Final Project Report

1. Contestant profile

Contestant name:	**Dr David Watson**
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Number of people in your team:	**8**

2. Project overview

Title:	Wetland creation in limestone quarries: enabling colonisation and enriching biodiversity
Contest: (Research/Community)	Research
Quarry name:	Chipping Sodbury, UK

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Cover image: Pond Water Quality Sampling. D.Watson, May 2018.

Abstract

Wetland habitats, chiefly deep mesotrophic lakes, will be a major component of the final restoration of the Chipping Sodbury limestone quarry complex. This research aimed to develop best practice in creating valuable biodiverse wetland habitats in and around the limestone quarry complex to augment the region.

Biogeochemical characteristics and ecological connectivity of existing wetland biodiversity within and surrounding the quarry complex were investigated. Water quality, aquatic and emergent macrophytes and macroinvertebrates were surveyed across a range of old established ponds, relatively new ponds and scrapes and waters in active quarry voids within the quarry complex. In addition, waters in voids in the region where quarrying had ceased and in Brinsham Stream which bisects the Chipping Sodbury site were surveyed. Data on priority species (Great crested new surveys and otter survey via wildlife capture cameras) were also recorded. Waterbody characteristics and networks were noted in the field and from inspection of aerial images. Waterbody age was determined through analysis of aerial images and consultation. Data were analysed using correlation and multivariate analyses to determine key factors influencing biodiversity, with a view to making recommendations for restoration to enhance wetland biodiversity.

Overall water quality was very good. Water bodies were found to be low-nutrient to mestrophic quality and this was reflected in the macrophyte community which resembled the NVC A9 *Potamogeton natans* community. Dissolved oxygen was strongly correlated with macrophyte richness (Spearman's Rho 0.87) (a total of 47 species recorded), which corresponded to shallow waterbodies. In turn, high macrophyte richness supported high macroinvertebrate diversity (a total of 56 families) (Spearman's Rank 0.58). Water nitrate levels (highest sample site mean 9.43 mg/L) also influenced macroinvertebrate richness and were of moderate concern, given their potential to lead to eutrophication. However orthophosphate levels were limiting (0.03 ppm or lower in most water bodies). Macroinvertebrate richness was also supported by proximity to a well-connected pond network (number of waterbodies within 500m), which emphasized the importance of a landscape-scale approach to conservation and restoration work for biodiversity resilience.

On the basis of this research, it was recommended that the key aspect of lake creation with flooding of quarry voids would be to maximize the creation of shallow areas to enable development of diverse communities. To create shallows a series of suggestions were made around the creative and cost-effective use of waste quarry materials and restoration blasting to create more lake edge habitat. In addition it was recommended that Hanson work with neighboring landowners to maintain wetland habitat connectivity and so enable natural colonisation.

Introduction

Freshwater habitats occur in a variety of forms, some natural and others manmade. They include ponds (small water bodies - less than one hectare, sometimes ephemeral (Scheffer, 2006) and succeeding to dry land), lakes are larger and defined by water quality; rivers/streams comprising flowing waters and a range of swamps, fens and mires (English Nature, 1997). Each supports a range of macrophytes (submerged, floating, emergent plants), associated macroinvertebrates and species of higher trophic levels. These habitats are substantially influenced by water quality, especially pH, nutrients, dissolved oxygen, depth and light availability. Many Invertebrate species are highly sensitive to changes in such environmental parameters and so are very useful bio-indicators of habitat quality (Action, 2000).

Pond numbers are declining nationally (Biggs *et al.,* 2005; Thornhill *et al.,* 2018), yet they are recognised for their significant contribution to freshwater biodiversity (Williams *et al.*, 2004). In particular, ponds support many specialist invertebrates and amphibians. In addition, it is increasingly recognised that biodiverse wetland landscapes are comprised of a variety of different water bodies (permanent and temporary) at different stages of succession and comprising many habitat niches (Hassall, 2014). This is due to highly variable physical and chemical environments from one pond to the next and, in order to develop highly resilient, biodiverse landscapes it is important to ensure that wetlands of all different ages and sizes are present.

In order to fully realise the benefits for biodiversity, it is also important that wetlands are functionally connected, allowing the interchange of species from one wetland to another. The benefits for colonisation of increased network connectivity for specialist species are increasingly well understood for amphibians (Langton *et al.,* 2001; Kupfer & Kneitz, 2000) and for freshwater invertebrates (Gledhill *et al.,* 2008; Hill *et al.*, 2018). Great Crested Newts (GCNs) *Triturus cristatus* need a network of breeding ponds, terrestrial foraging areas and refugia/hibernacula that enable survival as a stable metapopulation (JNCC, 2010). However, it is only recently that the need for connectivity is being recognised by national policy (e.g. Lawton (2010) Making Space for Nature), and in landscape-scale conservation practice. Even this policy needs to recognise that species' abilities to disperse vary, with some species being water or wind borne, able to fly or being more sedentary.

Restoration following mineral extraction often includes wetland elements (Whitehouse, 2008; RSPB, 2016.) The largest examples of wetland restoration usually follow sand and gravel extraction (Whitehouse, 2008; Hanson, 2013). As these deposits often lie within river floodplains, they are influenced by river water quality and inundation, readily fill with water once extraction is complete, can be readily colonised by early successional riparian species, and are often designed to support a matrix of habitats such as wet grassland, open water and reed beds (flora locale, 2012). In contrast hard rock quarries on porous geology such as Magnesian limestone can often remain dry without direct intervention e.g. clay liners (Durham County Council, undated). However in limestone areas where the natural water table is relatively high, once dewatering ceases, the quarry voids can fill, forming deep lakes with steep sides (Whitehouse, 2008; RSPB, 2016). Overall a wealth of research has been published on sand and gravel wetland restoration, but much less so on wetland habitat creation in limestone quarry voids.

Where there is a desire to create wetlands and enhance wetland biodiversity, this is often achieved by encouraging natural colonisation to maximise ecological value and encourage local ecotypes to establish (RSPB, 2016). To do this there will be a need to create the right conditions, find means of accelerating colonisation, ensure connectivity with other wetlands and (possibly) introduce species to promote wetland biodiversity.

Aims and Objectives. Given the predominance of wetland habitats in the final restoration of the Chipping Sodbury limestone quarry complex, the aim is to develop best practice in creating valuable biodiverse wetland habitats in and around the limestone quarry complex, to support a range of species including BAP and protected species and make a substantial and valuable addition to regional wetland biodiversity. Objectives were to:

- Review the context and model ecological connectivity of the Chipping Sodbury quarries
- Extend the understanding of water quality and wetland biodiversity of the Brinsham Stream and the complex of ponds within and surrounding the quarry complex.
- Establish the water and biodiversity qualities of similar limestone quarries in the region to identify factors that may affect the quality and speed of biodiversity development at the Chipping Sodbury complex

- Develop recommendations to improve wetland biodiversity within and around limestone quarries during the quarrying phase and so accelerate the development of wetland habitat on quarry completion.

Background Information and Site Description. Chipping Sodbury Quarry complex (51°55'75.7"N, 2°39'91.3"W) [Google, 2018]) (Figure 1) lies immediately north of the town of Chipping Sodbury, South Gloucestershire and comprises a series of carboniferous limestone quarry sites: Southfields (including 'Lake Edwards', in its present form since 1977 (Duncan, 2018) used for dust suppression and contains the processing area), Hampstead Farm (active), Barnhill (worked out and Geological SSSI, with old sump in place since 1999 and the extended lake since 2014 (Google Earth, 2018c)), the newly developed East Brinsham, and West Brinsham where extraction is yet to commence (Hanson, 2016).

Restoration is long-term and progressive, creating species-rich neutral grassland on quarry tips, new woodlands (including the Ridge Wood proposed LNR) and hedges, and enabling natural colonisation of top quarry benches to calcareous grassland and scrub. When quarry operations cease in approximately 30 years, the quarry voids will be allowed to flood through groundwater ingress to form a series of mesotrophic lakes and associated wetland habitats (Hanson, 2018).

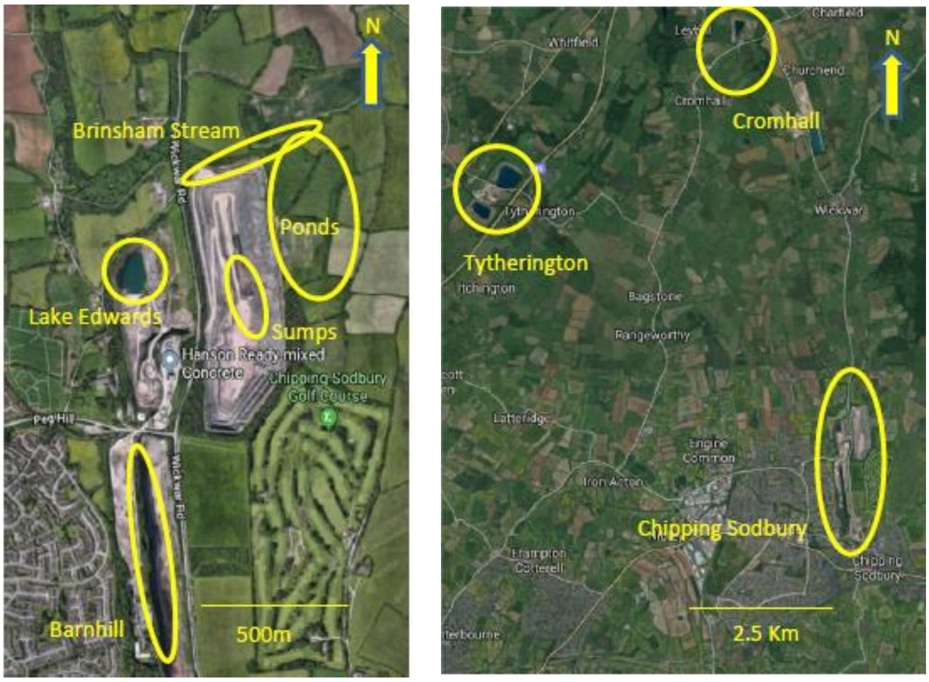

Figure 1. Study site locations.

Chipping Sodbury Quarry Complex (left): Barnhill, Lake Edwards (Southfields), Brinsham Stream, Hampstead Farm Sump, Old and New Ponds;

Quarry Sites (right): Chipping Sodbury Complex, Tytherington and Cromhall. Source: Based on Google Maps UK (2018).

Brinsham Stream (SNIC site) runs between the Brinsham quarry sites and those to the south (Hanson 2016). Stream flow is supplemented by the discharge of sump water from the Hampstead Farm void. The River Frome runs east - west to the south of Barnhill Quarry and takes water pumped from Barnhill. A series of new (created 2014, Greshon, 2014) and old (established) ponds created through clay extraction *circa* 2000 (Duncan, 2018; Google Earth, 2018) have been maintained east of Hampstead Farm to support the medium to high population of Great Crested Newts (Hanson, 2016). In the wider region, a variety of ponds (often remnants from small scale open cast mining for "celestine" (Lansdown *et al.,* 2006)) and wetlands are scattered across the landscape adjacent to the quarry complex. These water bodies range from newly created, well established and neglected ponds, to larger ponds and lakes. These include several flooded limestone quarries within approximately six miles of the complex such as Tytherington (51°59'37.4"N, 2°49'57.3"W), allowed to flood over the previous five years (Hemming, 2018) and Cromhall (51°62'35.7"N, 2°42'74.5"W), flooded to its current level approximately 12 years ago and used as a diving centre (Chen, 2018).

The South Gloucestershire Biodiversity Action Plan (South Gloucestershire Council, undated) regards the national and European protected species recorded at the Chipping Sodbury site include Lesser Horseshoe Bat *Rhinolophus hipposideros,* Great Crested Newt (GCN) *Triturus cristatus,* as priority species. It states that Ponds, rhines, rivers and water bodies are local priority habitats. Otter *Lutra lutra*,also recorded at the site plus GCN and Lesser Horseshoe Bats are all associated with healthy freshwater habitats and are key receptors on the site (WYG Planning and Design, 2011).

All study sites shared similar geologies but varied in size, age, depth and the period they have held water. As such they provided a range of conditions that should aid research into wetland biodiversity colonisation and enhancement.

Methodology

To inform future restoration, biodiversity and water quality surveys were undertaken April to August 2018 to enable spring and summer surveys (after Biggs *et al*.,1998). Standardised, replicated sampling was used for macrophytes and freshwater macroinvertebrates (after Drake *et al.,* 2007). However sampling also reflected variation in the number, accessibility and nature of water bodies available. Ponds, the Brinsham Stream, quarry pools and flooded quarries were surveyed to evaluate their composition and properties. Data review, consultation and digital mapping were also undertaken to characterise sites.

Data Review and Consultation. Baseline data from the ROMP review (WYG Design and Design, 2011) and conservation management monitoring work undertaken for Hanson were used to characterise the potential species to record for pond, stream and flooded quarry sites and to focus on target species previously noted including Great Crested Newts and otters (Greshon, 2014; Hanson 2016). ESRI ArcMap (v10.5.1) and aerial imagery was used to map the current extent of wetlands across the landscape around the quarry site. External stakeholders were consulted [South Gloucestershire Council; Avon Wildlife Trust; National Biodiversity Network and Natural England] on potential wetland biodiversity interests in the vicinity of the quarry complex.

Water Quality Assessment and Waterbody Characteristics. Water bodies and courses water quality parameters were determined due to their influence on wetland biota and restoration. Water quality surveys were undertaken in two events; May (14^{th} and 16th) and July (24^{th} and 26th) 2018, to determine seasonal influences on biota. For each event, sampling attempted at a range of wetland sites, reflecting their relative numbers: eleven ponds, two scrapes, two quarry sumps in Hampstead Farm, the Brinsham Stream up and down stream of the sump discharge point, and flooded quarry voids (Lake Edwards, Barnhill, Tytherington and Cromhall).

Water quality parameters were recorded in situ using a Jenway 540 meter (water temperature and pH) and Hach HQ40d multimeter (electrical conductivity and dissolved oxygen). Dissolved oxygen concentration was chosen as it is a key requirement for aquatic life (Metcalf, 1989); pH, due to its influence on the availability of minerals and potential to influence aquatic biodiversity (Biggs *et al.,* 2005); and electrical conductivity, as an indicator of nutrients (elements) in solution (Bruckner, 2013).

Subsequently in the laboratory, alkalinity was determined by titration (APHA, 1999a) and suspended solid concentrations were determined by filtration through 1.2 µm microglass fibre filters, as high levels of suspended solids can affect physical parameters such as light penetration, temperature changes and water depth - impacting aquatic biota (Bilotta and Brazier, 2008). The filtrate was then used to determine nutrient and metal concentrations; these were chosen as potential explanatory factors to eutrophication, plant growth limitation, or potential contaminants arising from the quarried limestone. Nitrate and ammonium were measured using Mettler Toledo ion-selective electrodes (Nico200 Ltd., 2012); soluble reactive phosphate (predominantly orthophosphate) using the molybdenum-blue method (APHA, 1999b); and potassium and metal ion concentrations by flame atomic absorption spectrometry (FAAS; USEPA, 2007).

The steepness of sampled areas (for macroinvertebrates) was qualified into four categories; very shallow (10:1 gradient), shallow (4:1), moderate (2:1) and steep (>2:1). Aerial imagery (Google Earth, 2018) was used to estimate the extent of shallow waters (less than 2 metres depth, after Whitehouse, 2008), the number of ponds within 100m and 500m of each waterbody and the time when water bodies were established, using historical imagery take at intervals from 1999. Staff managers and Landscape Architects were also consulted to verify dates for waterbody establishment (Chen 2018; Duncan, 2018; Hemming, 2018).

Wetland Biodiversity Assessment. To inform future restoration, biodiversity and water quality surveys were undertaken April to August 2018. GCN surveys were being undertaken by consultants in 2018 and this research supplemented and drew upon this work. Torch and bottle trap surveys were undertaken at all old and new ponds and scrapes east of Hampstead farm from 12th April to 8th June 2018.

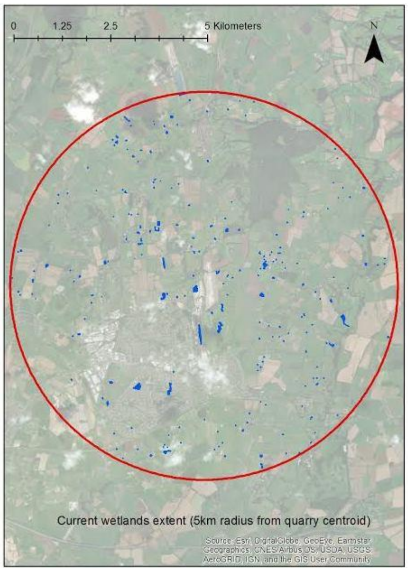

Figure 2. Current Wetland Extent (5 Km Radius from Quarry Centroid).

Macroinvertebrates were sampled from a representative subset of sites assessed for macrophytes and water quality. In May (14th and 16th) 2018 macroinvertebrates were sampled at 15 sites, and in August (7th and 9th) 2018 from 12 (due to some having dried up). Aquatic invertebrate sampling followed the National Pond Survey methodology (Biggs *et al.*, 1998).

Samples were collected through up to three minutes of vigorous sampling using a sweep net, in 30 or 60 second episodes within a given sampling location. Samples were sorted bankside in a white tray to identify invertebrates to family level. Most were recorded in the field, with small numbers preserved and identified in the laboratory. In the May sampling period, if newt efts were found in samples from ponds known to support Great Crested Newts sampling stopped at that point. A licence holder was present at all times. Consequently, the data may be subject to sampling bias.

Plant species, chiefly submerged and floating aquatic macrophytes plus emergent and wetland margin species (Pond Conservation Trust, 2002) were recorded where present at each sampling site during surveys in May (14th and 16th). In addition, on 20th July two transects were surveyed from the 'outer pond edge' (Biggs *et al*., 1998) across the largest old pond to determine the depth distribution of emergent and aquatic plant species. Charophyte species were recorded as a particular feature of ponds in the quarry complex and important in the region (JNCC, 2007).

Two wildlife Capture cameras were set up under the bridge over the Brinsham Stream and two at the old ponds east of Hampstead Farm to determine the extent to which otters and other species used the Brinsham Stream as a wildlife corridor or visited the ponds. The cameras were set up for two periods: 18th – 22nd June; and 20th July – 7th August 2018. When conducting water quality and other biodiversity surveys, waterbodies were checked for signs of otters, deer and other species.

Data Analysis. Data analysis has been undertaken to relate physical and chemical water quality and biological assemblages (invertebrate assemblages and wetland flora) between ponds and other water bodies to determine key factors influencing wetland biodiversity and habitat quality. Invertebrates were the key focus as, through their effectiveness in indicating environmental change, they are good indicators of environmental quality as well as valuable components of biodiversity (Environment Agency & Freshwater Habitats Trust, 2002).

Data were collated using Microsoft Excel (Microsoft, 2018) and via shared Google Sheets in Google Drive (Google, 2018a). Statistical analysis was undertaken using R v3.4.2 (RFSC R Core Team, 2018). To determine key environmental influences on macroinvertebrate biodiversity, constrained ordination was undertaken. Factors were included in a forward stepwise redundancy analysis (RDA). Explanatory variables were also tested for colinearity using Spearman's Rank and covarying variables ($\rho > 0.7$) were removed (Annex 3). Potential bias caused by reduced sampling in ponds where GCNs were present was partially accounted for by incorporating sampling effort (in seconds, Table 4) into the constrained ordination model.

Results

Data Review and Consultation. Feedback from local and regional consultees didn't provide any new data for wetland biodiversity in the vicinity of the quarry complex. Pond and other wetland sites were collated on a digitised map (Figure 2) that was used to determine the number of nearest neighbour ponds and other waterbodies (NN500) for a given water body and used in multivariate analyses.

Water Quality Assessment and Waterbody Characteristics. The very hot summer caused some waterbodies (scrapes and ponds) to dry out by July (Tables 1 and 2) and others were very low. All waters were circum-neutral to slightly alkaline. Quarry void waters were characterised by very low phosphate levels, relatively high nitrate levels slightly elevated zinc, and very low iron, manganese and potassium. The lowest Dissolved Oxygen levels were recorded upstream in the Brinsham Stream (mean 6.43 mg/L in May) though some new ponds had dropped substantially by July, due to severely reduced water levels and high water temperatures. Apart from Pond 6, pond waters were characterised by relatively high DO values and suspended solids, relatively low conductivity values, nitrate and ammonium levels comparable to other sites, very low phosphate levels, extensive shallow waters, higher temperatures, slightly elevated iron levels and traces of manganese. Waterbody characteristics were incorporated into multivariate analyses to determine key factors influencing wetland biodiversity.

Table 1. Summary statistics for key physical and chemical water quality parameters recorded for all sites in May 2018.

Mean values, (SD) = Standard Deviation, N Site = Number of sites sampled; n = Total samples across sites. Up/down stream relates to sump discharge point.

Sites	Diss Oxygen / mg/L	Cond / uS/ cm	Temp deg C	pH (Median)	Area Depth <2m, %	Sus Solids /mg/L	Ortho-phosphate /ppm	Nitrate /mg/L	Ammonium /mg/L	Tot Alkal /mg/L	Zinc /mg/L	Iron /mg/L	Manganese /mg/L	Potassium /mg/L	No. Sites Water Present
Old Ponds N Site = 3 n = 9	14.23 (2.66)	554.40 (80.34)	22.60 (2.10)	8.36 (0.38)	100.00 (0.00)	28.75 (29.22)	0.00 (0.00)	8.28 (6.78)	0.31 (0.03)	2181 (561)	0.00 (0.00)	0.11 (0.11)	0.04 (0.05)	0.00 (0.00)	3
New Ponds N Site = 7 n = 21	12.16 (2.65)	360.26 (124.85)	22.45 (1.21)	8.14 (0.61)	100.00 (0.00)	33.23 (60.91)	0.00 (0.00)	2.44 (2.19)	0.19 (0.07)	1258 (589)	0.00 (0.00)	0.31 (0.11)	0.06 (0.08)	0.00 (0.00)	7
New Scrapes N Site = 2 n = 6	11.98 (0.78)	329.25 (99.95)	27.45 (0.21)	8.74 (0.19)	100.00 (0.00)	16.82 (10.99)	0.00 (0.00)	1.70 (0.30)	0.20 (0.03)	1419 (90)	0.00 (0.00)	0.23 (0.14)	0.02 (0.04)	0.00 (0.00)	2
Quarry voids active N Site = 5 n = 15	10.81 (2.68)	844.40 (37.90)	15.26 (1.14)	7.83 (0.22)	3.40 (2.19)	7.02 (3.98)	0.03 (0.10)	9.43 (5.14)	0.47 (0.04)	2189 (433)	0.06 (0.08)	0.01 (0.04)	0.00 (0.00)	0.63 (1.66)	5
Quarry voids closed N Site = 4 TSS =12	11.56 (1.16)	645.87 (280.75)	15.51 (0.68)	8.49 (0.30)	6.50 (2.42)	3.48 (3.07)	0.02 (0.05)	5.23 (4.93)	0.40 (0.08	2042 (433)	0.06 (0.11)	0.06 (0.06)	0.02 (0.04)	0.42 (1.46)	4
Brinsham Up Stream N Site = 1 n = 3	6.43 (0.00)	846.00 (0.00)	11.20 (0.00)	7.71 (0.00)	100.00 (0.00)	10.17 (2.92)	0.27 (0.03)	3.83 (1.95)	0.39 (0.04)	2707 (29)	0.01 (0.01)	0.13 (0.01)	0.15 (0.01)	0.00 (0.00)	1
Brinsham Down Stream N Site = 1 n = 3	10.53 (0.00)	885.00 (0.00)	13.10 (0.00)	8.06 (0.00)	100.00 (0.00)	5.19 (0.30)	0.00 (0.00)	4.03 (0.18)	0.46 (0.03)	2533 (58)	0.14 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	1
Pond 6 (restored) N Site = 1 n = 3	11.68 (1.46)	628.33 (13.20)	23.73 (0.65)	8.00 (0.06)	100.00 (0.00)	167.04 (75.30)	0.07 (0.13)	1.95 (0.37)	0.41 (0.01)	2859 (119)	0.03 (0.01)	0.09 (0.08)	0.04 (0.06)	1.45 (2.52)	1

Table 2. Summary statistics for key physical and chemical water quality parameters recorded for all sites in July 2018.

Mean values, (SD) = Standard Deviation, N Site = Number of sites sampled; n = Total samples across sites. Up/down stream relates to sump discharge point.

Sites	Diss Oxygen / mg/L	Cond / uS/ cm	Temp deg C	pH (Median)	Area Depth <2m, %	Sus Solids /mg/L	Ortho-phosphate /ppm	Nitrate /mg/L	Ammonium /mg/L	Tot Alkal /mg/L	Zinc /mg/L	Iron /mg/L	Manganese /mg/L	Potassium /mg/L	No. Sites Water Present
Old Ponds N Site = 2 n = 4	11.15 (3.21)	501.00 (74.36)	25.63 (1.39)	8.33 (0.35)	100.00 (0.00)	15.73 (12.25)	0.00 (0.00)	1.70 (1.28)	0.23 (0.04)	2215 (268)	0.00 (0.00)	1.24 (0.57)	0.10 (0.18)	0.00 (0.00)	2
New Ponds N Site = 6 n = 18	8.03 (5.57)	505.58 (141.06)	26.59 (1.84)	7.81 (0.74)	100.00 (0.00)	60.50 (54.80)	0.00 (0.00)	0.82 (0.65)	0.44 (0.35)	1773 (574)	0.00 (0.00)	0.29 (0.44)	0.18 (0.34)	2.51 (4.43)	6
New Scrapes N Site = 2 n = 0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
Quarry voids active N Site = 4 n = 12	10.66 (1.04)	836.50 (11.21)	22.00 (3.55)	8.20 (0.14)	4.00 (2.00)	4.53 (1.81)	0.00 (0.00)	2.41 (1.07)	0.43 (0.06)	1924 (345)	0.01 (0.05)	0.00 (0.03)	0.00 (0.00)	0.00 (0.00)	2
Quarry voids closed N Site = 3 TSS =21	10.29 (1.33)	679.96 (199.93)	22.76 (1.12)	8.27 (0.21)	6.17 (2.34)	2.79 (2.53)	0.03 (0.09)	4.27 (4.53)	0.39 (0.11)	1757 (381)	0.00 (0.01)	0.01 (0.02)	0.00 (0.00)	0.31 (1.48)	3
Brinsham Up Stream N Site = 1 n = 3	8.44 (0.00)	796.15 (0.00)	19.92 (0.00)	8.20 (0.00)	100.00 (0.00)	4.75 (1.45)	0.01 (0.00)	1.87 (0.54)	0.39 (0.04)	2012 (546)	0.03 (0.02)	0.00 (0.00)	0.00 (0.01)	0.06 (0.00)	1
Brinsham Down Stream N Site = 1 n = 3	9.09 (0.00)	862.00 (0.00)	16.90 (0.00)	7.84 (0.00)	100.00 (0.00)	3.15 (0.11)	0.00 (0.00)	1.02 (0.78)	0.40 (0.03)	1486 (136)	0.05 (0.02)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	1
Pond 6 (restored) N Site = 1 n = 0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0

Aquatic-Emergent Macrophyte Survey. 146 plant species were recorded in and around the waterbodies and along the Brinsham Stream. Of these, 47 were classed as submerged and emergent macrophyte or as PSYM species (after Pond Conservation Trust, 2002), plus two stoneworts (Charophytes) (see separate specied lists submitted). Active quarry voids were species poor (Table3). Only two pioneer emergent species (*Agrostis stolonifera* and *Epilobium hirsutum* were recorded in the Hampstead Sumps. However six emergent species were recorded at Lake Edwards including *Phragmites australis* and *Carex* species. No macrophytes at all were recorded at Tytherington. Vegetation along Brinsham Stream comprised mainly common emergent macrophytes, though in addition the immersed species *Potamogeton crispus* and *P. natans* were recorded. The old and new ponds were supported the most biodiverse flora with a rich assembly of aquatic and emergent species, including Charophytes. In old ponds, Charophytes formed large, largely monoculture stands that formed a mat of decaying vegetation when, by July, water levels dropped substantially.

The transects of old established pond showed that from the outer pond edge down to approximately 0.5 m depth, macrophytes comprised mainly emergent species such as *Typha latifolia, Juncus* species, *Carex flacca Ranunculus flammula, Mentha aquatic, Schoenoplectus lacustris, Alisma plantago-aquatica* and *Pulicaria dysenterica*. Between 0.5 and 1.1m depth, *Charophyta* were most abundant with occasional *Equisetum fluviatile, Potamogeton natans, Schoenoplectus lacustris* and *Eleocharis palustris*. Below 1.6 m depth, *Potamogeton natans* was most abundant with occasional *Charophyta, Equisetum palustris* and some bare ground. Maximum water depth was estimated to be just over 2m in the deepest pond on site.

Table 3 Summary of Plant Species Survey Records; Total Number of Species Recorded Across sites (mean per site)

	No. Sites	No. Aquatic / Emergent species	No. Charophyte Species	No. Other species	Typical Aquatic/Emergent Species
Old Ponds	4	20 (7.5)	2	36 (11.5)	*Carex flacca, Juncus articulatus, Juncus inflexus, Potamogeton natans, Pulicaria dysenterica, Typha latifolia, Chara "hispida"*
New Ponds	4	26 (13.5)	2	57 (25.0)	*Agrostis stolonifera, Alisma plantago aquatic, Carex flacca, Eleocharis palustris, Glyceria notate, Juncus articulatus, J. conglomeratus, J. effuses, J. inflexus, Potamogeton natans, Schoenoplectus lacustris, Typha latifolia. Chara "hispida"*
New Scrapes	2	15 (10.0)	1	27 (16.5)	*Carex flacca, Deschampsia flexuosa, Juncus articulatus, J. effusus, J. inflexus,*
Quarry Voids Active	3	8 (2.7)	0	36 (12.3)	Varied
Quarry Voids Closed	4	15 (5.0)	1	51 (16.5)	*Agrostis stolonifera, Carex flacca, Juncus inflexus, Rannculus trichophyllus, Solanum dulcamara*
Brinsham Stream	2	14 (7.0)	0	37 (18.5)	*Apium nodiflorum, Epilobium parviflorum*
Totals	19	47	2	99	

Aquatic Macroinvertebrate Survey. In all, taxa representative of 56 families were recorded during the May and August surveys. The highest number of families were found in the oldest pond (P1, 34), and fewest within the scrape, which was dry by August (ASc3, 9) (Figure 4a). On average, the three newly created ponds supported 27 families (min. 26, max. 28). P6 (restored old pond) and the scrape tended to support commonly encountered taxa (but were sampled the least), whilst the stream sites contributed unique taxa (Figure 4b). The most frequently encountered orders were Diptera (true flies), Hemiptera (true bugs), Trichoptera (caddis flies) and dragonflies (Odonata) (Table 4).

Detrended Correspondence Analysis (DCA) (Annex 3) for May clearly identified the presence of taxa unique to the Brinsham Stream (BS1.US, BS2.DS) such as Elmidae (riffle beetles), Rhyacophilidae (net-spinning caddis), Perlodidae (stonefly) and Nemouridae (stonefly). Many other sites supported stillwater specialist taxa such as Lestidae (damsel fly) and Chaoboridae (ghost midge larva). In addition, Gyrinidae (whirligig beetle) and Culicidae (mosquito larvae), were indicative of the Hampstead sump (H1.S) and Ephemereliidae (*E. danica*), which was unique to the old pond (P1). The August data indicated that axis one was positively associated with a broader set of taxa common to still and flowing waters including Sphaeriidae (pea mussels), Erpodellidae (leech) and Leptophlebidae (mayfly), but negatively associated with still-water specialists such as Helophoridae (water scavenger beetles), Noteridae (water beetle) and Acroloxidae (freshwater limpet). The Brinsham Stream assemblages again clustered, with an indication that the quarry void sites (active or closed), supported similar communities to each other.

Constrained Ordination of Macroinvertebrates and Environmental Parameters. Macroinvertebrates were the key focus due to their sensitivity to environmental conditions and indicators of habitat quality and the influence of all environmental parameters recorded (water quality, waterbody characteristics and macrophytes) were included in this analysis. In the constrained ordination for May, the RDA was highly significant (ANOVA , $p < 0.001$, 999 permutations) and explained 36.7% of the variance in the macroinvertebrate assemblages. RDA axes 1 and 2 were significant (ANOVA, $p < 0.05$, 999 permutations) and accounted for 23.9% and 12.7% respectively and strongly associated with dissolved oxygen and nitrate respectively. Dissolved oxygen was highly correlated with macrophyte species richness (Spearman's Rho 0.87, Figure 4) and higher values of DO were associated with more diverse sites (e.g. P1 = 27 families, NP6 = 19)(Annex 3). In addition, Spearman's Rank between macrophyte and macroinvertebrate richness was 0.58. The July model was highly significant (ANOVA , $p < 0.05$, 999 permutations) and explained 22.7% of the variance in the macroinvertebrate assemblages on. Only RDA axis 1 was marginally significant (ANOVA, $p < 0.05$, 999 permutations), which accounted for all explained variation. The forward stepwise procedure identified the number of neighbouring ponds within a 500m radius (NN500) as the only significant explanatory variable, with diverse sites positively associated with this axis (e.g. NP4 = 23 families, P1 = 26).

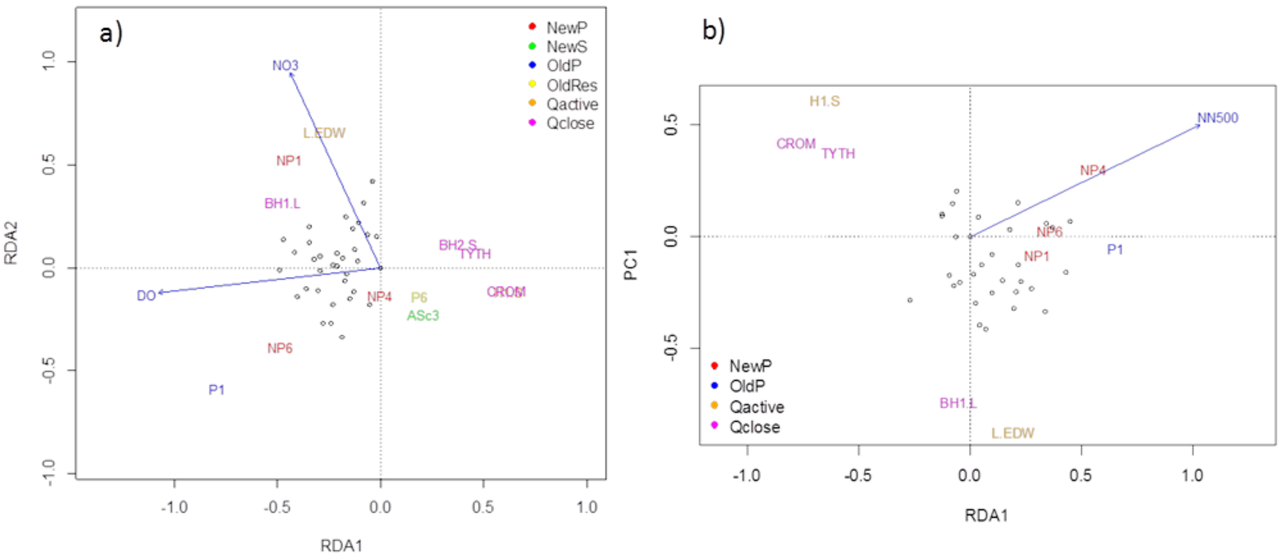

Figure 4. Redundancy analysis, macroinvertebrates: physical and chemical parameters. a) May 2018, b) August 2018. Key: OldP = Old Ponds; NewP = New Ponds, NewS = New Scrapes; Old Res = Old Restored Pond; Qactive = Quarry Void Active; Qclose = Quarry Void closed to extraction.

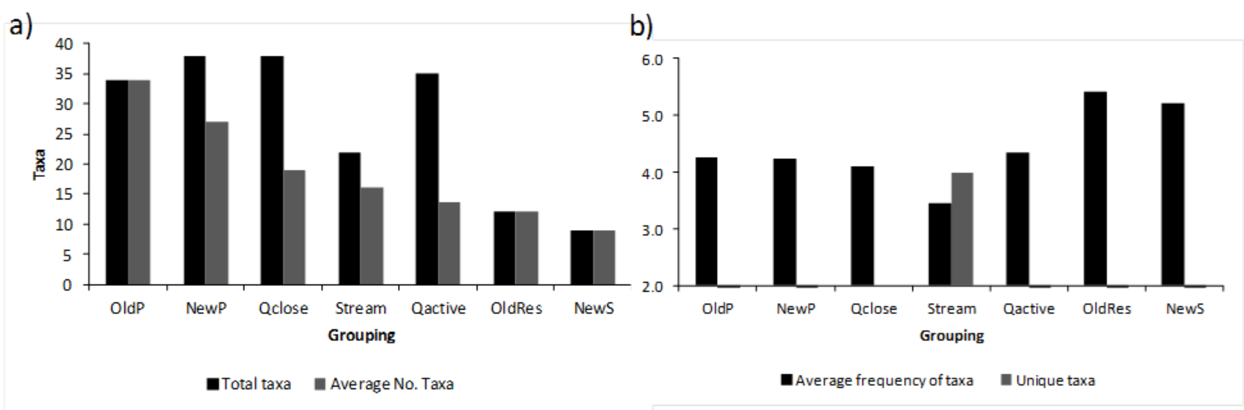

Figure 5 Macroinvertebrate diversity summary a) Total and average taxa (no. families) recorded within each water body type (May + August), b) The average number of water body types taxa recorded within (min. 1, max. 7), where a high number indicates the presence of commonly recorded taxa and the number of families recorded only within a given water body type (unique taxa).

Great Crested Newt and Otter Surveys and Other Wildlife records. GCNs were recorded in all old ponds, scrapes and new ponds surveyed for this project. They were reported breeding in all ponds (new and old). In addition, efts (species unknown) were recorded at Lake Edwards, Tytherington and Cromhall. GCNs had also been reported at Cromhall (Chen, 2018). Otter was recorded at the Brinsham Stream Bridge (image capture) as were muntjac deer, rabbits, rats, badgers and grey squirrels. No evidence of otters (spraints, images of tracks) was recorded at other survey sites. Badgers also visited the old ponds (images) and deer slots were recorded at several old and new ponds.

Table 4. Summary Statistics for Macroinvertebrate Surveys. May and August assemblages combined. Total numbers of families recorded for water bodies sampled. Green shading indicates families noted in PSYM analysis (Ponds Conservation Trust, 2002)

		ALDERFLIES	BEETLES	BIVALVES	BUGS	CADDISFLIES	DAMSELFLIES	DRAGONFLIES	FLATWORMS	FLY LARVAE
	Sample seconds May, July	Megaloptera	Coleoptera	Bivalvia	Hemiptera	Trichoptera	Odonata	Odonata	Platyhelminthes	Diptera
Old Pond	90, 180	1	6	1	7	3	2	2	0	6
New Pond	220, 540	1	6	0	6	2	2	3	0	8
Scrapes	60, 0	0	3	1	1	0	1	1	0	2
Brinsham Sream	360, 360	1	3	1	0	5	0	0	1	2
Quarry Voids Active	540, 360	0	6	0	7	3	1	3	1	6
Quarry Voids Closed	720, 720	1	7	0	6	6	2	2	1	7
	Sample seconds May, July	LEECHES	MAYFLIES	SHRIMPS	SNAILS	STONEFLIES	WATER SLATER	WORMS	MOTHS	
Old Pond	90, 180	Hirundinea	Ephemeroptera	Amphipoda	Gastropoda	Plectoptera	Isopoda	Oligochaetes	Lepidoptera	Total
New Pond	220, 540	0	3	0	3	0	1	1	1	37
Scrapes	60, 0	0	2	2	3	0	1	1	1	38
Brinsham Sream	360, 360	0	0	0	1	0	0	0	0	10
Quarry Voids Active	540, 360	2	2	1	0	2	1	1	0	22
Quarry Voids Closed	720, 720	0	2	2	1	0	1	1	1	35
		0	3	0	1	0	1	1	1	39

Discussion

Water quality across the sites was generally good or very good. The ponds and quarry lakes could be classed as hard oligo-mesotrophic waters in terms of pH (Interagency Freshwater Group, 2015). The presence of *Chara* species forming dense mats in old and some new ponds also suggest these waters are oligo-mesotrophic with this characteristic benthic vegetation. Some waters could be classed as being of Good Ecological Status in terms of dissolved oxygen (>7.0 mg/L in July) and most being of High Ecological Status (>9.0 mg/L in July) (Interagency Freshwater Group, 2015). With the exception of nitrate in some sites, nutrient levels were very low. Water quality for all ponds and lakes was high in terms of phosphate standards devised for the Water Framework Directive (<50 Ug/L: Defra/WG, 2014) except for the Brinsham Stream above the sump discharge point, which was moderate to poor, possibly reflecting agricultural sources. Zinc levels were generally low (Defra/WG, 2014), though some manganese concentrations were a little elevated. However the main concern was nitrate levels; most mean values gave cause for concern being above 1.0 mg/L (Loiselle *et al.*, 2016; McGoff *et al.*, 2017) due to the potential to cause eutrophication and algal blooms. The highest mean values were recorded in quarry void waters, indicating a contribution from groundwater. Multivariate analysis indicated that nitrate levels were a significant influence on macroinvertebrate assemblages.

The macrophyte communities recorded were diverse and contributed substantially to the ecological value of the wetland sites. The presence of *Chara* species forming dense mats in older clay-based ponds was a particularly interesting component (Lansdown *et al*., 2006) and these may have provided particular protection to invertebrates and GCNs during the July drought. The community resembled National Vegetation Classification A9 *Potamogeton natans* community, which is typically found in mesotrophic to fairly nutrient-poor waters (Rodwell, 2000). However a number of typical species were absent indicating that the community development was incomplete, possibly due to relative isolation, being relatively young ponds (up to 18 years) or a lack of a suitable seed source in the region.

The macrophytes provided a habitat for macroinvertebrates as indicated by the high correlation between macrophyte and macroinvertebrate richness. These rich macroinvertebrate assemblages were also strongly correlates with nitrate levels, dissolved oxygen and wetland connectivity/proximity (number of waterbodies within 500m). Dissolved oxygen was strongly correlated with macrophyte richness and shallow slopes/water, the latter two being heavily covariant. The importance of connectivity for landscape scale conservation and long-term resilience of specialist freshwater invertebrate species has been recognised by others (Gledhill *et al.,* 2008; Hill *et al.*, 2018).

In summary, this research clearly shows that shallow, low nutrient status calcareous waters linked to limestone quarries can be colonised by a diverse community of macrophytes. Due to their presence, the habitat they form and cover these macrophytes provide, the waters will be rich in dissolved oxygen and support a rich assemblage of macroinvertebrates. This project has shown that if the correct conditions are provided, species can readily colonise and biodiversity will be enhanced. However there needs to be a well-connected pond network in the surrounding region for macrophyte and macroinvertebrates to colonise such waterbodies. Furthermore this research also indicates that a range waterbody types will provide a range of conditions, increasing macroinvertebrate diversity e.g. closed quarries and Brinsham Stream providing habitat for some unique families.

Shallow lakes and ponds are less at risk of deoxygenation due to mixing of air into water by the wind (Interagency Freshwater Group, 2016). However the deep lakes that will form in the flooded voids at Chipping Sodbury (estimated to be around 80m AOD) will be relatively narrow, steep-sided (benched or with a steep dip slope) and very deep. As such they will be at risk of becoming anoxic at depth; at Cromhall aerators are deployed in summer to maintain dissolved oxygen levels (Chen, 2018). Therefore there is a need for a re-think about the creation of several large deep-water bodies as outcome of restoration at Chipping Sodbury as this may have limited potential for biodiversity enhancement.

Deep lakes are unavoidable but if extensive areas of shallows with a gradation of water depths can be created i.e. reduce the ratio of deep water to shallows, then this project has shown that biodiversity will benefit if there are sources nearby from which species can colonise. For example, despite being within an active area of the quarry Lake Edwards, this relatively isolated waterbody supported 21 families, where there were shallow areas at the margins of the lake, even though the aquatic plant species diversity was not particularly high (6 species). In contrast, Cromhall only supported 3 macroinvertebrate families and here the lake has steep sides with no edge or shallow area.

The shallows will need to allow for a zone of water draw down as it is very difficult to predict the actual final water depth (Veakins, 2018). Draw down zone may be 10-20 metres but with a shallow gradient over this distance rather than sheer drop or edge into deeper water, the draw down zone itself will develop into marginal habitat prone to flooding, which will have a biodiversity value.

Overall, the ecological value of the post-closure Chipping Sodbury quarry complex would be maximised through encouragement of the development of a mosaic of wetland habits ranging from deep lakes to shallows, marshy grassland, wet woodland, with some restoration blasting to create a softer contour/lake edge, with addition of subsoils and clay (RSPB, 2016). In advance of full quarry completion and flooding, the edge of the lake and adjacent areas could incorporate scrapes and ponds to allow freshwater habitat development. This will be dependent on there being sufficient clay to create the required landform. The aim of this type of restoration would be to create new wetland habitats that connect ecologically and possibly hydrologically with the surrounding landscape and habitats, providing ecological and hydrological connectivity between the quarry lake and the surrounding landscape once the lake is formed.

Recommended Restoration Prescriptions

To maximise biodiversity of lakes in the restored limestone quarries, the primary aim should be to create as much shallow marginal wetland habitat as possible to enable aquatic and emergent macrophytes and macroinvertebrates to establish and flourish, as has been achieved at several case study sites. Key to this aim is determining the level to which water will fill voids. Shallow margins can be developed by a more creative approach to restoration, often for little or no additional cost; waste quarry material that needs to be moved anyway could simply be moved to a different location than a disposal tip and deposited:

- Tipping waste overburden, rock and soil (low nutrient status) onto upper benches to create (gently) shelving and undulating edges in the drawdown zone of a lake (RSPB, 2016). These zones need to be as wide as possible and should coincide with the water depth range from zero to -2 or preferably -10 metres from the 'outer pond edge' of the lake (Biggs *et al.,* 1998). The zones would be particularly successful where springs run from bench walls, adding greater environmental and habitat variation. Locations – wherever quarry benches can be accessed to tip onto: Barnhill, Hampstead Farm, Southfields, Brinsham sites. Material extracted from Brinsham East and West and even translocate material already tipped in Compartment 3 could be relocated for this purpose. In Compartment 3 more wetland, wet grassland and wet woodland habitats could be created, which through proximity would promote colonisation of the flooded voids.

- Creating occasional small islands in this marginal zone or slightly deeper water, topped by gravel or sparse vegetation. Such structures may provide roosting or breeding sites for waterfowl and on their banks provide additional drawdown habitat for macrophytes and macroinvertebrates. At Chipping Sodbury islands could be created at the northern end of Barnhill and Southfields, and possibly parts of the Brinsham sites.
- Breaking up dip slopes in quarry voids within the drawdown zone (0 to -10m) to create an irregularly pock-marked surface that enables soil/sediment to collect and plant species to anchor and so provide locations for marginal and emergent habitats to develop.
- Linked to the above, restoration blasting to create a softer and more extensive contour/lake edge, with addition of subsoils and clay (RSPB, 2016).
- Facilitating natural regeneration to maximise ecological value through developing around the periphery of the quarry voids in advance of their flooding and so provide sources for colonisation. In addition, consider the regional pondscape, locating ponds to infill gaps in order to act as stepping stones to facilitate natural colonisation.
- Managing existing ponds in rotation to interrupt succession to dry land ponds (Sayer et al., 2013)
- In addition biodiversity could be further enhanced by floating planted rafts on the lakes, supporting macrophyte, macroinvertebrate and nesting sites for waterfowl (RSPB, 2016).

In addition to creating the conditions to favour natural colonisation, the regional pond network and connectivity with the Chipping Sodbury site would benefit from development and management. The large number of ponds within the vicinity of the quarry is the result of historical, superficial exploitation of celestine. As these ponds succeed to dry land or become overtopped by trees and scrub, they will lose their ecological value and therefore cease to be a source or stepping stone for colonisation of the quarry site. It is recommended that Hanson's work with local landowners and conservation groups to encourage the maintenance and enhancement of these waterbodies. Such work might be 'in kind', providing equipment or work teams occasionally. Not only would such work enhance the pond network in the region, it would also benefit community relations.

Long term monitoring will be needed to enable best practice to be applied to other quarries of a similar nature and help overcome the paucity of long-term monitoring to inform best practice in habitat creation/restoration (Parker, 1995).

Conclusions and Recommendations.

This project has demonstrated that to enable freshwater species to rapidly and successfully colonise flooded limestone quarries shallow, low nutrient waters and a range of waterbody and wetland habitats should be created and managed. Much of this work can be undertaken through progressive restoration in advance of quarry closure at little extra cost.

There is also a need to maintain connectivity for species movement through the wider landscape around the restored quarry complex. To achieve this, wetland management beyond the quarries is needed for long-term biodiversity enhancement. If successfully implemented, these approaches could add considerably to the wetland biodiversity value of the Chipping Sodbury Quarry complex and the region within which it sits. Long term monitoring will be needed to enable best practice can then be applied to other quarries of a similar nature.

To be kept and filled in at the end of your report

Project tags (select all appropriate): This will be use to classify your project in the project archive (that is also available online)	
Project focus: ☒Beyond quarry borders ☒Biodiversity management ☐Cooperation programmes ☐Connecting with local communities ☐Education and Raising awareness ☐Invasive species ☐Landscape management ☐Pollination ☒Rehabilitation & habitat research ☒Scientific research ☐Soil management ☐Species research ☐Student class project ☐Urban ecology ☒Water management Flora: ☐Trees & shrubs ☐Ferns ☒Flowering plants ☐Fungi ☐Mosses and liverworts Fauna: ☒Amphibians ☐Birds ☐Insects ☐Fish ☒Mammals ☐Reptiles ☒Other invertebrates ☐Other insects ☐Other species	Habitat: ☐Artificial / cultivated land ☐Cave ☐Coastal ☐Grassland ☐Human settlement ☐Open areas of rocky grounds ☐Recreational areas ☐Sandy and rocky habitat ☐Screes ☐Shrub & groves ☐Soil ☐Wander biotopes ☒Water bodies (flowing, standing) ☒Wetland ☐Woodland Stakeholders: ☒Authorities ☐Local community ☒NGOs ☐Schools ☒Universities

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Annex 2. Acknowledgements

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Annex 3. Details of Multivariate Analyses.

Correlation matrix A correlation matrix was generated in order to consider covariance amongst water quality and physical parameters (Figure 1) using Spearman's Rank to allow for non-parametric data, with complete cases only (i.e. differing *n* between variables).

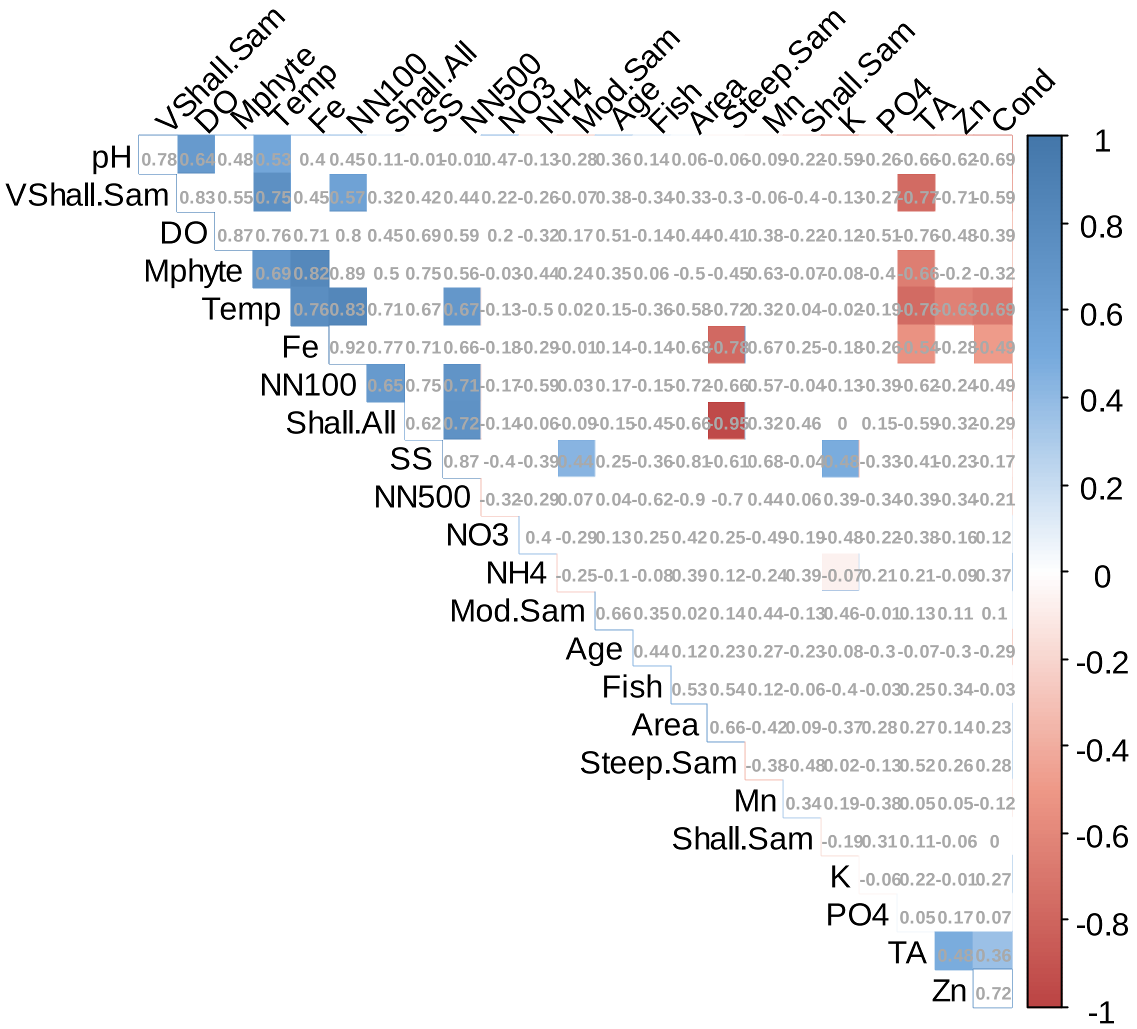


Figure 1. Correlation matrix (Spearman's Rank). Filled cells indicate *p* > 0.01.

Key: blue positive; red negative correlation

Unconstrained ordination

Water quality

Spatial variation in water quality was assessed using a principal coordinates analysis (PCA) of water quality data during May (Figure 2) and July (Figure 3) from across the study. PCA allows for negative numbers (arising from standardisation), as opposed to DCA or NMDS.

In May, the first ordination axis accounted for 37.6% of variance amongst the water quality factors, and was driven primarily by a conductivity and total alkalinity, to temperature gradient, which were inversely correlated. The second PCA axis explained 17.7% of variance and was most strongly associated with changes in manganese and pH, nitrate and dissolved oxygen (Table 1).

Table 1. Water quality variables associated with PCA axes one and two across 22 water bodies in May, 2018.

	SS	PO4	NO3	NH4	TA	Zn	Fe	Mn	K	DO	Cond	Temp	pH
PC1	0.36	-0.58	0.06	-0.71	**-0.84**	**-0.82**	**0.89**	0.15	-0.34	0.66	**-0.99**	**1.03**	0.67
PC2	0.12	-0.39	**0.87**	**0.59**	0.38	-0.06	-0.18	**-0.59**	-0.05	**0.72**	0.21	-0.15	**0.73**

In July, the first ordination axis accounted for 30.1% of variance amongst the water quality factors, and was driven primarily by a suspended solids and potassium, to dissolved oxygen gradient, which were inversely correlated. The second PCA axis explained 24.1% of variance and was most strongly associated with changes in total alkalinity and pH (Table 2).

Table 2. Water quality variables associated with PCA axes one and two across 15 water bodies in July, 2018.

	SS	PO4	NO3	NH4	TA	Mn	K	DO	Cond	Temp	pH
PC1	**0.96**	-0.35	-0.30	**0.77**	-0.10	0.24	**0.97**	**-0.81**	-0.06	**0.47**	-0.37
PC2	-0.04	**-0.56**	**-0.62**	-0.53	**0.81**	**0.57**	-0.32	-0.25	0.10	-0.42	**-0.83**

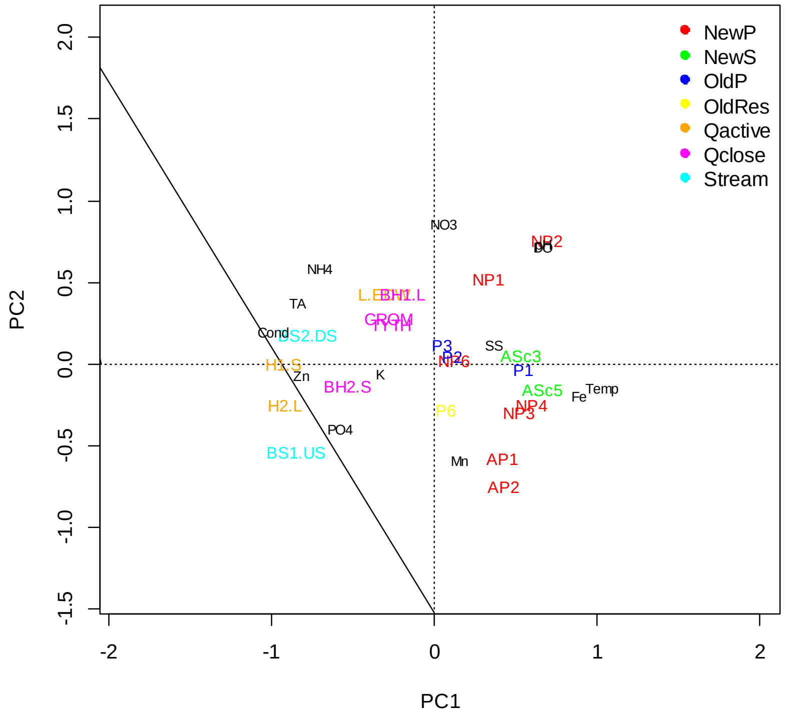


Figure 2 Principal coordinates analysis, water quality (May 2018)

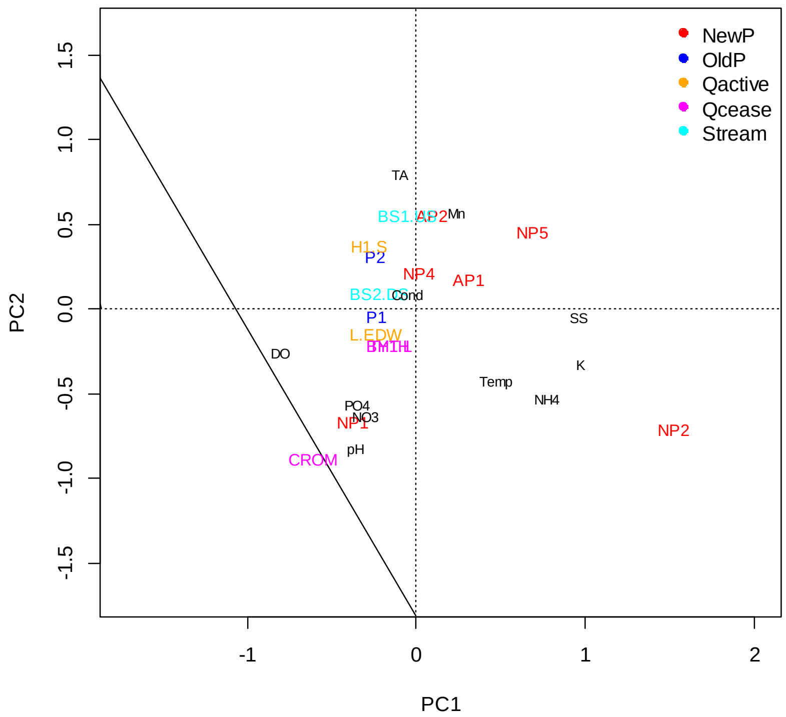


Figure 3. Principal coordinates analysis, water quality (July 2018)

Macroinvertebrates

Spatial variation in macroinvertebrate assemblage was assessed using a detrended correspondence analysis (DCA) of presence/absence data during May (Figure 4) and July (Figure 5) from across the study. Due to the presence of great crested newt (*Triturus cristatus*), the sampling effort for a number of the ponds with known GCN presence was reduced, with netting ceasing to take place wherever efts or adult newts were encountered. A licence holder was present at all times. Consequently, the data may be subject to sampling bias. To partially account for this effect, sampling effort (in seconds), was incorporated into the constrained model (Time_May).

In May, the first DCA axis accounted for the majority of variance across the dataset (see Decorana values, Table 3) and was heavily influenced by the presence of taxa unique to running water e.g. Elmidae (riffle beetles), Rhyacophilidae (net-spinning caddis), Perlodidae (stonefly) and Nemouridae (stonefly). This is reflected in the clustering of the Brisham Stream sites (BS1.US and BS2.DS, Figure 4). At the opposite, negative end of this gradient were stillwater specialist taxa such as Lestidae (damsel fly) and Chaoboridae (ghost midge larva). The second DCA axis related primarily to the presence of Gyrinidae (whirligig beetle) and culicidae (mosquito larvae), which were indicative of the

Hampstead sump (H1.S) and Ephemereliidae (*E. danica*), which was unique to the original newt pond (P1).

Table 3. Summary parameters of DCA analysis of May macroinvertebrate data

Axes:	DCA1	DCA2	DCA3	DCA4
Eigenvalues	0.475	0.184	0.150	0.122
Decorana values	0.551	0.189	0.137	0.067
Axis lengths	3.318	3.059	2.101	1.822

The July data was comparable to May with the first DCA axis again accounting for the majority of variance across the dataset (see Decorana values, Table 4). However axis one was positively associated with a broader set of taxa common to still and flowing waters including Sphaeriidae (pea mussels), Erpodellidae (leech) and leptophlebidae (mayfly), but negatively associated with stillwater specialists such as Helophoridae (water scavenger beetles), Noteridae (water beetle) and Acroloxidae (freshwater limpet). The Brinsham Stream assemblages again cluster, with an indication that the quarry void sites (active or closed), support comparable communities (Figure 5).

Table 4. Summary parameters of DCA analysis of July macroinvertebrate data

Axes:	DCA1	DCA2	DCA3	DCA4
Eigenvalues	0.431	0.171	0.123	0.077
Decorana values	0.506	0.170	0.075	0.022
Axis lengths	3.513	2.199	1.416	1.068

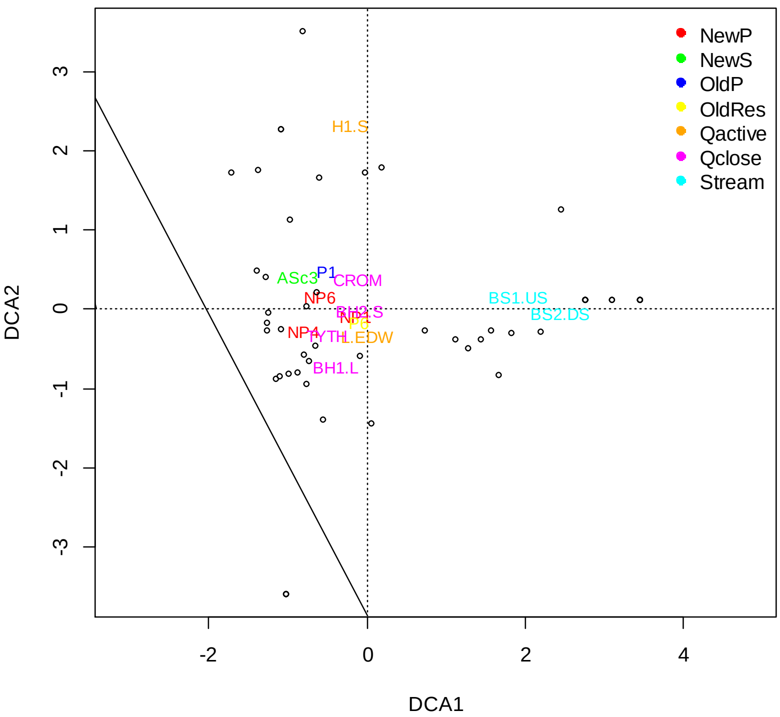


Figure 4. Detrended correspondence analysis, macroinvertebrates, (May 2018)

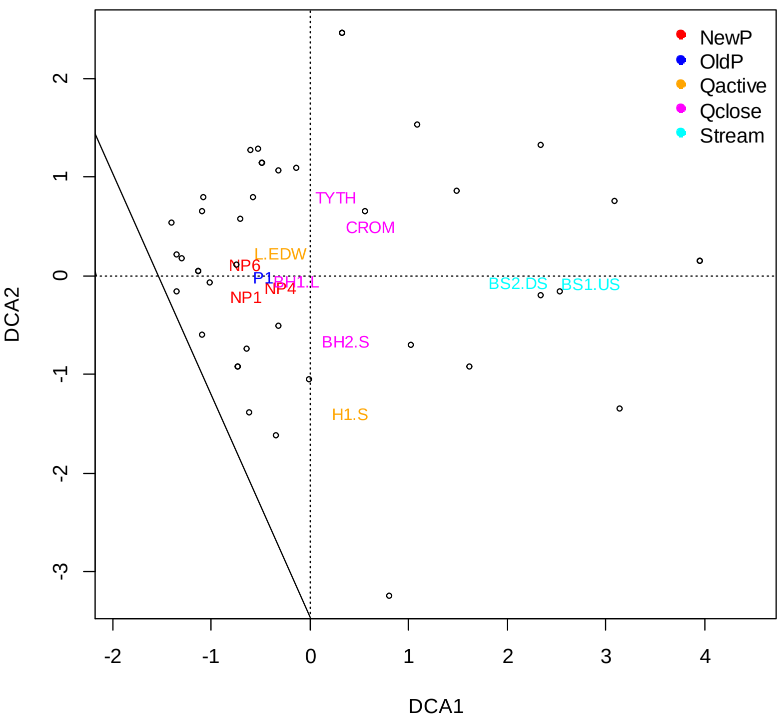
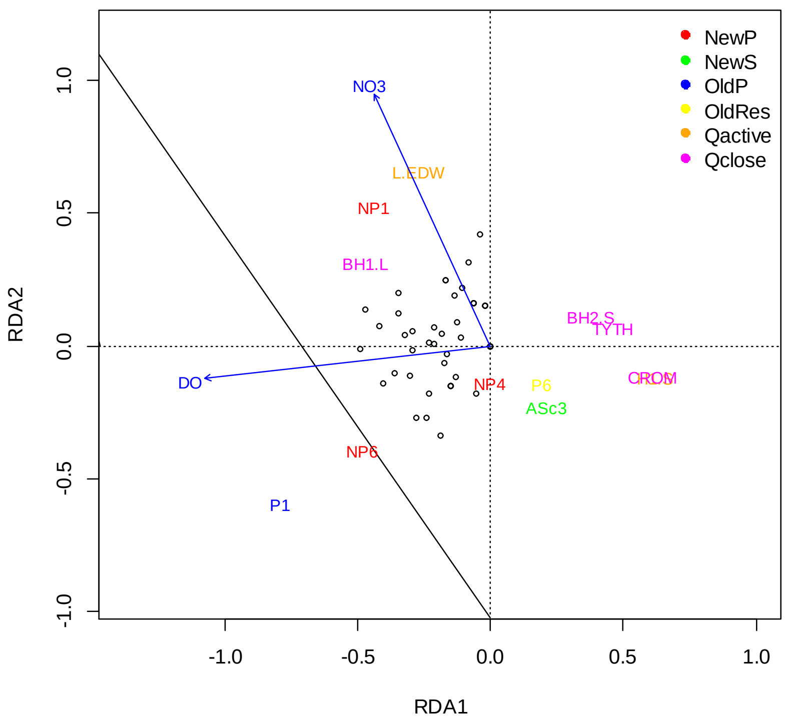


Figure 5. Detrended correspondence analysis , macroinvertebrates, (July 2018)

Constrained ordination

Factors were included into a forward stepwise redundancy analysis (RDA) that, according to previous research and literature, potentially had a causal influence upon the macroinvertebrate community. An RDA was selected due to relatively low turnover of species and the reduced effect of infrequently encountered taxa. Explanatory variables were also tested for colinearity using Spearman's rank (Figure 1), with a single variable retained for ordination from any two that had a correlation coefficient > 0.7 . As a result Fe, ShallowAll, VShall.Samp, NN100 and Temp were removed from the model. To partially account for the effect of unbalanced sampling effort during May sampling (see 0) the variable Time_May (seconds sampled), was incorporated into the model.

The May RDA was highly significant (ANOVA , $p < 0.001$, 999 permutations) and explained 36.7% of the variance in the macroinvertebrate assemblages. RDA axes 1 and 2 were significant (ANOVA, $p < 0.05$, 999 permutations) and accounted for 23.9% and 12.7% respectively. The forward stepwise procedure identified dissolved oxygen and nitrate as significant variables, which were associated with axes 1 and 2 respectively. Dissolved oxygen was highly correlated with macrophyte species richness



(Spearman's Rho 0.87, Figure 1).

Figure 6. Redundancy analysis, macroinvertebrates ~ physical and chemical parameters (May 2018)

The July model was highly significant (ANOVA , $p < 0.05$, 999 permutations) and explained 22.7% of the variance in the macroinvertebrate assemblages. Only RDA axis 1 was marginally significant (ANOVA, $p < 0.05$, 999 permutations) and accounted for all explained variation. The forward stepwise procedure identified the number of neighbouring ponds within a 500m radius (NN500) as the only significant explanatory variable (Figure 7).

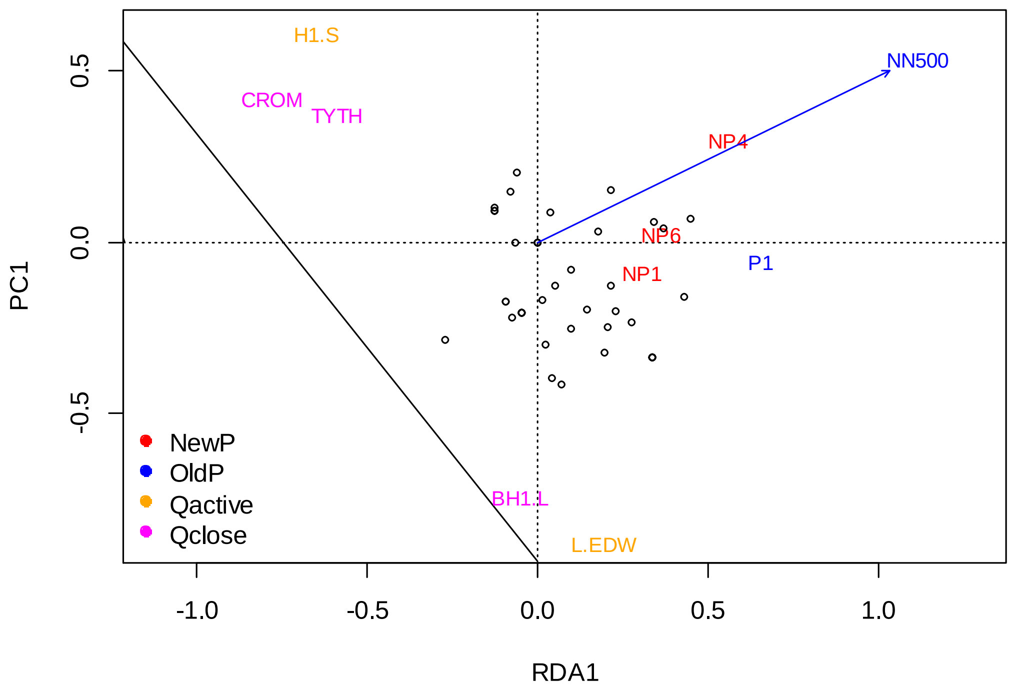


Figure 7. Redundancy analysis, macroinvertebrates ~ physical and chemical parameters (July 2018)

Contribution to taxon richness by each water body type

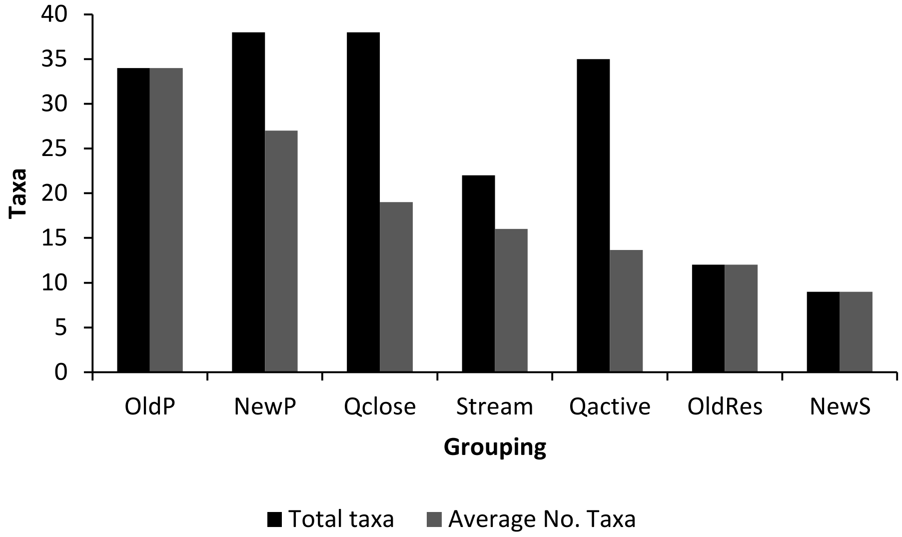


Figure 8. Number of taxa (total and mean per site) within each water body type

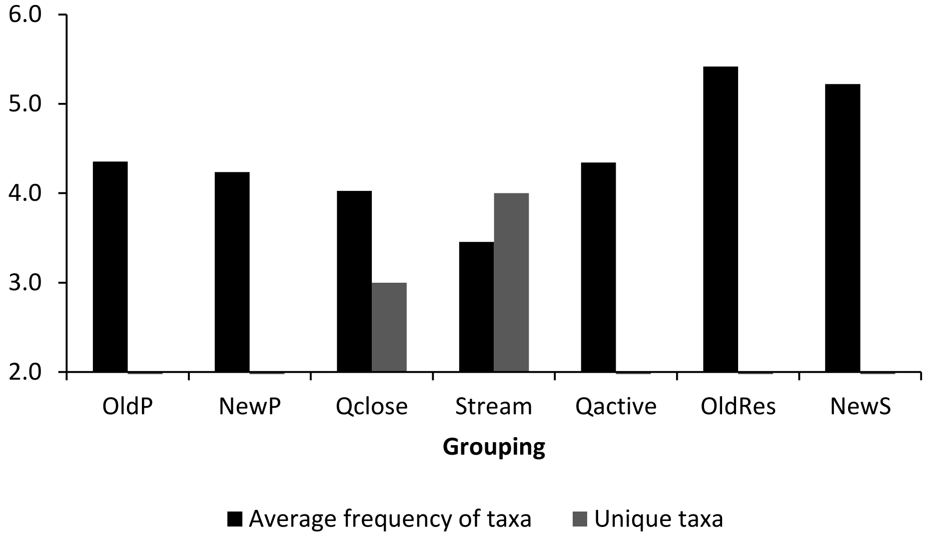


Figure 9. Mean frequency of taxa (mean number of groups taxa recorded) and number of unique taxa contributed by each water body type.