability they experience during wet and dry cycles creates a very distinct habitat (Williams, 1997; Jeffries, 2016).

Temporary ponds are of significant importance for the national biodiversity of invertebrates. Invertebrate species that inhabit both temporary and permanent waterbodies are expected to have an increased genetic diversity and species fitness than those which inhabit only permanent ponds. This is due to the need of the species to adapt to variable conditions and in future, it could be these species which persist under changing climatic conditions (Hogg and Williams, 1996; Williams, 1997).

Some specific benefits of temporary ponds can be seen in Table 5.

Table 5: Specific benefits of temporary ponds.

Benefit to	Importance	References
Natterjack toad (*Epidalea calamita*)	This rare, protected species reproduces in shallow, open, temporary ponds	(Wood, Greenwood and Agnew, 2003)
Fairy shrimp (Chirocephalus diaphanous) & tadpole shrimp (*Triops cancriformis*)	The life cycle of both of these rare species relies on the dry phase of temporary ponds. The eggs of the tadpole shrimp are drought resistant and believed to be the oldest extant species in the world.	(Williams, 1997)

Benefit to	Importance	References
Beetles (*Coleoptera*) and true bugs (*Hemiptera*)	Having overwintered in permanent ponds, temporary ponds provide abundant food source and low competition for egg-laying and development of young	(Williams, 1997)
Migration	Drying of temporary ponds encourages invertebrates to disperse to other waterbodies, encouraging migration and colonisation. Mites passively migrate on the bodies of adult insects.	(Williams, 1997)
Gene fitness	Increased gene fitness than species only persisting in permanent water bodies. Species more resilient to climate change.	(Hogg and Williams, 1996; Williams, 1997)
General	Some species communities favour ephemeral ponds and rely on a dry phase for their lifecycle. Some invertebrate species can become dormant and "dehydrated" in the dry phase and reawaken when water returns	(Hinton, 1960; Biggs et al., 1994; Williams, 1997)

3.1.3 Interactions between species and management

Although agricultural ponds are beneficial for biodiversity, the exact relationship between pond characteristics, successional stage and biodiversity is very complex. Conditions that may be beneficial for one species or community may not be beneficial for another, or the conditions could promote competition between two desirable species (Hassall, Hollinshead and Hull, 2012). For example, conditions required for the rare natterjack toad are incompatible with the presence of rare stoneworts (Beebee, Denton and Buckley, 1996), and great crested newt will predate on the tadpoles of the natterjack toad (Biggs et al., 2001). This is why a diverse pondscape, with ponds present in all different successional stages across a set area, is important. Céréghino et al., (2008) found that mid-successional ponds had a greater species diversity than early or late successional ponds. It is believed that this is due to the increase in floristic diversity (before one or two species become dominant), a mix of both sunny and shaded water (before scrub shades the whole pond), and also due to the limited amount of emergent vegetation, which can reduce invertebrate populations.

A summary of the characteristics of different pond vegetation coverage is provided in Table 6.

Table 6: Characteristics of different pond vegetation types.

Vegetation type	Characteristics	References
Submerged vegetation	Clearer water. Greater flora and fauna diversity. Greater abundance of *Odonata* exuviae.	(Céréghino et al., 2008; E. Raebel et al., 2012)
Floating vegetation	Clearer water. Greater flora and fauna diversity. Greater abundance of Odonata exuviae.	(Céréghino et al., 2008; E. Raebel et al., 2012)
Emergent vegetation	Emergent species can become dominant. Reduced *Odonata* population. Reduced flora species diversity.	(Céréghino et al., 2008; E. Raebel et al., 2012)
Woody vegetation	Encroachment can reduce pond biodiversity. Can be beneficial for some bird species. Shading can protect water from increased warming. Partial shading can increase aquatic plant diversity.	(Gee et al., 1997; Riley et al., 2018; Lewis-Phillips et al., 2019; Walton, 2019)
Vegetation diversity	More diverse pollinator communities. Increased feeding and nesting habitat for birds.	(Davies et al., 2016; Walton, 2019)
Flowering plants	More invertebrate pollinator species and therefore more predators e.g., birds.	(Lewis-Phillips et al., 2020)

In addition to vegetation type, it is important to acknowledge the spatial ecology of ponds when considering pond management for biodiversity benefits. Ponds greater than 100m apart results in a large reduction (40%) in species richness in the individual ponds (Raebel et al., 2012). However, Sayer et al., (2013) found very biodiverse ponds in a landscape with one pond every six hectares, over an area of 243ha. Many small ponds in an area have a more beneficial impact than larger ponds situated further apart from one another (Raebel et al., 2012).

There is discussion and some disagreement over the value of late-successional and terrestrialised ponds (ponds that are fully terrestrialised). The general consensus is that ponds should be actively managed. If not managed ponds can become terrestrialised within 20–30 years, which in turn suggests that ponds have been historically managed by people (R. E. Walton et al., 2021). However, the limited research regarding the importance of terrestrial ponds (and using only a few specific species to determine “value”) means that terrestrial species could be inadvertently lost through pond management (R. E. Walton et al., 2021).

Biggs et al., (1994) strongly advocate retaining all terrestrialised ponds as unique habitats in their own right. Permanent abandonment would lead to eventual terrestrialisation of all ponds, which would negatively affect communities of aquatic fauna. Therefore, it suggested that ongoing creation of new ponds within the locality to provide open-water habitat is actively pursued at the same time (Biggs et al., 1994). In addition, overgrown ponds could be categorised as a type of woodland fragment, which can allow species to disperse between larger parcels of woodland (Davies et al., 2016). Without these fragments, wooded refuges could be completely lost from open agricultural landscapes.

Conversely, whilst the ideal scenario may be to create new ponds and promote a more extensive pondscape, land use pressures mean that this is not viable in many areas (Sayer et al., 2013), especially within agricultural landscapes where the primary focus is on maximising land area for food production. This makes the restoration and maintenance of mid-late successional ponds the most accessible option. Studies have shown that, once ponds are restored, diversity of invertebrates, and macrophytes can increase 3-5 years after pond management (Sayer et al., 2012; Davies et al., 2016).

The different provisions of ponds at differing successional stages highlights the main conclusion of many pond researchers: management of the pondscape – ensuring that there is a size and age diversity of ponds across the agricultural area – is more important than the management or successional stage of individual ponds (Hassall, Hollinshead and Hull, 2012).

3.2 Regulating services: The carbon cycle

3.2.1 General role in the carbon cycle

It is difficult to generalise the role of ponds in the carbon cycle. However, it is likely that they have a disproportionate effect on the carbon cycle relative to their size, due to the intensity of geochemical processes within them (Holgerson, 2015; Biggs, von Fumetti and Kelly-Quinn, 2017a). It is still not clear if ponds are ultimately a net source or sink of greenhouse gases, with the natural variability of ponds making it hard to calculate generalised figures (Biggs, von Fumetti and Kelly-Quinn, 2017a). Smaller waterbodies tend to have a greater contribution to carbon sequestration but also in emitting greenhouse gases due to more rapid carbon fluxes (Downing, 2010). Jeffries et al., (2022) estimate, to a 95% confidence interval, that there are 2.63 million tonnes of organic carbon stored in pond sediments across Great Britain.

There are three main processes which affect a pond's greenhouse gas flux:

1. **Carbon burial in sediment.**

Organic sediment (such as soil runoff, leaf litter etc.) can be transported into ponds and settle at the bottom, becoming a store of carbon-rich material. Over time, this sedimentation will cause the terrestrialisation of the pond. Estimates of carbon (C) burial rates in England range from 79-247g C m^{-2} $year^{-1}$ (Taylor et al., 2019) which can lead to overall storage rates of 23.4 – 246.4 tonnes C ha^{-1} or 20.7 – 74.4mg C cm^{-3} (assuming an average 20cm sediment depth) (Jeffries et al., 2022). Alternative figures for sediment carbon stocks are 4.18 +/- 2.12 kg C m^{-2} (41.8 +/- 21.2) tonnes C ha^{-1} across the top 10cm of pond sediment (Gilbert et al., 2021).

This places small ponds at the upper boundary of English habitat's carbon burial potential, comparable to grassland, bogs and woodland (Taylor et al., 2019; Jeffries et al., 2022). When combined with current UK pond number estimates, this could mean that between 1.41 – 3.84 million tonnes organic carbon are stored in agricultural pond sediments across the UK (Jeffries et al., 2022).

2. **Methane and nitrous oxide release from sediment decomposition.**

Depending on their locations and purpose, agricultural ponds generally receive a high volume of nutrient and sediment-rich runoff through fertiliser applications, soil erosion etc. This, coupled with their generally small, shallow, low-flow nature, can create an ideal situation for anaerobic and eutrophic conditions, which leads to the production of methane and nitrous oxide (Downing et al., 2008; Malyan et al., 2022). Studies vary in how significant these emissions may be, from 1.1 – 28.5 g CO_2eq m^{-2} $year^{-1}$, which is equivalent to 0.7% – 19.7% of an annual pond carbon burial rate in Northumbria (Taylor et al., 2019). However, on a national level, methane production from agricultural ponds could be significant, and often not accounted for/underestimated in national greenhouse gas inventories (Peacock et al., 2021; Malerba et al., 2022). Release of nitrous oxides from ponds is expected to be insignificant (<1%), as the majority produced within the pond is likely to remain within the ponds (Malyan et al., 2022).

3. Carbon dioxide release from degradation of dissolved carbon and soil respiration as ponds dry out.

Carbon dioxide is also released from sediment and litter decomposition. Compared to their water volume, small ponds receive high inputs of carbon through sedimentation, leaf litter and runoff, which can increase respiration of microbes within the pond sediment and therefore, increase production of CO_2 (Hope, Kratz and Riera, 1996; Kelly et al., 2001; Kortelainen et al., 2006; Rubbo, Cole and Kiesecker, 2006). This process seems to be rapidly increased when ponds dry out and sediment is exposed to the air, with conditions changing from anaerobic to aerobic (Gilbert et al., 2017). This causes microbial mineralisation rates to increase, particularly in the surface layer of sediment, and release of carbon dioxide (Fromin et al., 2010). This can cause a rapid shift of a pond from a sink to a source of greenhouse gases within a matter of days.

3.2.2 Effect of management on carbon cycle

Due to their heterogeneous nature, it is very hard to provide a universal figure on the impact of agricultural ponds on wider carbon cycles. A study by Gilbert et al., (2014) highlights this point, with ponds within 30m of each other, of a similar size, age and soil type, having variable levels of organic carbon (1% - 19% sediment Organic Carbon). The deciding factor in this study was the presence of vegetation, especially moss swards that covered sediment when ponds dried out. However, many other deciding factors (Table 7) exist for other situations.

Compared to other freshwater systems, agricultural ponds are highly variable spatially, but also temporally. Therefore, they can move from a sink of carbon to a source in a relatively short time-period (Gilbert et al., 2017). Carbon is undeniably sequestered in pond sediment; however, this carbon can be turned into methane in the pond and re-released. This effect may result in large numbers of artificial ponds acting as a carbon source, with some studies estimating that up to 93% of artificial water bodies (including ditches and ponds) may be a source of GHG (Peacock et al., 2021). However high levels of uncertainly exist in mapping and measuring carbon fluxes for small artificial waterbodies (Peacock et al., 2021).

Ponds can be managed on a local level to reduce GHG emissions. Actions could include removing excessive shading or macrophyte coverage in the pond to prevent anaerobic conditions building up (Rabaey and Cotner, 2022), or conversely increased low level vegetation coverage on riparian sections to reduce drying out (Gilbert et al., 2017). The risk of ponds fully drying out for periods of time longer than two weeks can be reduced (Fromin et al., 2010; Gilbert et al., 2017), and internal pond management reduced unless necessary to precent sediment disturbance (Blaszczak et al., 2018; Peacock et al., 2021). A pond’s wider catchment can also be managed to reduce GHG emissions, for example reducing nutrient runoff into ponds by improving surrounding landscape management and fertiliser use, as well as installing buffer strips around the margin of ponds (Malerba et al., 2022).

Table 7: Summary of pond variables that affect the carbon cycle.

Pond variable	Details	References
Size or depth of pond	Shallow ponds warm up at a fast rate, speeding up decomposition, respiration and therefore GHG emissions. Shallow ponds also dry out quicker, leading to exposed sediment which releases CO_2.	(Holgerson, 2015; Peacock et al., 2021; Malerba et al., 2022; Malyan et al., 2022)
Wetting and drying cycles	Wet-dry cycles are an important driver. CO_2 flux can increase during the drying period as microbial activity switches from anaerobic to aerobic decomposition. This effect is reduced once sediment fully dries and then increases again as pond wets back up. Pond margins are larger drivers of CO_2 emissions due to microbial community being accustomed to cycles. This effect can cause rapid change from sink to source.	(Fromin et al., 2010; Gilbert et al., 2017; Freer et al., 2014)
Surrounding land use and nutrient levels	Nutrient, organic carbon and sediment influx into pond can be significantly increased depending on surrounding land use. Ponds receiving nutrient rich runoff likely to increase GHG emissions, especially carbon dioxide.	(Gilbert et al., 2014; Peacock et al., 2021; Malerba et al., 2022; Malyan et al., 2022)
Pond vegetation	Dense floating layers of macrophytes on pond surfaces can create anaerobic conditions in water, leading to CH_4 production. Sometimes excessive plant or algal coverage is associated with elevated nutrient levels in water, or from excessive shading of the pond surface. The same effect can also be caused by dense emergent plants which can increase transport of methane from sediment to surface. Presence of some species such as Et al., has also been related to reduced carbon burial, through exudation of compounds that increase microbial activity.	(Gilbert et al., 2017; Yvon-Durocher et al., 2017; Taylor et al., 2019; Malyan et al., 2022; Rabaey and Cotner, 2022; Freer et al., 2014)

Pond variable	Details	References
Temperature	As ponds warm, microbial activity increases, releasing greater amounts of GHG. Shallow, small ponds are likely to warm at a quicker rate. This effect is more pronounced for methane production compared to carbon dioxide.	(Yvon-Durocher et al., 2017; Davidson et al., 2018; Peacock et al., 2021; Malerba et al., 2022; Malyan et al., 2022)
Disturbance	Human management or disturbance can increase GHG emissions through exposing or compacting sediments, as well as alterations to inflow and outflows.	(Gilbert et al., 2014; Blaszczak et al., 2018; Peacock et al., 2021)
Water chemistry	Ponds with water pH above 8 (alkaline) can have reduced CO_2 emissions due to carbonate buffering. Methane and nitrous oxide emissions are not affected by water pH.	(Webb et al., 2019; Peacock et al., 2021; Malyan et al., 2022)

The time taken for ponds to become carbon sinks is unknown and research on the effects of vegetation on carbon burial is also limited (Taylor et al., 2019). In a study by Taylor et al., 2019, the actual carbon storage of studied ponds were, on average, 13.09% lower than originally estimated. As the ponds aged and waters became shallower, methane emissions increased, which could offset any net burial of carbon. However, despite the carbon flux increasing as the pond dried, after 20 years, the ponds were overall net sinks of carbon. It is also believed that the burial rate of carbon in ponds can be 20 – 30 times greater than other habitats such as woodland and grasslands. Jeffries et al., (2022) state that carbon accumulation is limited in the first 1 – 3 years following pond creation and also found that there was no significant relationship between sediment depth and carbon stock. There is no currently published data exploring whether restoring current ponds or creating new ones is more beneficial for capturing and storing carbon.

Footnote: It is understood that UCL (Pond Restoration Research Group) are currently monitoring the carbon flux of a number of restored, overgrown and open-canopy ponds as part of a current research project.

3.3 Regulating services: Flood, silt and nutrient management

Traditional agricultural land management has been heavily linked to increased downstream flood risk (O’Connell et al., 2007). Intensification of agriculture has reduced the amount of natural interception structures such as hedges and increased the amount of land left bare over the winter. It has also reduced the capacity of soil to absorb and moderate rainfall, leading to increased surface runoff (Holman et al., 2003). Small agricultural ponds can capture and temporarily store some of this runoff. This can reduce downstream peak water flows, downstream sediment movement and pollution (Newman et al., 2015; Robotham et al., 2021).

Individual ponds can have large local impacts. One medium sized (8,000m^3) online agricultural pond in France reduced total nitrogen runoff by 30%, and in the north of England three ponds managed to capture 7.6% of suspended silt, 6.1% silt and clay and 3.2% of phosphorus, despite only covering <0.02% of the catchment (Robotham et al., 2021). A “pondscape” involving 14 ponds in an area (including both online and offline ponds) captured approximately 15% of all sediment run off (Robotham et al., 2021). In real terms, this equated to 83 tonnes of sediment being captured and therefore prevented from entering watercourses downstream. On a larger scale, a significant increase in agricultural ponds across a 230 km^2 catchment in Texas, managed to reduce downstream reservoir sedimentation by 55% (Berg et al., 2016). There is potential that this sediment, rich in phosphorus and organic carbon, could be removed from the attenuation ponds and spread on fields as a soil conditioner. The resulting carbon emissions created from the drying out of this sediment has not been investigated in peer-reviewed literature.

A single 800 – 1,000m^3 online pond in Northumbria managed to delay the time taken by a river to reach its peak flow by five minutes for a large storm of 96mm in 36 hours (Dadson et al., 2017). By itself this is impressive, but multiple small interventions such as ponds are needed to make a noticeable difference at a catchment scale (Dadson et al., 2017). This was shown in a study in a medium sized agricultural catchment in the north of England where multiple small (200 – 2,000m^3) and cost effective (£1,000 – £10,000) runoff attenuation features were used to reduce the large flood peak (one in 12 year storm) by 30% (Wilkinson et al., 2019). It is important to note that the reintroduction natural ecosystem engineers such as beavers are also becoming more widespread in England. Beavers can create natural ponds or standing water, which in turn can have significant effects on downstream flow and sediment movement (Puttock et al., 2021).

A potential threat to agricultural ponds is that they tend to have small individual water catchments. This can be beneficial as it reduces the risk of the pond being hydrologically connected to a pollution event. However, due to their size and potentially limited hydrological inputs, if a pond is connected to a pollution source or experiences a pollution event, it can be difficult for the water quality to recover as there may be little opportunity for dilution (Biggs et al., 2005b; Biggs, von Fumetti and Kelly-Quinn, 2017a; Williams et al., 2020). In addition, nutrients retained in small ponds can often be remobilised during major storm events and then lost from the pond (Robotham et al., 2021). In some cases, fully constructed wetland systems are more appropriate than a series of linked open ponds, if nutrient removal is the primary aim of the system (Newman et al., 2015).

3.4 Evidence gaps in academic literature.

Undertaking this literature review has revealed a number of research gaps. The gaps in knowledge and research include:

1. An accurate number of ponds on agricultural land in England.
2. The current condition of agricultural ponds in England, with an agreed definition of how to define the “good”/“poor” condition of ponds or their function.
3. The actual national numbers of restored ponds, with monitoring to assess how they change over time.
4. An agreed definition on what constitutes a “restored” pond versus a “managed” pond. Restoration is a management continuum. A scale or scoring system may be useful to defining different levels of intervention.
5. An understanding of the importance of terrestrialised ponds for biodiversity.
6. The impact of climate change on ponds, most notably, the impact of temperature and rainfall variations on physical and chemical pond parameters.
7. Knowledge of the interactions between hydrological and thermal changes on pond species to help predict which will flourish and which may struggle under new climatic conditions.
8. Catchment/landscape-wide studies of ecosystem service provision of ponds and if there is an optimum density and size variability within certain areas (pondscape dynamics).
9. Full carbon cycle analysis of agricultural ponds under different management regimes and lifecycle stages to help inform management for carbon sequestration.
10. Standardised method needed for recording emissions/fluxes of gases from waterbodies to enable comparison between studies.
11. Whether there is a difference in the carbon sequestration ability of a newly created pond compared with a restored pond.
12. A better understanding of creating and managing ponds for carbon sequestration purposes compared with biodiversity purposes.
13. The impact of spreading pond organic sediment on agricultural fields on carbon emissions.

Current pond restoration guidance

4.1 Main sources of information reviewed

A review of best practice guidance for restoration and general agricultural pond management was undertaken using published information from the last 20 years. Whilst much of the current guidance focussed on restoring ponds for the benefit for biodiversity no current guidance was identified was restoring ponds for carbon benefits.

4.2 Main Principles of Pond Restoration and Management in Agricultural Landscapes

4.2.1 Restoration Strategy

There is a recognition in the reviewed information that there is a need for ponds with successional-stage diversity across a landscape, from open water through to overgrown ponds. Species diversity in pond landscapes is greatest when pond diversity maximised, and therefore the need for having ponds that vary in terms of shading and successional stage is crucial (Sayer et al., 2012).

There is limited guidance provided on what proportion of ponds should be restored in a particular area. Sayer et al. (2022) suggest that 20-30% of ponds in a landscape should remain untouched to provide this diversity. Sayer et al., (2013) recommend managing ponds on rotation to create heterogeneity of a pondscape. The importance of having a diversity of pond types in the landscape is also recognised in the Countryside Stewardship capital items WN5 and WN6 pond assessment form, where the purpose is to create networks or complexes of at least three ponds (Rural Payments Agency and Natural England, 2021).

A strategic approach to pond management and restoration is also identified for the benefit of specific species. Langton et al., (2001) suggest that, in addition to the ponds themselves, the management of land in between ponds needs to be considered on a region or parish level with regards to conserving great crested newt (*Triturus cristatus*), as the species live in metapopulations across the landscape.

As part of a considered approach to pond management, Freshwater Habitats Trust (2013) identified the importance of considering pond density. As the number of ponds increases in the landscape, the need for micro-management of individual ponds for a species can often be reduced as the inherent variety of the ponds provides landscape-scale protection. They also suggest creating new ponds nearby rather than desilting ponds that become very shallow and seasonal. This is similar to recommendations by Biggs et al., (2001) and Williams (1997) who warn against “restoration” of temporary ponds as unique habitats with rare species could be lost. However, in agricultural landscape, the availability of land to create new ponds may limit this course of action.

From the experience of the Norfolk Pond Project and others across England, the restoration of overgrown ponds, resurrection of infilled ("ghost") ponds and the creation of new ponds are all required to provide biodiversity and a range of habitats, as well as other benefits, and these actions should be conducted as part of an integrated management plan.

4.2.2 Survey and assessment

It is generally agreed that it is important to have a diversity of pond types in the landscape and therefore not all ponds require restoration or management. Most sources recommend the need for surveying and assessment of ponds before considering pond management/restoration in order to make informed management decisions and avoid damaging a pond's existing value. For example, detailed survey and assessment guidance is provided by Freshwater Habitats Trust (2015) including a risk assessment of pond management based on the surrounding land use and the presence of existing wetland plants.

The reviewed guidance also identifies the potential for ponds to have archaeological interest, and those in the Brecks of Norfolk to have geological interest as 'pingos' or kettle lakes, a legacy of the last glaciation (Norfolk Wildlife Trust, 2023).

Countryside Stewardship capital items WN5 and WN6 require an assessment of existing biological interest (and historic features) to have been completed for pond restoration, although this is not a specific requirement for the less intrusive annual management options of WT4 and WT5.

4.2.3 Water quality

Several sources identify the need to consider the quality of water entering ponds from the immediate catchment area and to ensure that ponds are protected from sources of pollution (Biggs et al., 2017; CaBA, 2018; Sayer et al., 2022). The guidance from CaBA also refers to the fact that measures which seek to restore natural processes – natural water quality, sediment, and hydrological regimes – are an important component of pond restoration.

Non-intensive agricultural land such as semi-natural grassland is the best land use around a pond. Where this is not possible, such as in arable and intensive grassland systems, a grassland buffer around the pond is essential to intercept any chemical inputs on the adjacent agricultural land, as well as providing a habitat in its own right (Freshwater Habitats Trust, 2015). A grassland margin of at least 10 – 20m is suggested as a buffer against sprays and drainage (Rural Payments Agency and Natural England, 2022).

The need for a margin is recognised within Natural England's Countryside Stewardship pond restoration capital items WN5 and WN6, where the items can only be selected in combination with a pond buffer strip option (if the pond is next to cultivated land or intensive grassland).

4.2.4 Timing of works

The recognised optimal timing of pond restoration or management is generally accepted as being between late August – end of October, largely after the bird breeding season and when ground conditions are suitable (Sayer et al., 2022). Freshwater Habitats Trust (2015) state that there is no ideal time of year to manage a pond as different animal and plant species have different rhythms of breeding, growing, and dispersing, so the least damaging time for one species can be the most damaging for another. They also note that there have been cases where great crested newt ponds have been managed in winter, impacting the population of newts which were hibernating underwater and in the banks.

Pond restoration under Countryside Stewardship capital items WN5 and WN6 is to be undertaken between late July and the end of January, and preferably between August and October. The guidance recognises that the timing of restoration work is dependent, in part, on the presence of protected species. For instance, work on a pond with water voles should be undertaken between October and January, while work on a pond supporting great crested newts should be undertaken between November and January.

4.2.5 Tree and scrub cover

The amount of tree and scrub cover around a pond is a consistent theme amongst the reviewed sources. General advice is avoid restoring ponds with veteran trees. Due to their value to bats, birds and amphibians, the advice is to retain some mature trees, scrub, and bramble but crucially open the canopy so that pond shading is low (<10 – 20%) (Sayer et al., 2022). Pondside trees are also recognised as providing a source of shade, leaf litter (food for water louse and shrimps) and woody materials (a refuge and a substrate for egg laying) (CaBA 2018).

Freshwater Habitats Trust (2015) state that there can be no exact prescription for the amount of shade a pond should have. Each pond should be judged on its own merits depending on what is likely to benefit from, and what may be harmed by, the management.

Sayer et al., (2022) recommend that trees and scrub should be removed/coppiced along 50 – 75% of the pond margin, particularly on the southern and western sides. Countryside Stewardship capital items WN5 and WN6 are broadly consistent with this approach, requiring the removal woody cover from at least three-quarters of the pond margin, especially on the southern side.

Guest and Harmer (2006) in the Atlas of Amphibians in Cheshire and Wirral suggest that judicious pruning of shading branches, rather than resorting to intrusive dredging, may allow sufficient improvement of ponds for amphibians through enhanced growth of emergent vegetation and increased invertebrate populations.

It is generally recommended that large trees within the wet basin of a pond can be removed, but it is best to not to pull out trees from the dry banks as this has the potential to disturb the ground/archaeology integrity. The return of some wood to the pond edge after restoration is recognised to be of benefit to specialist invertebrates and fungi due to the general benefits of dead wood (Sayer, Hawkins and Greaves, 2022).

There is limited guidance available on the disposal of woody debris in terms of whether is chipped, left to rot down or burnt. There is a requirement under Countryside Stewardship capital items WN5 and WN6 for cut vegetation to be placed far enough away from the top of the bank to prevent decaying material from falling in and polluting the pond. The Freshwater Habitats Trust (2015) advises to use any cut wood for hibernacula for amphibians.

4.2.6 Silt/sediment removal

It is commonly recommended to only remove soft silt in a pond and to avoid reprofiling or removing the clay/pond lining in order to maintain diversity of pond profiles. This not only maximises biodiversity but also respects the archaeology of the pond (Sayer et al., 2022). Sayer et al., (2022) recommend soft sediment is removed from at least three-quarters of the pond and Norfolk Wildlife Trust (2023) suggest at least one third to one half of the pond’s area. The removal of all sediment in one operation is not recommended. This is reinforced by Countryside Stewardship option WT4 and WT5 and capital items WN5 and WN6, advising not to manage the whole pond in one operation. Disposal or re-distribution of silts needs to be carefully considered; any contaminated silts may potentially impact on other habitats or historical features.

The removal of all sediment in one operation is not recommended as some of the sediment layers will contain seeds of wetland plants. Sayer et al., (2022) quote academic research by Alderton et al., (2017) which shows that seeds which can remain viable in a seedbank for over 150 years. Restoration of terrestrialised ‘ghost ponds’ in Norfolk has led to the re-emergence of rare wetland plants many years or decades after burial. Re-profiling or cutting deeper than the original pond profile is not permitted under Countryside Stewardship capital items WN5 and WN6.

There is limited guidance of the use of pond liners in the restoration of agricultural ponds, beyond where needed for the restoration of dew ponds, as mentioned below. This is considered likely due to the benefits of using natural substrates as described below, the value of seasonal ponds in their own right as well as the cost involved to line agricultural ponds.

Specialist restoration is required of certain ponds in farmed landscapes. For example, dew ponds commonly found in the chalkland and limestone areas of England are often lined with stone, concrete or modern artificial liners and therefore require specialist contractors. Yorkshire Wildlife Trust provide guidance for restoring dew ponds in the Yorkshire Wolds. Dewponds can also be significant elements of historically important areas, the value of which can be enhanced further by specialist restoration.

4.2.7 Planting versus natural colonisation

There is sometimes a desire to see instant results following pond restoration, and therefore the want for stocking with wetland plants. However, natural colonisation is generally now accepted as the best management option. It allows for diversity in results and as previously described, plants can re-emerge from dormant seed banks. Stocking plants from garden centres can lead to major problems with invasive species (Norfolk Wildlife Trust, 2023), as well as the introduction of cultivars of wetland plants into the landscape. The introduction of plants (and animals) to ponds that have been managed or restored under the Countryside Stewardship scheme is not permitted without the express permission of Natural England. Fish, wildfowl, and non-native plants also cannot be artificially introduced.

4.2.8 Livestock grazing and fencing

Ponds were historically accessed by livestock as drinking water sources. However, since the late twentieth century, agricultural fencing has commonly been used to prevent or control livestock access to ponds. Where livestock access has been prevented, natural succession has accelerated and led to the development of scrub and trees.

Guidance generally now supports low intensity or occasional grazing to maintain the openness of ponds and the marginal and emergent plant communities (Natural England, 2010; CaBa, 2018). Trampling and grazing by livestock also creates poached muddy margins, including a mixture of bare and vegetated ground with a micro-topography of small temporary pools and wet mud. This provides perfect habitat for many terrestrial, semi-aquatic and aquatic plants, including some very rare species, and invertebrates (Freshwater Habitats Trust, 2013). Williams (2018) noted the strategic use of fencing on ponds at Otmoor, Oxfordshire, where fencing was used to restrict livestock access to part of a pond in order to create a range of pond edge types.

Under Countryside Stewardship option WT4 and WT5, there is a requirement to graze or cut the margins of the pond. There is a presumption against fencing around a pond for capital items WN5 and WN6, except when the pond is situated adjacent to intensive grassland. Partial fencing that excludes stock from part of the pond may be considered. Fencing a pond managed under WN5 and WN6 requires the agreement of Natural England.

4.2.9 Maintenance after restoration

A review of guidance indicates that ponds require a degree of proactive maintenance to provide biodiversity benefits. Sayer et al., (2022) suggest regular small-scale management (every 3 – 6 years) to clear scrub regrowth, mowing of pond margins and to undertake “patch scraping” to remove dominant plants such as bulrush. The creation of bare substrate can also be beneficial for a range of species.

Footnote: Under Countryside Stewardship, WT4 and WT5 are annual payments received through the course of the agri-environment agreement. The management requirements are maintenance focused and advice differs slightly from WN5 and WN6 capital payments. WN5 and WN6 are capital payments for one-off, more intrusive, pond restoration.

4.3 Themes emerging from current research

A number of agricultural pond management themes have emerged from the academic literature. Where these have replicated the themes that emerged from the grey literature, text has been concentrated in the grey literature section.

4.3.1 Catchment/landscape level approach

Although small and localised in terms of size, agricultural ponds are part of a much bigger and connected landscape. As the agricultural landscape is heavily modified by human activity, ponds can have a significant beneficial impact upon local biodiversity and hydrological functioning. This catchment/landscape level approach should be considered as part of any management regime and ponds should be considered as part of a wider hydrological network. Ponds can be part of the solution to restore landscape function but cannot be the sole solution (Sayer, 2014).

Conversely, pond function and health can be adversely affected by surrounding land use. For example, protecting ponds from nutrient enrichment is beneficial as methane emissions from waterbodies are linked with levels of eutrophication. This requires coordination with surrounding land practices (Peacock et al., 2021). Any management needs to take into account and reduce these impacts if long-term management of ponds is to be successful (E. Raebel et al., 2012). Therefore, it is critical that ponds are considered as a part of landscape-level integrated management plans.

4.3.2 Diversity is key

By their nature, agricultural ponds are very diverse in terms of shape, size, location, physical and chemical characteristics. This variety ensures that ponds are good at supporting a range of rare and common species (Bilton et al., 2009). A multiple number of small ponds can have greater conservation value than a single large pond of the same area (Oertli et al., 2002). However, larger ponds can also harbour species not found in smaller ponds (i.e. some species might require a pond of a certain size) (Oertli et al., 2002).

Variation can also occur within a single pond. Variation may be spatial, for example difference in shading levels around pond, or ponds with half their perimeter fenced, or temporal, for example a pond that dries out fully or exposes pond edges on a regular basis (Jeffries, 2016). Temporal changes also occur in the medium to long term, with ponds gradually changing characteristics over time without artificial management. This is not necessarily a negative, but provision needs to be made to account for the habitat loss of a pond in that particular successional stage. Therefore, a range of pond sizes and types is needed, and management practices should be on a landscape scale to ensure that a wide range of pond types are created across a landscape.

4.3.3 Unique pond management

Although ponds should be considered as part of a wider integrated landscape approach, each pond will be specific in its requirements. This is particularly important when considering what ecosystem services a particular pond is providing, and what the aim and/or effect of management will be on this service provision (Hassall, Hollinshead and Hull, 2012). From a carbon perspective, exclusion of livestock from the pond edge can help reduce poaching and nutrient flow into the pond, which can reduce overall pond methane emissions (Malerba et al., 2022). However, management can also have unintended impacts upon biodiversity. For example, management of woody plants around a pond will benefit pollinators due to an increase in flowering plant richness and abundance (Walton, 2019), but terrestrial species could be negatively impacted by the removal of this habitat (R. e. Walton et al., 2021). This may be an acceptable impact for a particular pond but needs to be carefully considered within the wider pondscape catchment before management is carried out.

4.3.4 Restoration opportunities

As many ponds have received little or low levels of management in recent years, the restoration of these ponds provides a great opportunity for habitat restoration and biodiversity conservation. Restoring or managing ponds can lead to an increase in biodiversity for a period of time after management (Sayer et al., 2012). However, selecting the most appropriate ponds for restoration is key, with a timetable of restoration for ponds in a pondscape needed to ensure that a mosaic of habitats is still available (Hassall, Hollinshead and Hull, 2012).

Restoring infilled agricultural ponds (ghost ponds) provides a good opportunity to return nonaquatic land back to fully functioning ponds. The process of digging ghost ponds out can also lead to plant conservation opportunities as dormant seed from historic vegetation are often able to germinate and recolonise rapidly after excavation if the works have been carried out carefully (Alderton et al., 2017).

5 Academic literature review of agricultural ponds and climate change

5.1 Impact of Climate Change on Agricultural Ponds

Climate change will have large physical, chemical, and biological impacts upon agricultural ponds in England. The most likely drivers of these impacts will be from:

- Changes in average, maximum and minimum air temperatures
- Changes in precipitation pattern, intensity, and volume
- Changes in rates of evaporation
- Changes in hydrological functioning
- Changes in land management in response to climate change

The expected impacts of these drivers are summarised below.

5.1.1 Water temperature

Climate change is likely to increase average, maximum and minimum water, and air temperatures. In general, ponds are likely to become warmer over time, especially small ephemeral ponds that are shallow or have a low volume of water (Matthews, 2010; Holgerson, 2015).

In general, increased water and sediment temperatures are likely to significantly increase methane production from ponds (Davidson et al., 2018; Malyan et al., 2022). This is partly due to the increase in decomposition rate of organic carbon in response to increasing temperature. This decomposition uses oxygen present in the water column, which results in an anaerobic environment favouring methane production through methanogenesis (Yvon-Durocher et al., 2017; Malyan et al., 2022). Methane emissions increase significantly above a water temperature of 17°C, with increase of 11% per 1°C, or 2.8 times with 10°C rise (Malyan et al., 2022).

When combined with additional nutrient loading, methanogenesis (methane production) can be amplified (Davidson et al., 2018). Increased temperature could also result in an undesired increase in algal growth; this can also accelerate anaerobic conditions and thereby increase methane production in the water column (Clarke, 2010; Peacock et al., 2021). As small waterbodies often have elevated nutrient levels and are likely to be warmer due to climate change, emissions of greenhouse gases are likely to increase as a result (Bastviken et al., 2004; Downing, 2010).

5.1.2 Hydrological cycles

Rainfall is expected to become more sporadic and unpredictable as the climate changes, and evaporation rates could increase during summer months; this is likely to have a large effect on smaller, temporary or shallow ponds (Clarke, 2010; Jeffries, 2016). This evaporation may lead to more frequent drying out or longer periods of time without water input, and lower water quality as a result (Clarke, 2010; Matthews, 2010; Jeffries, 2016). This is likely to lead to a greater number of seasonal or semi-permanent ponds, which have a greater chance of becoming eutrophic and can be a greater source of methane (Tranvik et al., 2009). An increased amount of wetting and drying cycles could lead to current species richness reductions (Grillas et al., 2021), although this effect may be offset by species ranges being increased or altered due to climate (Rosset, Lehmann and Oertli, 2010). Either way, changes in hydrology may have a greater impact on species than temperature changes (Moss, 2014).

An increase in heavy rainfall could result in greater nutrient and sediment loading of ponds, due to increased runoff and erosion (Clarke, 2010). However, greater volumes of rainfall have potential to reduce methane production as water becomes more diluted and can decrease contact with sediment (Holgerson et al., 2015).

5.1.3 Species composition and ranges

In general, the spatial ranges of plant and animal species will change due to a changing climate. This may mean that the prevalence of invasive non-native species may increase as their range expands (Clarke, 2010). This could increase the biodiversity of some ponds as a greater number of species could inhabit them, but increased water pollution from land-use change and runoff may neutralise this increase (Rosset, Lehmann and Oertli, 2010). Many freshwater invertebrate species are sensitive to variations in water temperature as they are unable to regulate their body heat, and therefore may be disproportionately negatively affected by water temperature changes (Matthews, 2010).

The effect in the UK may be regional, with great impacts predicted in the south of the country, compared to the north, where impacts are less likely to be as extreme. Therefore, a regional context must be considered.

It is possible that species that inhabit both ephemeral and permanent ponds are more likely to persist in a changing climate due to their genetic fitness and adaptability (Hogg and Williams, 1996; Williams, 1997). It may be more prudent to focus on the ecosystem functioning of waterbodies than to fixate on the presence of particular species (Riley et al., 2018) as species compositions change over time across a pondscape.

5.1.4 Water Quality and Wider Landscape Change

Wider landscape change due to climate change is likely to occur. For example, change in agricultural practices and agricultural intensification causing increased runoff could negatively impact upon ponds and wider pondscapes (Clarke, 2010). Changes in precipitation and evaporation will affect the concentration or dilution of minerals/salts and anthropogenic contaminants such as agri-chemicals (Matthews, 2010). These impacts could be seen with a temperature rise of 1 to 2°C or a precipitation decline of 5% to 10% (Covich et al., 1997). Low water volume and high-intensity rainfall can also increase a pond’s turbidity, resulting in lower water quality (Matthews, 2010). In general, unless managed correctly, agricultural ponds are likely to receive lower quality water as a response of climate change.

5.2 How to make ponds more resilient to future climate change

A major theme of improving pond resilience to climate change is adaptability. This is important for both the physical pondscape, but also the management objectives and aspirations of it. For example, it is important to recognise that ponds are shifting and dynamic ecosystems, and these processes may speed in years to come. Changes to a pond's design can help slow this process down, but the process itself is natural and cannot be stopped.

It should also be recognised that pond species assemblages will shift and change, and that management focus should be on whether species are harmful/invasive, not whether they are "non-native" (Clarke, 2010).

Specific advice to improve resilience of ponds against the direct impact of climate change include:

- Increasing shade around waterbodies could help counteract the effects of rising air temperatures (Clarke, 2010). However, it is commonly accepted that heavily shaded ponds were shown to have a lower species richness (Sayer et al., 2012) and therefore it is not clear which factor would have the biggest impact upon species diversity.
- Integrated, catchment/landscape wide approach to ponds should be used, with a greater emphasis to create and improve ponds in 'non-protected areas' such as agricultural land (Clarke, 2010).
- Improve understanding of pond carbon flux dynamics to better understand the local causes of GHG emissions, and then implement strategies to reduce this effect.
- Improve water management on a catchment-wide scale; for example, implementing soil management practices to reduce erosion, sediment loss and washout events.
- The addition of vegetated buffer strips around ponds to reduce nutrient, sediment and agri-chemical concentration entering ponds.
- Ensuring, longer term water supply for ponds by connection to drainage systems
- Design new ponds so they increase in depth, rather than size when rainfall occurs. This will help to reduce GHG emissions as water has reduced mixing with sediment, leading to lower amounts of methanogenesis (Holgerson, 2015).
- New pond creation and restoration should be targeted in areas that allow for more resilience to climate change. In particular this should include locations which will receive sufficient water to maintain ponds in the long term.

6 Conclusions and Recommendations

6.1 Conclusions

The reviewed literature on agricultural ponds is a good example of academic studies informing and advising on the latest management practices. Several academic study groups have worked to provide a large number of practical studies, which have informed English pond management advice in the last 20 years.

It is clear that ponds are complicated and diverse habitats, with local and nationwide diversity a key characteristic. Diversity comes in the form of size, depth, water chemistry, drying regime, wetting regime, original function, management, water source, flora, and fauna. All ponds are unique and management must always be prescriptive to that particular pond and location. The historical origins, purposes, and location of ponds within a pondscape and landscape should be assessed before any management decisions are made: a “one-size-fits-all” approach is not recommended. Additionally, it is not recommended to impose mandatory management of ponds as this could increase infilling by landowners who do not have the resources to manage their ponds (Hill et al., 2018).

Despite their relatively small size and total area, agricultural ponds have a disproportionate effect on local biodiversity, carbon cycles and hydrological network (Biggs, von Fumetti and Kelly-Quinn, 2017b). Ponds must always be considered as part of a wider functioning landscape as they affect and are affected by, the surrounding area.

Any management of a pond or pondscape should always consider the wider catchment/landscape area. For example: what type of pond is currently lacking in the area? Are any ponds isolated? What are the current risks to ponds in the area? Additionally, the management of an individual pond can sometimes be very prescriptive to a certain species if that species is unique to that pond. However, caution must be taken with this approach as species presence is a dynamic feature of ponds. There are also limitations with pond surveying due to set point-in-time assessments and species movement, and therefore the value of species dispersal and colonisation should be recognised. For example, habitat functionality, species community richness and wider pondscape species assemblage is sometimes more important than individual species presence, and therefore management should not become too focussed on preserving one particular species in one particular pond.

6.2 Key recommendations for pond management

- Study local catchment and landscape before conducting pond management.
- Focus on function – why are you managing or restoring the pond or ponds.
- The inevitable effects of climate change must be considered. This will be regionally specific and may impact upon direct biodiversity improvement management, although the two many not always be mutually exclusive
- Wider context is key – surrounding land management and local pondscape.
- Encourage diversity of pond types within a catchment/landscape.
- Minimise nutrients and sediment entering the pond via land management or buffer strips.
- Important not to focus on particular species but focus on a dynamic and resilient pondscape.
- Support the concept that management can be a continuum of actions. Small selective management can be just as beneficial as large-scale interventions.
- Support pond creation and management, but management requirements require flexibility to encourage management.
- Facilitate collaboration between networks of farmers to encourage pondscape level working.
- A balance is needed between pond creation, restoration, and resurrection if infilled (ghost) ponds.

7 Case studies

7.1 Bird abundance vs open- and closed-canopy ponds

Lewis-Phillips, J., et al., (2019) surveyed bird populations across eight open-canopy and eight closed-canopy ponds in Norfolk. Open-canopy ponds were those that had undergone scrub removal within the last five years. They had low shading and a prevalence of aquatic macrophytes. Closed-canopy ponds had not been managed for 20 – 40 years. The shading of the water was over 85%, with a significant lack of aquatic macrophytes. Surveys were undertaken between May 2016 and April 2017 and were split into breeding, post-breeding, and winter seasons.

Across all survey seasons, higher bird populations and greater bird species richness were consistently found at the managed, open-canopy ponds, compared to the unmanaged, closed-canopy ponds. Open-canopy ponds also had the greatest abundance of red and amber listed birds of conservation priority. It is hypothesised that farmland birds preferentially visited open-canopy ponds due to the increased abundance of food in the form of aquatic invertebrates. Reduced shading on open ponds resulted in an increase of aquatic macrophytes, which in turn supported a greater number and increased diversity of invertebrate species.

However, some species, such as Eurasian Woodcock *Scolopax rusticola* and Brambling *Fringilla montigringilla* were only present at the closed-canopy ponds over winter. This highlights the need for a mosaic of ponds in different successional stages so that the greatest biodiversity can be supported across a landscape. Individual ponds that are shaded and deemed to have a low biodiversity should not necessarily be “improved,” as this could lead to the decline of species that rely on that pond’s specific characteristics.

7.2 Resurrecting ghost ponds

Alderton, E., et al., (2019) identified that, in addition to creating new ponds and restoring existing ones, there is the option to re-excavate ponds historically lost through agricultural infilling, called “ghost ponds”. It has been proven that propagules of aquatic plants can remain viable in the buried pond sediment for over a century and following excavation of the pond, these aquatic plant species can rapidly recolonise the new waterbody, leading to the resurrection of potentially now locally rare macrophytes.

Ghost ponds can be identified from aerial imagery, historic maps, and ground-truthing to assess for areas of wet depressions. Re-excavation of the ghost pond can be achieved by sensitively digging a test trench with a 360 excavator until the original pond sediment layer is found. The infill will typically consist of local soil and agricultural wastes with the sediment layer being a dark silt, potentially including remnants of plant matter and shells. The sediment layer can be used to determine the original profile of the pond and it is this that could contain key historic aquatic plant propagules so it is important that this silt layer is not excavated.

Works should be conducted in the winter and left to fill with rainwater, with a 7-10m buffer strip around the pond to protect from agricultural practices. Of the ponds studied, aquatic plants were present within the newly resurrected ghost ponds within 12 weeks, due to the viable propagules present in the pond sediment. After 12 months, aquatic plants were dominant and water was clear. Biodiversity was similar to that of nearby restored ponds. As ghost ponds will typically be present on damp, less-productive areas of arable land, reinstating them is not believed to have a significant impact on crop yield. On the contrary, reinstating these ponds could bring many benefits to the farmed landscape.

7.3 Using paleoecology to determine historic biodiversity of a pond

Walton, R., et al., (2020) carried out a paleoecology study of a small, shallow (535m^2, 135cm deep) “marl pit” pond in Norfolk. A single sediment core of 124cm was taken and 34 subsamples of sediment were dated and analysed. Four core zones (~1652 – 1757; ~1780 – 1904; 1907 – 1981; 1989 – 2008) were identified and present-day surveys were undertaken before restoration (2008 – 2011) and after restoration (2012 – 2017) for comparison. Restoration consisted of sediment dredging and significant woody vegetation removal.

It is believed that the pond was largely unshaded for the initial 200 years and that specific aquatic macrophyte dominance varied between the decades. The long-term persistence of the open canopy suggests that regular pond management was historically undertaken and indeed, it was found within the sediment cores that significant woody vegetation management was conducted on at least three occasions since the 1800s. It is also noted that sediment removal from the pond could have taken place in the past but it is not believed that this would have affected the results of the core sample.

Present-day restoration of the pond led to the return of many aquatic species not seen since before 1907. It is hypothesised that the restoration works disturbed and permitted the emergence of historically buried propagules. New colonists to the pond also arrived and it is concluded that pond restoration increases aquatic macrophyte diversity, which in turn creates a habitat of complex structure, supporting many species including invertebrates and amphibians.

7.4 Benefits of a pondscape in a farmed landscape

A study by Sayer, C., et al., (2013) was conducted on a Norfolk farm of 243ha, with 40, mainly spring-fed ponds in arable fields with grass buffers. The surrounding land-use is typical of an intensive agricultural system. The ponds have been found to have exceptionally high biodiversity, with Great Crested Newt (*Triturus cristatus*) occurring in 28 ponds, one with rare Crucian Carp (*Carassius carassius*) and across the pondscape; 20 dragonfly species being identified including 16 breeding species, 23 floating and submerged plant species, 14 duck species plus other birdlife, and presence of the threatened Great Silver Water Beetle (*Hydrophilus piceus*).

The ponds have been managed on a rotation since the 1960s through sensitive scrub removal and part-pond sediment dredging, with only three or four ponds being managed in any one year, with some being left to naturally terrestrialise. Pond biodiversity peaked 3-5 years following management but some species, especially water beetle species, were only found in particular ponds which highlights the need for a diverse pondscape. Managing ponds at different times will create a diversity of pond shading levels, water oxygen levels and plant communities, which will in turn affect the presence of fauna. The mobility of species should be considered – highly mobile species will be able to disperse to nearby suitable ponds and consideration should be given to less mobile species before management.

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Appendix 1

Introduction

It is estimated that there are 478,000 ponds in England. However, the exact value is unknown. To aid pond restoration and inform management, it is important to understand historical pond distribution. Pond numbers can also be used to interpret potential carbon budgets and stores. SCALGO was used to develop a workflow (Figure A1) to help identify pond locations across a landscape.

SCALGO Software

SCALGO is a 3D hydrological modelling software, which uses terrain data to determine hydrological functioning within a landscape. The software helps to identify features of interest and allows for the interpretation of flow networks, including large water catchments and smaller, individual areas of pooling. SCALGO provides information on large spatial extents and allows for quick analysis of hydrological properties and widens our understanding of hydrological connectivity.

“Depressions” are included within this terrain data. These identify recessions in the terrain which lack a natural outlet and may allow water to pool during a rainfall event. Volumes and areas of water are associated with each depression. These depressions allow for the identification of ponds where a ground truthing survey may be impossible at first and allows for desktop surveys over a large spatial extent, which may otherwise be difficult.

However, since depressions count as any region where pooling may occur, this also may count slight dips in the terrain, lakes, or portions of rivers and ditches. As such, it is necessary to apply further constraints to the data that limit the output in order to successfully identify ponds. These may include constraints to area, volume, or geometry. These constraints were applied using ArcGIS Pro (see Figure A1).

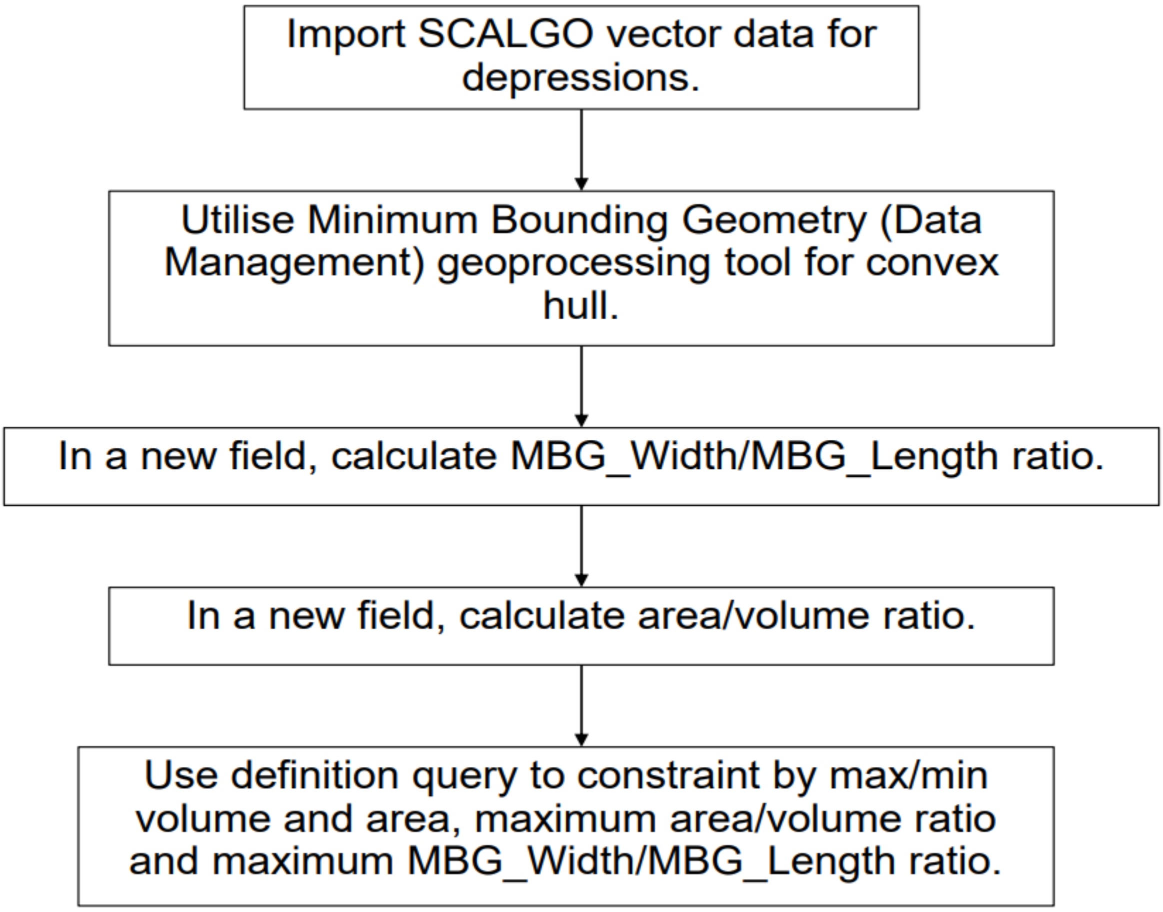

Figure A1: Workflow for identifying ponds using SCALGO data.

Method

To calibrate the data constraints, several extended Phase 1 habitat surveys with large quantities of confirmed, ground-truthed ponds were selected. SCALGO successfully identified most ponds within these areas as depressions, with associated area and volumes. By exporting the volume and area, a volume-to-area ratio could be calculated to isolate ponds from large shallow depressions. Applying limits to maximum/minimum area and volumes allowed further restrictions on the dataset to remove other miscellaneous depressions within the dataset.

Since depression data has assigned geometry, it was also possible constrain long, thin polygons from circular ones, hence eliminating rivers and ditches from the dataset. This is called “Minimum Bounding Geometry” (MBG*). This final dataset was then overlain with landcover data from Natural England, to further delineate depressions within a “built-up area.” The final output provided a list of possible ponds.

Results

The three sites used were Hulton Park (357ha) in Bolton, the area surrounding Stoke Albany (c.300ha) in Leicestershire, and Wrexham Road (324ha) in Chester. Existing ponds were identified using data from previous extended Phase 1 habitat surveys, or prior knowledge of ponds within the area. Figure A2 provides a visual depiction of the SCALGO data and the outputs received when constraints were stacked.

Table A1: Number of ponds identified after constraints were applied to the dataset for three sites.

Constraints – with the introduction of increasing parameters	Hulton Park	Stoke Albany	Wrexham Road
SCALGO depression baseline	956	573	1409
a) No. of depressions with area <3000m^2	945	570	1386
b) No. of depressions with area <3000m^2 but >10m^2	909	551	1370
c) Total no. of depressions with area <3000m^2 but >10m^2 and with volume <3000m^3	909	551	1367
d) Total no. of depressions with area <3000m^2 but >10m^2 and with volume <3000m^3 but >10m^3	288	136	308
e) row (d) plus **Minimum Bounding Geometry Width:Length ratio >0.3**	230	49	219
row (e) plus **Depressions in landcover category “not built-up”**	228	49	191

Results	Hulton Park	Stoke Albany	Wrexham Road
Ground-truthed number of ponds present	66	10	17
Ground-truthed number of ponds present identified within SCALGO dataset	46	8	9
Percentage of ground-truthed ponds correctly identified	70%	80%	53%
Percentage of ground-truthed ponds missed	30%	20%	47%
Percentage of depressions incorrectly identified as ponds	80%	84%	95%

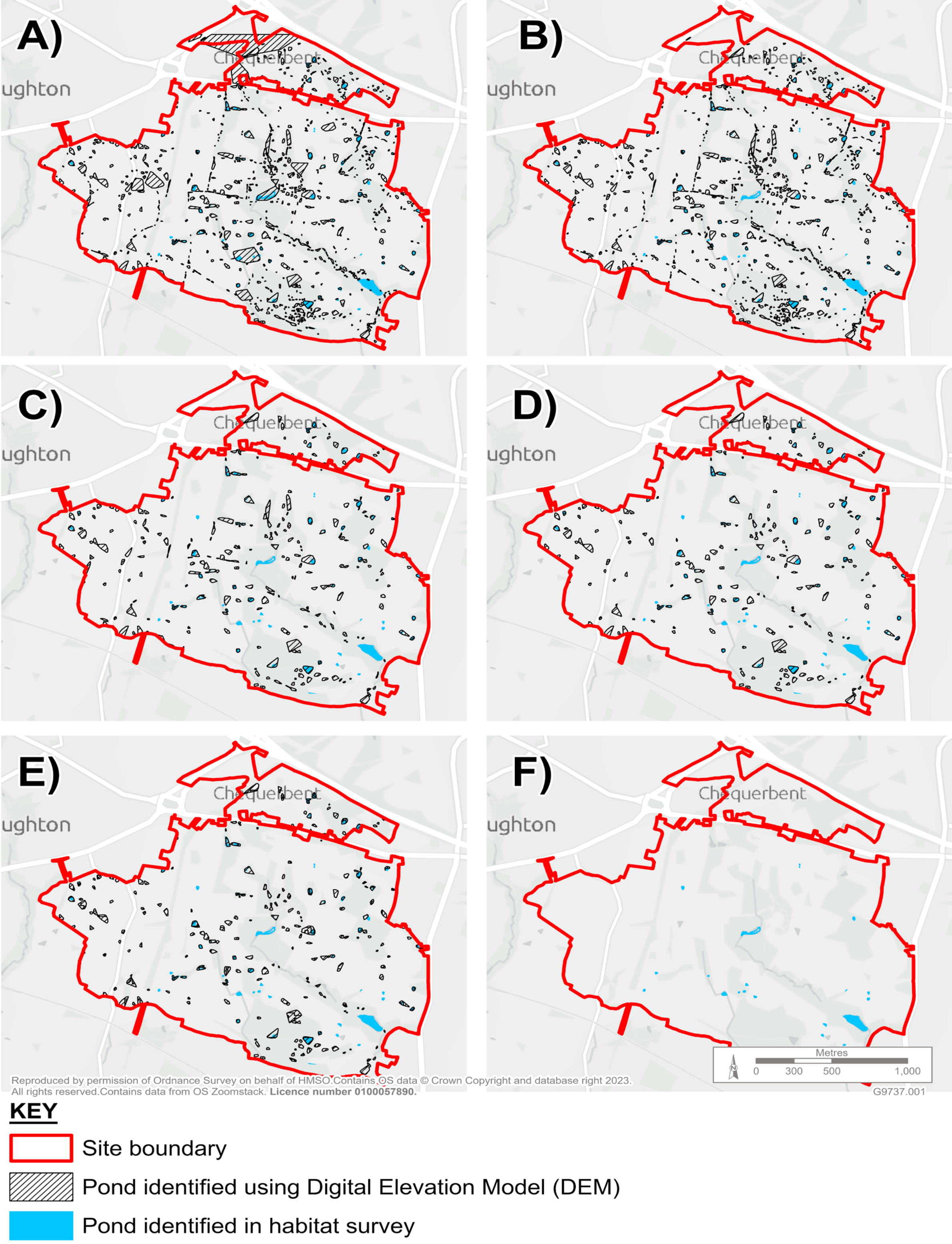

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Figure A1: SCALGO output showing depression data for Hulton Park with constraints stacked:

A) Initial SCALGO depressions output, showing all depressions with a volume and area >0m^3/0m^2.

B) Dataset once constrained to area, where 10m^2 < Area < 3000m^2.

C) Dataset once constrained to volume, where $10m^3 < Area < 3000m^3$.
D) Dataset once constrained to geometry, where MBG width:length > 0.3.
E) Dataset once constrained to landcover, where landcover type ≠ built up areas.
F) Existing ponds that were missed during analysis.

Due to the LiDAR data reflecting from surfaces of water to generate terrain data, smaller depressions being lost within larger depressions, and merging of individual depressions, it was often impossible to constrain the data effectively without removing legitimate ponds. For example, Hulton Park produced a final output of 228 potential ponds, but only correctly identified 46 out of a possible 66 ponds present. Therefore, this method did not provide sufficient accuracy to be used without significant manual analysis. This is both time consuming and risks omitting potential ponds.

As such, an alternative methodology is recommended. It is proposed to use the same terrain data as previously specified in conjunction with artificial intelligence to identify structures like ponds by their slope properties. This avoids the caveats identified as slope can be identified even within larger depressions and avoids issues of conjoined depressions as the gradient between them changes.

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