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Ecosystem services provided by urban ponds and green spaces: a detailed study of a semi-natural site with global importance for research

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ABSTRACT

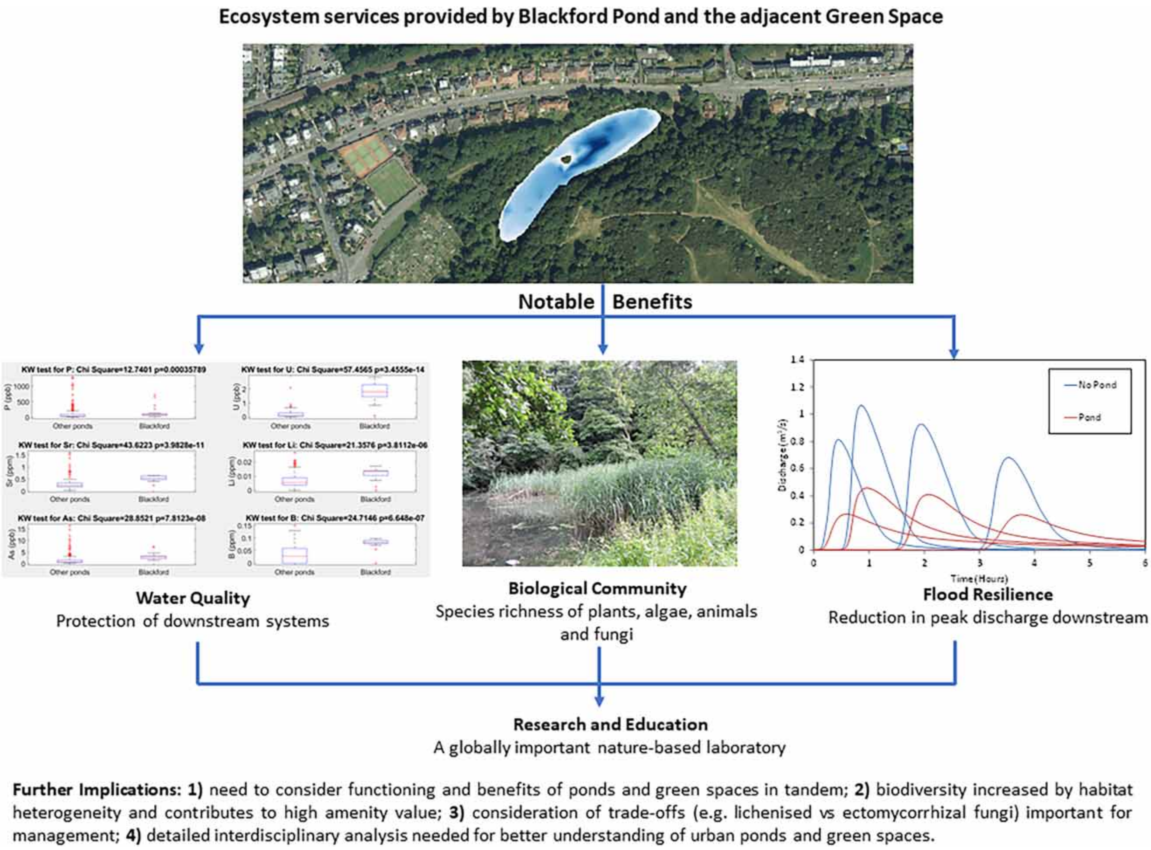
Ponds and the adjacent green spaces are an important part of urban blue-green Infrastructure (BGI) and contribute to a number of ecosystem services, including alleviation of flood risk, amelioration of climatic fluctuations, and improvement of runoff water quality, as well as biodiversity and amenity values. Multiple benefits associated with urban ponds have only recently started to be appreciated, and examples of in-depth interdisciplinary insights remain rare. This paper gives an account of the ecosystem services provided by Blackford Pond, a semi-natural water body located within a nature reserve and nominated as a site globally important for scientific research. Despite elevated levels of polluting substances and eutrophication, the overall species richness of the site is high and the biodiversity of the locality is enhanced by the ecotone effect. The diversity of available plant hosts and substrates appears to benefit the fungal community and the abundance of aquatic invertebrate fauna appears to benefit the higher trophic levels. Hydrological modelling clearly shows that the pond increases the flood resilience of the surrounding area, despite not having been designed as a drainage feature. The application of the Natural Capital Planning Tool (NCPT) also reveals higher values (in relation to the values of amenity grassland) of such ecosystem services categories as biodiversity (+4.76 per hectare), aesthetic values (+4.67), flood risk regulation (+0.41), air quality (+0.28), local (+0.6) and global (+0.14) climate regulations. The discussion highlights a number of trade-offs among different ecosystem services (e.g. water quality vs. diatom research value, flood resilience vs. air quality and carbon capture, biodiversity of ectomycorrhizal vs. lichenised fungi), and considers which of the multiple benefits provided by the site may have not been fully reflected in NCPT calculations or the economic estimates obtained using contingent valuation (e.g. effects on hydrology, water quality, wildlife corridors, education and research value). The simultaneous consideration of biodiversity, hydrology, water chemistry and amenity, education, research and other values presented in this paper contributes towards a better understanding of the ecology and overall functioning of urban ponds, and helps to increase appreciation of their benefits and promote their public acceptability and further implementation.

Key words: biodiversity, birds, flood resilience, fungi, natural capital, plants

HIGHLIGHTS

- Detailed insight is necessary to appreciate ecosystem services benefits.
- Among those, biodiversity, amenity value and flood resilience are the most important.
- Positive benefits also revealed for water quality and climate regulation.
- Overall species richness depends on the diversity of microhabitats and can be high despite problems with water quality.
- Ecological functioning is key for the understanding of ecosystem services.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Well-developed green and blue-green Infrastructure (GI/BGI) is becoming essential for modern urban development (Fenner 2017; Fenner *et al.* 2019; O'Donnell *et al.* 2020). Together with the adjacent green spaces, ponds are an important part of urban BGI and contribute to a number of ecosystem services, including alleviation of flood risk and improvement of runoff water quality, as well as amenity and biodiversity values (Hill *et al.* 2017; CIRIA 2019b; Higgins *et al.* 2019). Particularly important for biodiversity is the provision of habitats, especially when acting as wildlife corridors or 'stepping stones' connecting with other similar areas scattered throughout the urban landscapes (Council Directive 1992; Hassall *et al.* 2016). Previous studies have shown that urban ponds can have a high biodiversity value in terms of aquatic macroinvertebrates, sometimes comparable to non-urban ponds (Hill *et al.* 2017).

Importantly, it is not only the water body itself that provides an important contribution to biodiversity and other ecosystem services, but also the area adjacent to a pond, with the emergent and surrounding vegetation being an important factor in determining the biodiversity of a pond ecosystem (Hassall *et al.* 2016). These terrestrial features contribute considerably to the biodiversity of the terrestrial as well as the aquatic taxa (Krivtsov *et al.* 2020b). When properly managed, ponds and the adjacent green space (GS) are characterised by substantial amenity value and should therefore be regarded as an important component both of BGI and, more generally, of urban green infrastructure (GI).

Due to logistical reasons and policy priorities, the research addressing ponds' water quality tends to concentrate on specific macroinvertebrate indices (Briers & Biggs 2003), while conservation studies of ponds are often centred around a selected taxonomic group; e.g. in Britain, the relevant research is predominantly focused on amphibians, and in particular, the habitat suitability for great crested newts *Triturus cristatus* (Jehle 2000; O'Brien 2015). The favourite subjects for plankton research are either diatoms (Żelazna-Wieczorek & Nowicka-Krawczyk 2015) or cyanobacteria (Waajen *et al.* 2014). While there are also studies on other taxa and every single study in isolation is a valuable piece of research, this context means that many taxa remain understudied. Indeed, research providing simultaneous insight into the occurrence and ecology of a comprehensive range of biological organisms inhabiting both aquatic and adjacent terrestrial habitats associated with urban ponds is rare (Hassall *et al.* 2016).

Multiple benefits associated with urban ponds have only recently started to be appreciated, and examples of in-depth interdisciplinary insights are also scarce. Studies have tended to focus on a single aspect of ecosystem services provided, or taken a wider view of several aspects without examining their specific details (Jose *et al.* 2015; Oertli & Parris 2019; Alves *et al.* 2020). The research-based evidence for multifunctional pond management within the BGI network is therefore limited (Hassall *et al.* 2016).

This paper aims to address these research gaps by adopting a holistic approach and giving a detailed account of several ecosystem services provided by Blackford Pond, a semi-natural water body located within a Local Nature Reserve (LNR) in the southern part of Edinburgh (UK). Previous sociological research provided economic estimates of the net present values for eight ponds in the area (based on the value perceived by the local residents), and Blackford Pond featured highly on that list (Jarvie *et al.* 2017). The main focus of the present paper is on biodiversity and other ecosystem services. In particular, the research will examine whether the high economic value previously deduced from the residents' perceptions is underpinned by commensurate levels of biodiversity across a range of biological groups, and how it relates to the provision of other ecosystem services. The paper also provides an insight into the water quality and flood resilience benefits, based on analysis of the site's hydrology. To address these research questions, the connections among a range of aspects of the ponds' multiple benefits and the taxonomic richness and ecological interactions of flora and fauna present at the pond are explored in detail. The value of ecosystem services is then assessed using the Natural Capital Planning Tool (NCPT), which was fine-tuned using the monitoring and modelling results on biodiversity and hydrology. The discussion further addresses the relevance to conservation, management, public engagement and perception issues within the broader conceptual frameworks of nature-based solutions (NBS) and Blue-Green Cities (BGC); it also highlights a number of trade-offs among various ecosystem services, and considers which of the multiple benefits provided by the site may not have been fully reflected in the NCPT analysis or economic estimates previously obtained using contingent valuation.

2. DATA AND METHODS

2.1. Site description

Blackford Pond is located within the city of Edinburgh, about 3 km south of the centre (Figure 1). It is a semi-natural feature established in the 19th century (Jarvie *et al.* 2017) in a natural glacial hollow (Miller 2017). The surrounding landscape has been subject to obvious anthropogenic influences, including changes to the hydrology, geomorphology and vegetation cover. The site is well-managed by the Natural Heritage Service of the City of Edinburgh Council with maintenance of the pond's shoreline and the surrounding areas undertaken on a regular basis.

The pond is relatively large, with a surface area of 7,780 m^2 and a volume of 6,480 m^3 (data obtained through a hydrographic survey carried out as part of this research). It is situated on one of the access routes to the Hermitage of Braid Visitor Centre and is also adjacent to Blackford Hill, which offers good hikes as well as superb views over the city and surrounding hills. The area around the pond is popular with joggers and walking groups, dog walkers, families, birdwatchers, wildlife recorders and nature conservation enthusiasts. Consequently, the locality is enjoyed every day by many visitors and provides high amenity value. Interpretation boards are situated both at the pond itself and close by detailing aspects of the natural history and geology of the site (Figure 2).

The pond's catchment area is 0.19 km^2 (190,000 m^2) and the pond covers approximately 4% of this (Figure 3). The south and east of the catchment is dominated by Blackford Hill (Figure 4) which rises to 164 m above ordnance datum (AOD). Below Blackford Hill towards the west side of the catchment is a valley that flows in a northerly direction towards the pond. There is not a permanent flow in the valley, although there is surface water flow over the waterlogged soil during major events and a wetland area near where the valley meets the pond (68 m AOD). On the far western side of the catchment are allotments which drain into the valley. The rest of the catchment consists of a mixture of grassland and trees. The outflow from the pond is from its northern edge through a pipe into the nearby Jordan Burn.

Blackford Hill has igneous bedrock with no superficial deposits and only a thin overlying soil. In the rest of the catchment, there is a sedimentary base rock of the Kinnesswood Formation with superficial till deposits and

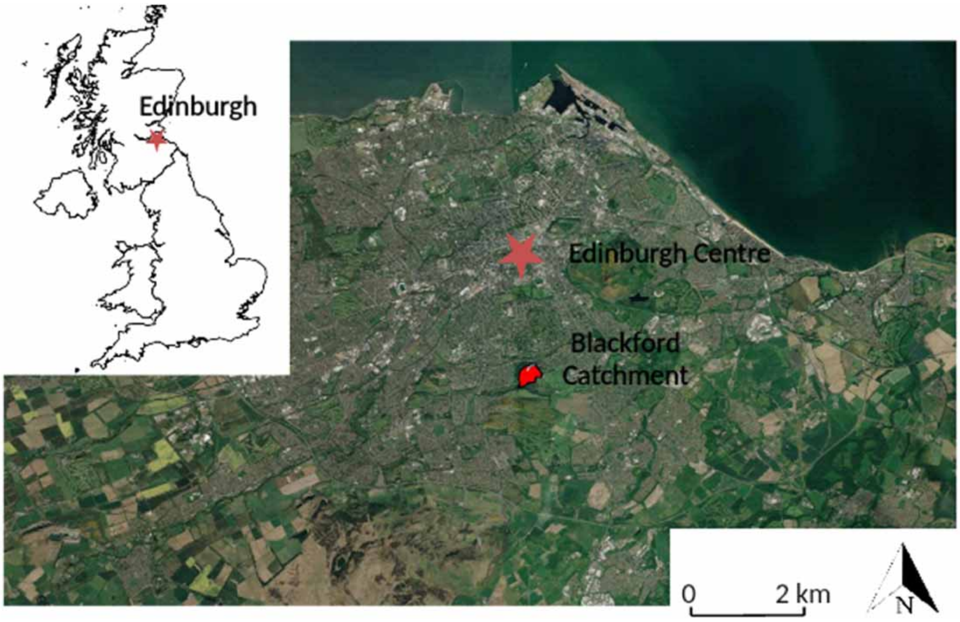


Figure 1 | The location of Blackford Pond within Edinburgh.

Figure 2 | (a) View across Blackford Pond, with interpretation board by path, (b) reed habitat at western end of pond, (c) view across pond with algae visible in the water, and (d) edge of pond with marginal vegetation.

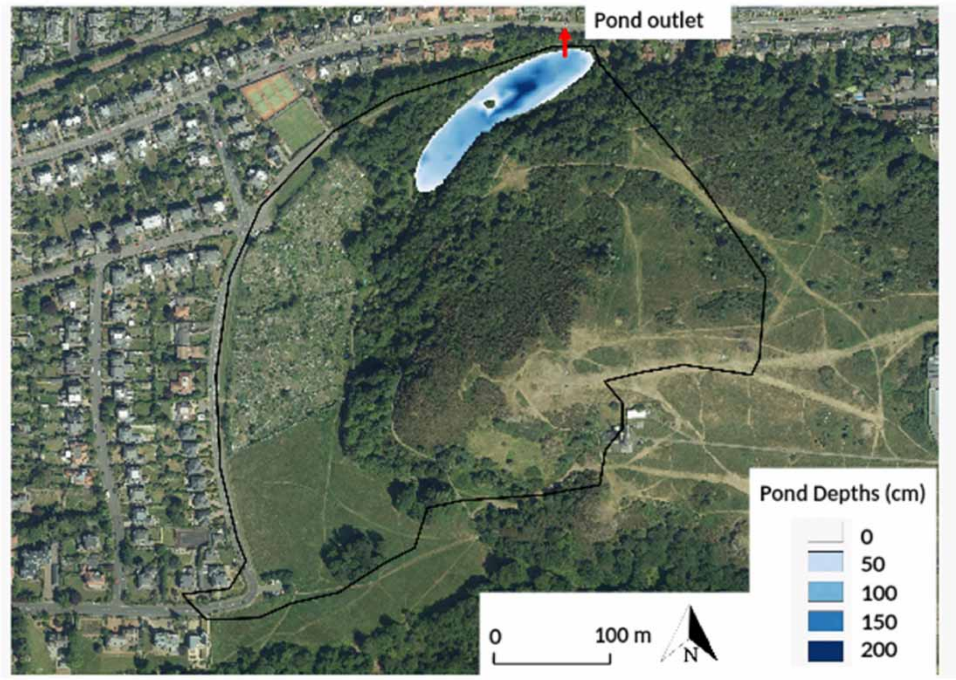


Figure 3 | Blackford Pond catchment and pond depths.

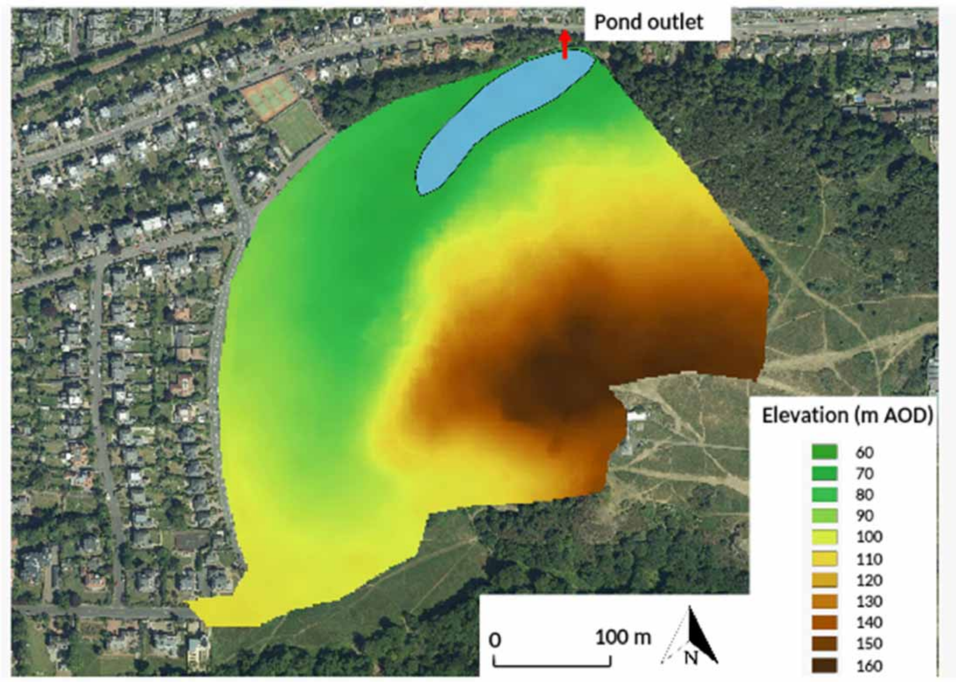


Figure 4 | Blackford Pond Digital Elevation Model obtained from 2 m LiDAR data.

freely drained brown soils (National Soil Map of Scotland 2017; Geology of Britain Viewer 2019). Land-use is predominately woodland around the pond, with allotments and amenity grassland covering the majority of the rest of the catchment.

2.2. Biodiversity surveys

Biodiversity surveys of the pond and the adjacent area were variously undertaken from 2018 to 2021. Both native and non-native species of vascular plants were recorded in and around the pond in a variety of habitats, including deciduous woodland, woodland edge, open water, marginal habitat and unpaved path. Bryophyte species were recorded on wooded and shaded banks, concrete walls, cobbled path, logs, trees and tree bases. A mycological survey of both non-lichenised fungi and lichenised fungi was carried out in the area around the pond. In addition, a number of tree species were surveyed for epiphytic lichens. Vertebrates at the site were also recorded; this includes birds, amphibians, fish and mammals. The biodiversity records are being deposited with The Wildlife Information Centre (TWIC) in publicly available databases.

2.3. Water quality and hydroecology monitoring

The pond's hydrobiological community and water chemistry were monitored between April 2018 and May 2019. This included monthly measurements of the chemical water quality using standard field sensors and via inductively coupled plasma mass spectrometry (ICP MS) analysis of water samples, and estimating the abundances of planktonic organisms and macroinvertebrates by standard methods. Walley Hawkes Paisley Trigg (WHPT) scores and the average score per taxon (ASPT) were estimated using a Microsoft Excel spreadsheet supplied by the Freshwater Biological Association (FBA). Both indices are commonly used for the assessment of pollution impact on the biodiversity of lentic and lotic ecosystems (Chadd 2010).

2.4. Hydrological and hydrodynamic modelling

Hydrodynamic and hydrological modelling was undertaken through coupling of the well-established modelling tools designed by Newcastle University and simulated using the time series of precipitation and air temperature data obtained from the UK Met Office. Hydrological modelling used the SHETRAN model for simulating the long-term flows into and out from the pond and hence the monthly residence times of the pond (Ewen *et al.* 2000). Hydrodynamic modelling used the CityCAT model for simulation of extreme events (Glenis *et al.* 2018). SHETRAN was also used to provide initial conditions for the CityCAT event-based simulations.

A 2 m resolution Scottish Public Sector LiDAR (Phase I) dataset was used in the CityCAT model of the catchment with a 285 by 282 grid. SHETRAN uses a 5 m grid resolution of the catchment based on the 2 m LIDAR data. This gives 122 by 118 vertical columns with 20 cells in each column containing the soil and geology information (the model has a limit of 200 by 200 vertical columns). Simulations were run for 19 months from 1 January 2018 to 31 July 2019 using daily SEPA rainfall measured by the Comiston raingauge located 2 km southwest of the pond. These dates correspond to the period of the observations as part of the ecological studies. Average monthly potential evaporation is used, with the data obtained from the CHESS dataset (Robinson *et al.* 2016, 2017). Various parameters values for the soils, geology and land use were obtained from standard libraries (Lewis *et al.* 2018).

CityCAT simulations were undertaken for one-in-100 year events of different durations (15 min to 6 h). It should be noted that in CityCAT simulations, infiltration is calculated using the Green-Ampt equations (Green & Ampt 1911) as a function of the soil hydraulic conductivity, porosity and suction head (Chow *et al.* 1988; Kutílek & Nielsen 1994; Warrick 2003). The ability of water to infiltrate at any particular grid cell depends on whether the soil moisture content is already at field capacity. If the soil is not saturated, any additional precipitation is assumed to infiltrate. However, once saturation is reached, the infiltration is no longer allowed and any further precipitation is converted to surface runoff. To account for the different infiltration rates, two CityCAT simulations were run for each event under wet initial conditions and under dry initial conditions, with the initial conditions obtained from the SHETRAN simulations. Wet initial conditions correspond to 4 April 2018 and dry initial conditions to 19 July 2018. Under the wet initial conditions, most of the main valley is saturated and so does not allow infiltration, whereas under the dry initial conditions apart from in the pond, none of the soils are saturated and so there is more infiltration.

2.5. Evaluation of ecosystem services

In order to provide more quantitative details of the ecosystem services provided by the pond, the NCPT was applied (Hölzinger *et al.* 2019; Ncube & Arthur 2021). The NCPT allows for a systematic assessment of the likely impact of developments on the ecosystem services it provides, with the values produced by the tool developed from a wide range of experts, stakeholders and surveys. In this case, it was applied by assuming a change of land use of two areas. Firstly, from amenity grassland to a pond covering the surface area of Blackford Pond (7,780 m^2) and secondly, from amenity grassland to a lowland mixed deciduous woodland (2,900 m^2) for the habitats at the western end of the pond. In addition, this analysis takes into account the estimated 670 people living within 300 m of the pond. Hence, the resulting calculations of impact scores for this scenario reflect the differences in values of specific ecosystem services categories and can be used for gauging the overall value of the ecosystem services provided by the site in relation to the amenity grassland reference values.

The NCPT methodology stipulates that the coefficients used in calculations can be adjusted within the allowable range based on the local conditions and expert knowledge. Hence, the results on biodiversity and flood resilience, together with expert knowledge of the site, have been used to fine-tune the NCPT settings. The main changes were: firstly, for the 'Biodiversity' category, the 'Biodiversity Demand Multiplier' was increased from 0.5 to 0.8 (the acceptable range is from 0 to 1) to take into account the qualitative assessment of the pond and the range of species found; secondly, for the 'Aesthetic Values' category, the 'Population Density Demand Multiplier' was increased from 0.3 to 0.7 (the acceptable range is from 0 to 1). This takes into account that the pond attracts visitors from a much greater distance than the standard 300 m used in the tool, with 500 m being the estimated distance in the contingent valuation analysis (see Discussion).

3. RESULTS

3.1. Biodiversity

A total of 95 species of vascular plants were recorded (Supplementary Material, Appendix A1), with both native and non-native species present in and around the pond in a variety of habitats, including deciduous woodland, woodland edge, open water, marginal habitat and unpaved path. *Alnus glutinosa*, *Ilex aquifolium*, *Rubus fruticosus* agg., *Sambucus nigra*, *Ulmus glabra* and *Acer pseudoplatanus* were particularly frequent. The plants present appear to represent a combination of planted individuals and naturally occurring or naturalised examples.

The bulk of the recorded vascular plants were herbaceous (69 species), with the majority of these being native. Herbaceous vegetation includes specialist aquatic or mesic species (e.g. *Carex* spp., *Caltha palustris*, *Cyperus longus*, *Iris pseudoacorus*, *Lemna minor*, *Lythrum salicaria*, *Mentha aquatica*, *Phragmites australis*, *Typha latifolia*), as well as typical representatives of terrestrial flora (Supplementary Material, Appendix A1). The latter includes a number of non-native species, e.g. invasive *Impatiens glandulifera*, potentially invasive *Tellima grandiflora* and naturalised *Mimulus* sp. The other records mostly represent species that are common or reasonably common to the Edinburgh area (Supplementary Material, Appendix A1). Although many of these are native species, at least a proportion of them have been planted: as part of a renovation project for the pond in 2009–2010, the City of Edinburgh Council planted up the edge of the pond with *Iris pseudacorus*, *Mentha aquatica* and *Carex* to help stabilise the banks (BBC 2010). A small number of cultivated *Viola* have been planted close to the path fairly recently, the authors suspect by a member of the public.

In total, 22 species of bryophytes were recorded at the site (Supplementary Material, Appendix A1). The majority of bryophytes found at the site are mosses; the liverworts are represented by *Lophocolea bidentata*, *Lunularia cruciata* and *Metzgeria furcata*, occurring at the wall, tree base and stone microhabitats, respectively.

A fungal survey highlighted 83 species of non-lichenised fungi (Supplementary Material, Appendix A1). Non-lichenised fungi comprise a range of Ascomycota and Basidiomycota, most are saprobic (56 species) with the rest being parasitic, mycorrhizal or inhabiting the phylloplane (20, 5 and 2 species, respectively). A couple of species recorded on site deserve a special mention: *Melanophyllum haematospermum* is uncommon (NBN atlas has only one record in central Scotland), while *Rhodocybe gemina* is a nationally rare species in the UK (Scottish Biodiversity List 2013). Both are notable finds and an addition to their recorded sites. There appear to be no records of *R. gemina* from Edinburgh or the nearby area, with only three Scottish records (GBIF.org Downloaded 11 August 2020).

Twenty-six species of lichenised fungi in the area around the pond were recorded (Takezawa 2019) in the 2019 survey (Supplementary Material, Appendix A1), while 34 species were revealed in 2021 (Supplementary Material); overall, this amounts to 40 separate taxa. Three of these lichens (*Halecania viridescens*, *Xanthoria ucrainica* and *Opegrapha viridipruinosa*) have 'Nationally Scarce' (NS) status (known from $<$100 to 10 km^2). Eight calcicolous lichen species were recorded on mortared wall and stonework. The rest were epiphytic lichens observed on tree trunks and reachable branches (Supplementary Material, Appendix A1 and Supplementary Material). The highest diversity of lichens was found on *Alnus glutinosa* and *Acer pseudoplatanus*. The epiphytic lichen species present indicate intermediate air quality in terms of air pollution (Takezawa 2019), using Stoakley and Ellis's questionnaire linking epiphytic lichen types to air pollution levels (Stoakley & Ellis 2016). This may reflect the nearness of the busy Cluny Gardens/Charterhall Road. Historic lichen records by James Edward Smith from the nearby

Hermitage of Braid in the 18th century (British Lichen Society mapping data; University of Bradford) provide evidence of a more diverse epiphytic community including pollution-sensitive species no longer found in the city, e.g. *Pertusaria pertusa*, and the pollution-sensitive old woodland species (Coppins 1976), *Sticta limbata* and *S. fuliginosa*.

Although terrestrial invertebrates were not surveyed in this study, the observed habitats and the diversity of plants and fungi are presumed to support a substantial number of species in that group (Krivtsov *et al.* 2003a, 2004, 2006).

The majority of the vertebrates recorded at the site were birds (Supplementary Material, Appendix A1), with rails, ducks, swans, corvids and passerines all frequently encountered. Essential for the wetland birds is the presence of a vegetated island. This island is an artificial feature created and maintained mainly for the birds (The City of Edinburgh Council Countryside Ranger Service n.d.). Reed habitats are available on the western side of the pond, hosting coot, warbler and moorhen nests. Due to the ecotone grading between pond edge and woodland, the biodiversity of the locality is enhanced by the occurrence of woodland bird species.

In addition to the residents, more bird species use the site irregularly, in particular during migration periods; for example, the records of the Scottish Ornithologists' Club include mandarin duck, fieldfare, greylag goose, barnacle goose and twite – see, e.g., Scottish Bird Report 7.3 (1972).

In addition to birds, the amphibians *Bufo bufo* and *Rana temporaria* were also observed and the fish *Gasterosteus aculeatus* were caught during sampling. The only mammal recorded during the survey period was *Rattus norwegicus*, brown rat, a population which was increasingly visible during the autumn of 2019 and throughout 2020.

3.2. Water quality and hydroecology

Chemical water quality in the pond is indicative of eutrophication, with total dissolved Phosphorus (P) levels occasionally exceeding 700 ppb. Among the 11 BGI ponds recently studied in Edinburgh area, Blackford Pond was characterised by the highest levels of Uranium (U), the highest median values for Strontium (Sr) (albeit not the outliers), and the second highest levels for Lithium (Li), Arsenic (As) and Boron (B, unpublished data) – see Figure 5. This appears to be reflected in the biological water quality, with a number of pollution-sensitive taxa (e.g. damselfly larva) not registered in the sweep samples obtained at the pond. The observed biological water quality is broadly comparable to other urban ponds in Edinburgh (Krivtsov *et al.* 2020b, 2020c) but is lower than the expected values reported elsewhere (Noble & Hassall 2015).

Filamentous algae, in particular *Cladophora* and *Spirogyra*, were present in the periphyton throughout the season and were frequently encountered in the planktonic samples, while *Oedogonium* was an important

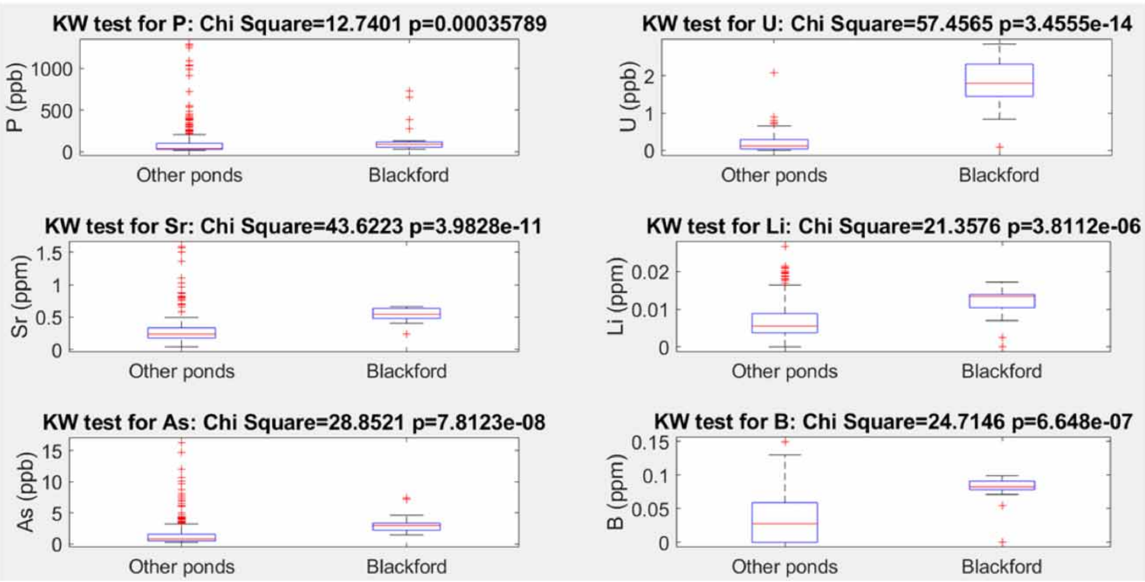


Figure 5 | Water chemistry (levels of P, U, Sr, Li, As and B) at Blackford Pond compared to a selection of other BGI ponds in the area. The results of the Kruskal-Wallis (KW) test (including the Chi-square parameter and the probability value) are given in the title for each subplot.

member of the community in June. Diatoms were always present, with *Cocconeis* being frequent in June, July, September and January.

The most interesting feature of the pond's planktonic community was a remarkable bloom of *Volvox* observed between August and November. After that *Volvox* was present in lower quantities until the end of winter and re-appeared again in the May 2019 sample. Rotifers were not recorded in the summer and were also absent from the March 2019 sample (which was characterised by very clear water). However, they were present on other occasions, with particularly high population density in October, January and February. It, therefore, appears that they have benefitted from the increase in *Volvox* numbers and may have consequently contributed to the demise of its population.

Large zooplankton were present throughout the investigation period and were mainly represented by *Daphnia* and *Cyclops*. *Chydorus* occurred in some samples in rather smaller quantities, but in May 2019 it was the only representative of zooplankton found. It should also be noted that in May 2018 the only representative of zooplankton found in the samples was *Bosmina coregoni*. Hence, it appears that the change of zooplankton community at the end of spring/early summer may be characteristic for the ecosystem dynamics of this pond.

The macroinvertebrate community appeared to be fairly diverse, with the WHPT score of the samples usually ranging between 40 and 50. It should be noted, however, that the macroinvertebrates are mainly represented by animals tolerant of eutrophic conditions (e.g. *Asselus aquaticus*, *Bithynia tentaculata*, *Physa fontinalis*, *Radix balthica*, *Sphaerium* spp., *Glossiphonia complanata*, *Theromyzon tessulatum*, Chironomidae, Corixidae and Planorbidae), with some of them found in rather substantial quantities. Consequently, the ASPT index is usually in the 3.4–3.7 range, indicating a considerable potential for biological water quality improvement (Figure 6). In addition to nutrients, the macroinvertebrate community may have also been affected by other pollutants (Bloor *et al.* 2005).

3.3. Overall species richness

The overall figures for the number of taxa belonging to various biological groups recorded at the site can be seen in Table 1, this includes both the taxa recorded in the green space around the pond and those recorded within the water. These data were used to calculate Shannon diversity and Pielou evenness indices (Bandeira *et al.* 2013), estimated as 0.86 and 0.42, respectively. It should be noted that although these estimates may be indicative of the overall biodiversity and thus conservation value of the site, they are also likely to be influenced by the logistical limitations as well as inevitable differences in the research effort – for instance, fungi tend to produce fruit bodies for a limited time period, and in some years, no fruiting may occur (Krivtsov *et al.* 2003b). It is acknowledged that

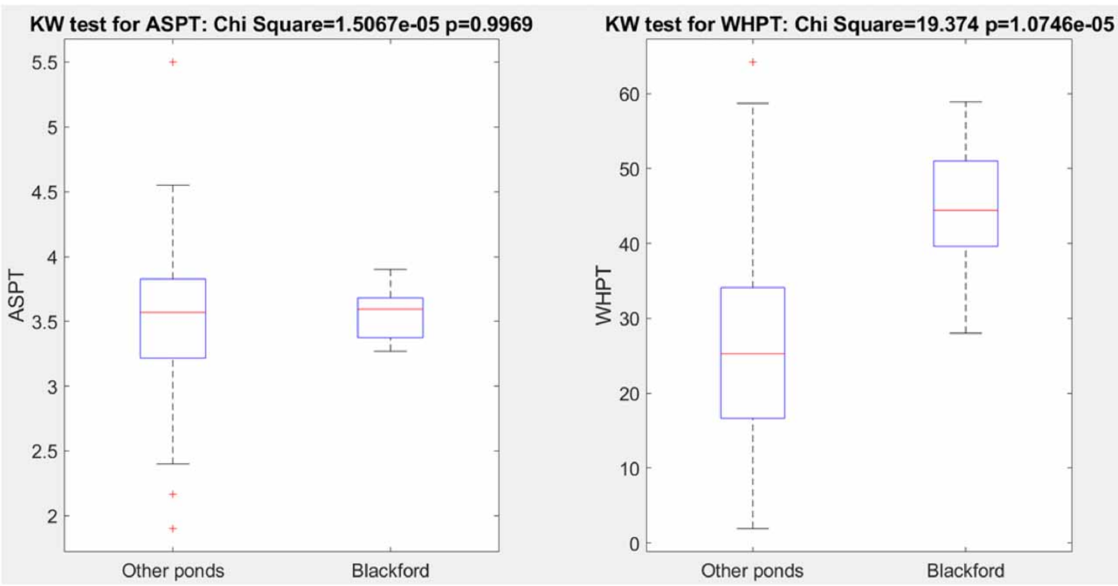


Figure 6 | Comparison of macroinvertebrate indices at Blackford Pond with other urban ponds in the area. The results of the Kruskal-Wallis (KW) test reveal that the WHPT index at Blackford Pond is significantly higher, while for the ASPT index, there is no significant difference.

Table 1 | Taxonomic richness of biological groups recorded at Blackford Pond

Biological groups	Recorded Taxonomic richness
Higher plants	95
Bryophytes	22
Lichenised fungi	40
Other fungi	83
Algae/phytoplankton	37
Zooplankton	32
Terrestrial and aquatic vertebrates	29
Aquatic macroinvertebrates	38
Total	376

for all the investigated groups the species list obtained in this study is not complete, and further research may reveal additional taxa – see Colwell *et al.* (2004) for discussion related to the species accumulation curves.

3.4. Modelling results

Water discharges from the pond for the SHETRAN simulations are shown in Figure 7. Higher values of discharge are noted for winter months and lead to shorter residence times (Table 2), with a minimum value of 14.1 days from January to March 2018. In summer, however, the higher evapotranspiration results in smaller values of discharge and consequently in longer residence times, with a maximum value of 67.4 days from July to September 2018. This has profound implications for the aquatic community and biogeochemical cycling.

Figure 8 shows the results of CityCAT simulations under dry and wet initial conditions. The pond reduces the flow velocities and flowrates, and also increases the lag between the rainfall and the peak flow (Figure 8 and Tables 3 and 4), although the total volume of water is the same in both cases. This is because the pond has

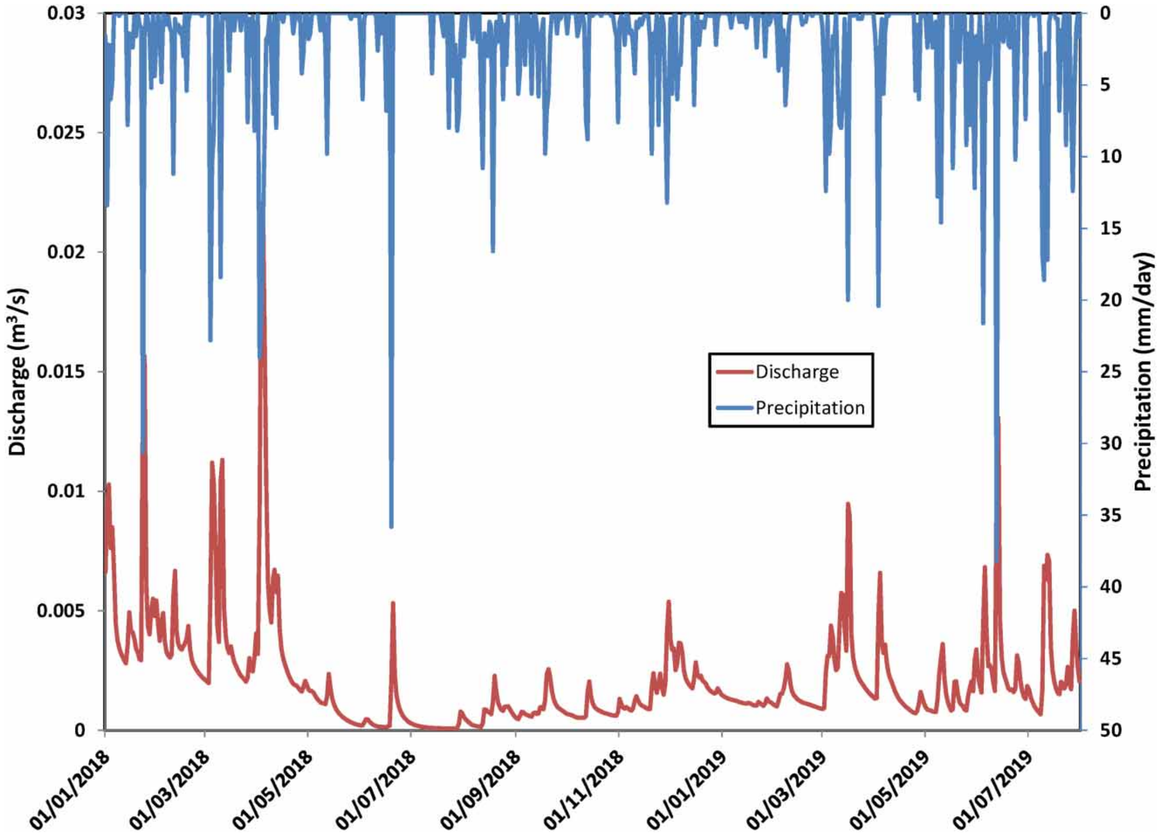


Figure 7 | Pond discharges (m^3/s) simulated using SHETRAN plotted in relation to the rainfall (mm/day). Note the relatively short delay between the peaks in precipitation and the corresponding peaks in discharge.

Table 2 | Blackford Pond simulated pond nominal residence times using Shetran

Month	Residence time (days)
Jan–Mar 2018	14.1
Apr–Jun 2018	26.7
July–Sept 2018	67.4
Oct–Dec 2018	38.5
Jan–Mar 2019	35.0
Apr–Jun 2019	26.2

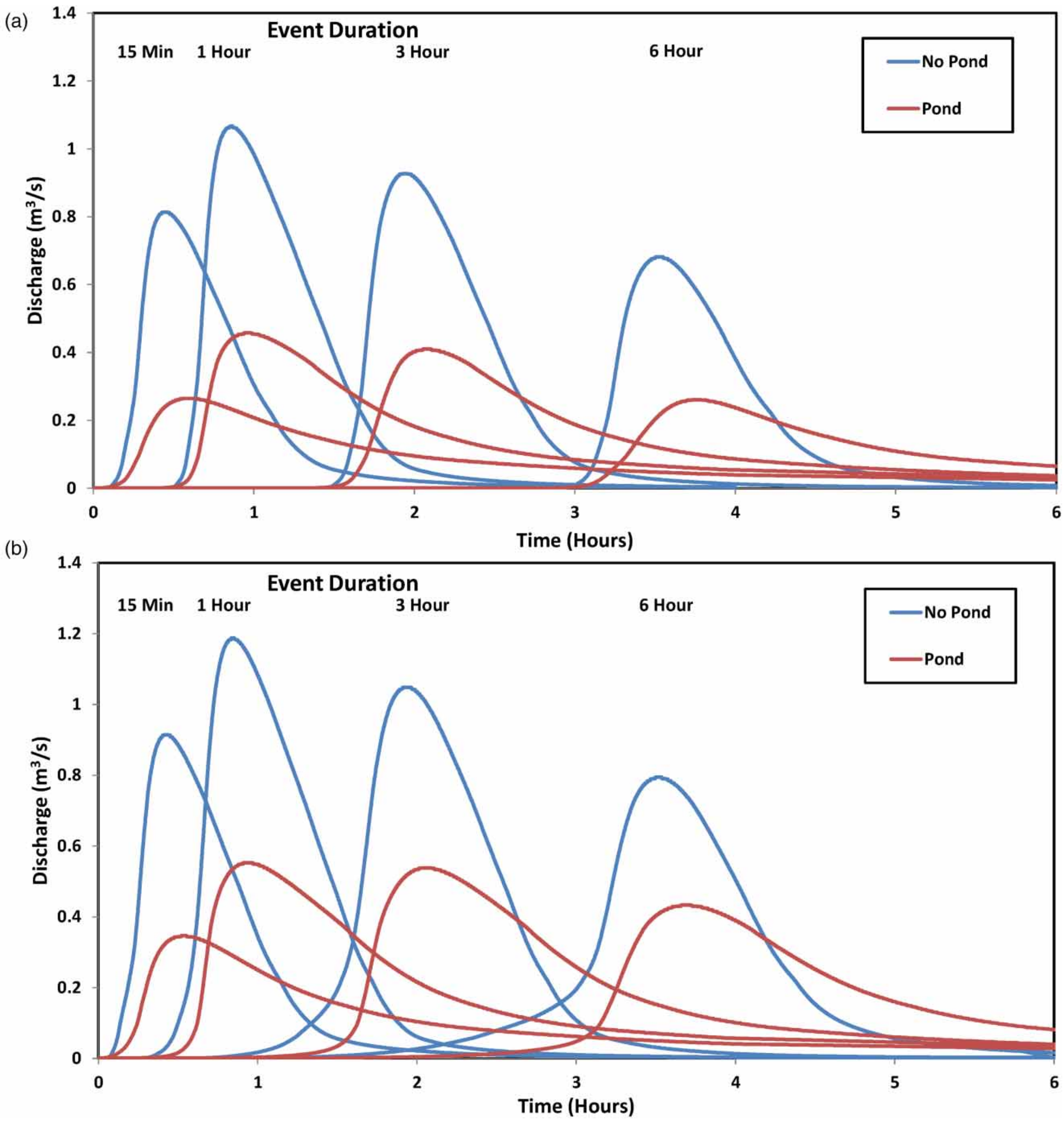


Figure 8 | CityCAT simulated discharges (m^3/s) for a one-in-100 year rainfall event of four different durations. This is both with the pond present and with no pond. (a) Dry initial conditions and (b) wet initial conditions.

not been designed as a detention pond and so it is full at the start of this event. The increase in the lag between the rainfall and discharge peak as a result of the pond is between 4 and 11 min and the reduction in peak discharge is between 45 and 67%. The reduction is greatest for the 15 min event under dry initial conditions and smallest for

Table 3 | Blackford peak discharges and delayed time to peak (compared with no pond) under wet initial conditions for a one-in-100-year event of different durations

			No Pond		With Pond	
Storm Duration	**Total Rainfall (mm)**	**Peak Rainfall Rate (mm/h)**	**Peak discharge (m^3/s)**	**Delay (minutes)**	**Peak discharge (m^3/s)**	**Delay (minutes)**
15 min	24	227	0.91	20	0.35	27
30 min	31	182	1.12	19	0.50	25
1 hour	38	136	1.18	21	0.55	25
2 hours	46	94	1.13	23	0.56	29
3 hours	52	74	1.05	26	0.54	34
6 hours	65	47	0.79	31	0.43	42

The delay is from the peak rainfall to the peak discharge.

Table 4 | Blackford peak discharges and delayed time to peak (compared with no pond) under dry initial conditions for a one-in-100-year event of different durations

			No Pond		With Pond	
Storm Duration	**Total Rainfall (mm)**	**Peak Rainfall Rate (mm/h)**	**Peak discharge (m^3/s)**	**Delay (minutes)**	**Peak discharge (m^3/s)**	**Delay (minutes)**
15 min	24	227	0.81	22	0.26	31
30 min	31	182	1.02	21	0.42	27
1 hour	38	136	1.07	22	0.46	27
2 hours	46	94	1.02	24	0.45	30
3 hours	52	74	0.93	27	0.41	35
6 hours	65	47	0.68	32	0.26	43

The delay is from the peak rainfall to the peak discharge.

the 6 h event under wet initial conditions. The highest discharge is for the 1-h event under wet initial conditions with a peak value of 1.18 m^3/s without a pond with a corresponding peak discharge of 0.55 m^3/s with the pond. Figure 9 shows the maximum surface water depths for this event with and without the pond and its impact can clearly be seen. As expected, away from the pond the depths are the same in both cases with significant surface water in the valley flowing north towards the pond. The results show that both the presence of the pond and the initial conditions are important in regards of the peak discharge and the lag time from the peak of the rainfall event to the peak discharge. Thus, the application of the coupled SHETRAN and CityCAT models gives a realistic quantitative estimate of the local peak flow reduction provided at the pond outlet under a range of scenarios. This reduction was achieved even though the pond was not designed for flood alleviation and does not have any additional capacity (other than above the crest) for water storage at the start of a rainfall event. Detention ponds that cover a smaller fraction of the catchment (in this case, the pond covers 4% of the catchment) but with the capacity to temporarily store water have been shown to be more effective at reducing the peak flow and increasing the flood resilience (Ahilan *et al.* 2019; Ghofrani *et al.* 2019).

3.5. NCPT results

The overall impact of the pond is positive, with a development impact score of +11.35 per hectare (Figure 10). The benefit of the pond is highest in the 'Biodiversity' and 'Aesthetic Values' categories with values of +4.76 and +4.67, respectively. The 'Biodiversity' corresponds well with the large range of species found within and close to the pond. The increased 'Aesthetic Values' depend on visitors' overall perceptions to the pond and woodland as opposed to amenity grassland. The only negative change is for 'Recreation' which has a value of −0.57, as the presence of a pond as opposed to grassland reduces the sports/physical exercise opportunities. It should be noted, however, that this measure does not consider the large numbers of people walking adjacent to the pond for enjoyment and jogging for physical exercise. The 'Flood Risk Regulation' was manually adjusted by

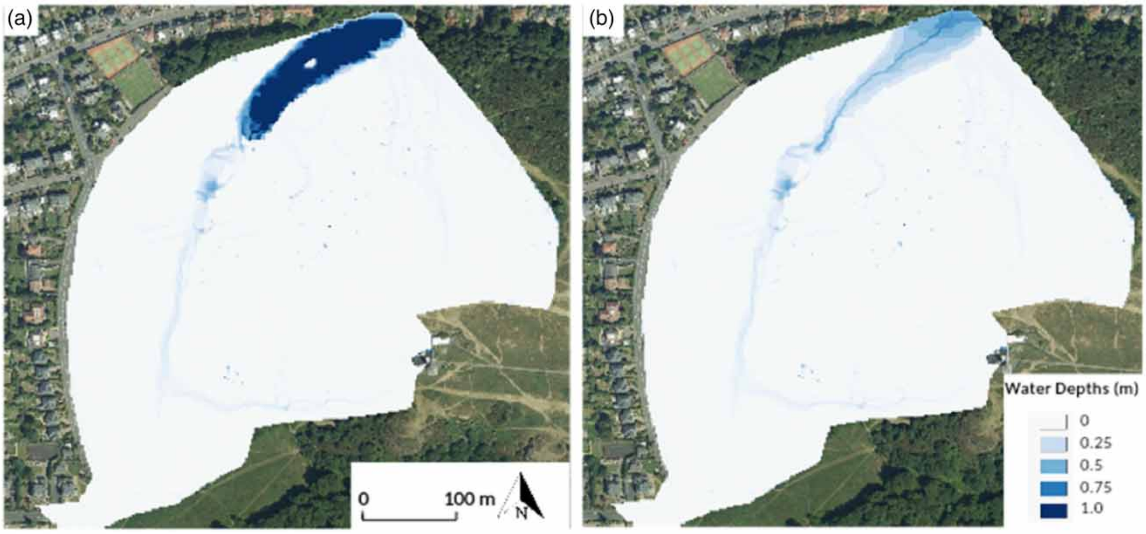


Figure 9 | CityCAT simulated maximum water depths for a one-hour, one-in-100-year rainfall event under wet initial conditions (a) with pond and (b) no pond.

Development Impact Score
Average Per-Hectare

Ecosystem Services Impact Scores	Max Possible	Impact Score (Adjusted)	Min Possible	Unadj. Scores
1. Harvested Products	+3.63	+0.27	+0.00	+0.5
2. Biodiversity	+7.31	+4.76	-0.69	+4.8
3. Aesthetic Values	+4.67	+4.67	-2.33	+4.7
4. Recreation	+0.67	-0.57	-2.33	-0.6
5. Water Quality Regulation	+1.58	+0.79	-3.16	+0.8
6. Flood Risk Regulation	+2.80	+0.41	-0.20	+0.1
7. Air Quality Regulation	+1.02	+0.28	-0.51	-0.1
8. Local Climate Regulation	+2.19	+0.60	-1.10	+0.6
9. Global Climate Regulation	+4.43	+0.14	-0.57	+0.1
10. Soil Contamination		+0.00		+0.0
Development Impact Score	+28.30	+11.35	-10.89	+11.0

Figure 10 | A screenshot showing the results from the NCPT as a consequence of changing amenity grassland to a pond and woodland.

changing the benefits the pond provides to consider the reduction in flood risk downstream, which the modelling work has highlighted. This increased the score from +0.1 to +0.41 per hectare.

It should be noted that the coefficients used in the calculations of ‘Harvested products’ were manually decreased to reflect the limited possibilities allowed on designated local biodiversity sites (LBS) in that respect. This led to a more modest increase (+0.27) in the ecosystem services value in that category compared to the default calculations (+0.5).

Positive scores were also returned for air quality and local and global climate regulations. These improvements reflect the effects of surrounding vegetation on trapping airborne pollutants (Leung *et al.* 2011) and their subsequent pathways towards immobilisation within the pond's sediments (Krivtsov *et al.* 2020a, 2020c), storage of organic carbon in sediments (Krivtsov *et al.* 2020a) and the positive effects on the amelioration of the urban heat island effect (Robitu *et al.* 2004, 2006; Charlesworth 2010). The fact that the results of the NCPT analysis revealed positive scores for climate regulation both on the local and global scales are particularly noteworthy. The presence of a water body is beneficial for the local vegetation and other biota (smaller scale) and contributes to the overall resilience to climate change (larger scale). In addition to the contribution towards global climate regulations, the pond and surroundings also have a local effect on alleviating the urban heat island effect (Rinner & Hussain 2011; Oláh 2012).

Overall, the increase in the total ecosystem services value provided by the pond and surrounding area, in comparison to the reference values for amenity grassland, corresponds to 29% of the total range for potential changes. Hence, the NCPT has shown that, overall, the total ecosystem services value provided by the pond and surrounding area is considerably higher than for amenity grassland. It should, however, be noted that the NCPT calculations do not take into account a number of factors related to, e.g., the educational value of the pond or its global significance for research (see Discussion). If those variables were fully considered, then the estimated difference in the ecosystem services value between the pond site and the amenity grassland reference would be much greater.

4. DISCUSSION

The discussion will concentrate on the interpretation of the results including comparison with studies conducted elsewhere, implications for the management of this and other similar ecosystems, and relevance to other research within the wider frameworks of GI, urban biodiversity and BGC.

4.1. Biodiversity and ecology

A combination of monitoring and modelling approaches is indispensable for the correct interpretation of ecological patterns and environmental dynamics (Krivtsov *et al.* 2008). The results of thorough ecological surveys reported here were obtained over multiple visits, and the data on species richness can now be used for benchmarking against other ponds and lakes, and (with certain caveats) for comparisons with other types of ecosystems. The present values of diversity and evenness will also be a useful reference point for assessing the long-term trends and the effectiveness of any future management actions.

The site's biodiversity benefits from the presence of a nationally rare species (*Rhodocybe gemina*), nationally scarce species (*Halecania viridescens*, *Xanthoria ucrainica* and *Opegrapha viridipruinosa*), uncommon species (*Rigidoporus corticola*, *Melanophyllum haematospermum*) and two species which are classed as in decline in Scotland with conservation action needed (*Larus ridibundus* and *Plantago media*) – see, e.g., Scottish Biodiversity List (2013).

The pond's placement within the larger LNR also allows movement of species to and from the site; the LNR is located close to other green spaces, such as the Braid and Craiglockhart Hills, as well as a railway line with vegetated banks. The pond and its surrounds, therefore, contribute to the provision of ecological corridors or stepping stones within the city; this is similar to another case study reported elsewhere (Krivtsov *et al.* 2020b) and is an important aspect of ecosystem services associated with GI (Ellis 2013).

The species richness of the flora of the pond and surrounding area may be influenced by several factors, such as pond age, pond size and plantings. However, a study of nine urban ponds, including Blackford, did not find a clear relationship with size alone: although Blackford had the second-highest number of plant species of the ponds surveyed, most of the other ponds had a higher number of species in comparison to their area (Krivtsov *et al.* 2019; O'Donnell *et al.* 2020).

The diversity of habitats within and around the pond enable a range of higher plant species to flourish and the variety of microhabitats and substrates supports a diverse selection of bryophytes, fungi and lichens. In particular, the diversity of available hosts and substrates appears to benefit the fungal community, with a large number of species, both saprophytes and parasites, exploiting a range of host species and substrate types. It should be noted, however, that the wooded areas around the pond have high proportions of plants associated with endomycorrhizae, which do not form macroscopic fruit bodies and could only be detected using molecular techniques not applied in this research.

The abundance of aquatic invertebrate fauna appears to benefit the higher trophic levels, in particular the populations of amphibians and fish as well as some of the resident and visiting waterfowl. Suitable aquatic vegetation supports herbivorous birds. Essential for the wetland birds is the presence of a vegetated island, where the nests of ducks, swans, coots and moorhens can be conveniently observed during the late spring period.

Availability of terrestrial GS around the pond is also beneficial for the bird community. Many woodland birds were encountered at the site singing during the nesting period. This further contributes to the amenity value, being an attraction both for birdwatchers and the general public. Bird migration sometimes brings unexpected species to the pond, which attracts birdwatchers from farther afield.

4.2. Water quality and hydrology

Inputs from the catchment – in particular, suspected leaching from the allotments and the presence of the road – influence the chemical water quality, as the aquatic invertebrate and planktonic communities reflect.

The eutrophic state of the water quality is further exacerbated by waste from the waterbird population; leftover food is given by the public to the birds also contributes (The City of Edinburgh Council Countryside Ranger Service). It should also be noted that the sediments of the pond have elevated concentrations of polluting substances (Krivtsov *et al.* 2020a). Despite this, the overall species richness of the site is high, and the accumulation of pollutants in sediments provides evidence that the pond, at least to some extent, is acting as a safeguard buffer for the downstream ecosystems. This pollutant store, however, may be mobilised in extreme events.

Surprisingly, our data reveal the scarcity of cyanobacteria and dinoflagelates which are known to benefit from eutrophication in lentic ecosystems (Krivtsov *et al.* 1999a, 1999c; Krivtsov 2001). Furthermore, the sampling revealed no active chrysophytes, despite the fact that chrysophycean cysts were present in the samples of suspended particulate matter. Nevertheless, eutrophication has promoted the spectacular *Volvox* bloom and the elevated abundance of rotifers (especially *Keratella*) observed in our study (see Supplementary Video (https://www.researchgate.net/publication/358614527_BlackfordPaperMicroscopySupplement)). Blackford Pond is prone to regular algal blooms (The City of Edinburgh Council Countryside Ranger Service). A further survey focusing on aquatic plants would be of benefit to establish the impact of the high nutrient levels on floral species composition.

The water quality is also impacted by the hydrology, with the difference in the residence times of water between seasons being substantial. There is scope for water quality improvement, which could encourage the presence of aquatic invertebrate taxa not currently found at the site, though the properties of the catchment (coupled with the nutrient and pollution deposition sources mentioned) make this challenging. Edinburgh Council have made various attempts to improve water quality and reduce algal blooms in the past, e.g. with barley rafts (The City of Edinburgh Council n.d.). Water quality of a pond may be improved by a wetland placed at the inflow (Verhoeven *et al.* 2006; D'Arcy *et al.* 2007). However, the application of such measures at Blackford Pond may have limitations. Although there are reeds and other aquatic vegetation growing in Blackford, at the end of the pond adjacent to the allotments, the area these cover appears to be too small to act as an efficient filter bed to reduce the amount of nutrients entering the pond. It is possible that increasing the area of wetland at this side of the pond could benefit the water quality and reduce the likelihood of algal blooms, but the effects on water birds and visitor access would need to be carefully considered. Continued education of visitors around the feeding of birds may help reduce the amount of waste bread and other foods that add to the enrichment of the water.

The results have clearly shown that the pond increases the flood resilience of the surrounding area, despite not having been designed as a drainage feature. CityCAT modelling reveals that, depending on the initial conditions, the presence of the pond delays the peak discharge after an extreme precipitation event and reduces it between 45 and 67% with bigger reductions for shorter events. Modelling using the same tools and parameters was carried out for eight other BGI ponds during the same time period that surveying and modelling was undertaken at Blackford (Krivtsov *et al.* 2019, 2020b, 2020c); the reduction in peak discharges for simulated rainfall events was higher at Blackford Pond than at the other sites due to its larger surface area.

It should also be noted that the presence of Blackford Pond contributes to the flood resilience downstream, far beyond the outflow point.

Regardless of the pond's presence, the surface runoff is particularly prominent for the simulations carried out with saturated conditions, while under the initial unsaturated conditions, the peak discharges are delayed, and their magnitudes are smaller; a similar effect was also noted in our other studies. A recent review (Myers &

Pezzaniti 2019) has noted the importance of the initial conditions for simulations of the hydrology and flood resilience and pointed out that the aspects of their relationships remain understudied. The findings presented in this paper help to address this important research gap.

4.3. Amenity value and multiple benefits

Biodiversity is an important prerequisite of the amenity value of the pond, with the water birds in particular being an obvious draw for visitors. The road provides access by car, bike or bus from the city, with a small car parking area available. Footpaths leading in from neighbouring amenity areas provide access from other parts of the city, and the path around the north side of the pond is also wheelchair accessible. The playpark, benches and wide paths enable the pond area to be enjoyed by a range of visitors. These provisions make this a very accessible site for its use for recreation, exercise and dog walking. Furthermore, a permanent orienteering course at Blackford Hill encompasses the pond within its limits (Blackford Hill and The Hermitage POC 2020).

This study did not systematically collect data on the numbers of visitors to the site and their reasons for visiting the site, which will depend on their background (Higgins *et al.* 2019). It is worth noting, however, that the site has remained open throughout the recent COVID-19 lockdown and has been important for local people taking their daily exercise. Further studies should aim to obtain estimates of the visitors to the site during that period and elicit full implications for the provision of ecosystem services alleviating the effects of the pandemic.

Previous research (Jarvie *et al.* 2017) used the contingent valuation methodology (CVM) to gauge how local residents (i.e. those living within 500 m distance) perceive advantages and disadvantages of having a pond in their neighbourhood. The study obtained an estimate of £298,439 per annum for the amenity of Blackford Pond, using an online and postal survey. The net present value of the pond (based on the total benefits and costs over a 50-year period) was estimated at £7,165,189. These estimates were based on the perceived willingness of the local public to pay for the pond's ecosystem services and habitat benefits, and the results of our research presented here provide further insight into the details of biodiversity and ecosystem services responsible for the high economic values obtained previously. Further details of the contingent valuation used by the quoted research are available (Jarvie *et al.* 2017), while the arguments regarding the validity of CVM are discussed in Carson *et al.* (2001), Hausman (2012) and Haab *et al.* (2013).

The NCPT analysis presented here and contingent valuation used in the previous study help to elicit the cumulative effect of biodiversity and amenity values, including some of their intangible aspects (e.g. beneficial effects on mental health and general wellbeing). It should, however, be noted that the quoted monetary estimates are rather conservative as they were based on the population living within 500 m radius from the pond only. The NCPT methodology is also limited in that respect as it considers the population density only within a limited radius. In reality, the pond's location is well-connected by transport routes and is regularly enjoyed by visitors from other parts of Edinburgh and adjacent areas, as well as by tourists, which has also been noted for another important Edinburgh pond located in the Royal Botanic Garden Edinburgh (RBGE; Krivtsov *et al.* 2020b). Furthermore, neither the NCPT nor the quoted estimates based on the contingent valuation by the local residents are likely to account for the full extent of the multiple benefits and ecosystem services related, e.g., to education and scientific research (discussed below), or the effects on hydrology and water quality, or for the provision of wildlife corridors for enhancements of biodiversity in other areas of the city. Further research on multiple sites is needed to accumulate extensive data on biodiversity, hydrology and other ecosystem services accompanied by the results of contingent valuation. The availability of such data would enable statistical analysis to reveal details of relationships among specific aspects of biodiversity and ecology of various taxa and the amenity value perceived by the public, as well as providing better grounding for allocating the quantitative estimates of ecosystem services and improving the methods of economic valuation.

4.4. Research and education value

Blackford Pond has been used as a study site for biological, ecological and taxonomic research for many years, particularly in the study of aquatic microorganisms. It has played an important role in the study of diatom genetics, taxonomy and ecology, as well as studies of algae (O'Rourke *et al.* 2015), cyanobacteria (Hašler & Poulíčková 2010), Protista (Beale & Schneller 1954; Pringle & Beale 1960) and microbial community ecology (Pagaling *et al.* 2013). Interactions between actinobacterial parasites and their plant hosts have also been studied at this site (Pozzi *et al.* 2015). Most notably, samples taken from the pond provided much data for Mann and colleagues, with over 30 research papers based on or involving samples from Blackford Pond (Mann 1988, 1999;

Mann & Stickle 1991, 1995; Mann & Chepurnov 2005; Poulíčková *et al.* 2008, 2015; Mann & Poulíčková 2010), with several new species of diatoms first described from specimens from Blackford Pond, e.g. *Sellaphora auldreekie*, *S. blackfordensis*, *S. capitata*, *S. lanceolata*, *S. obesa* in 2004 (Mann *et al.* 2004), *S. pausariae* (Mann & Poulíčková 2019); and *S. bisexualis*, for which samples from Blackford were among those studied (Mann *et al.* 2009). Images prepared from Blackford Pond samples are also included in the book, *The Diatoms: Biology and Morphology of the Genera* (Round *et al.* 1990).

The area around the pond also has considerable value as a resource for formal and informal education and citizen science. The Friends of Hermitage of Braid and Blackford Hill organise regular volunteering events and the LNR hosts nature-themed events such as bat walks, fungal forays and invertebrate workshops (Friends of Hermitage of Braid and Blackford Hill 2020). These sorts of events enable engagement of the local community in practical conservation and maintenance tasks. Observations of the bird life of the site continue to be recorded by groups, societies and individuals. The Lothian Amphibian and Reptile Group coordinates yearly 'toad patrols' in spring to help prevent the deaths of toads migrating to their breeding ground through the urban environment, and monitors toad numbers as part of this (Lothian Amphibian and Reptile Group, personal communication 2020).

Citizen science, involving non-professionals in biological and other observational recording, is a widely recognised method of public and community engagement and biological data gathering, and can contribute to a range of research (Tweddle *et al.* 2012; Rae *et al.* 2018). The concept of 'bioblitzes' (events where citizen scientists gather to find and record as many species as possible at a site in an allotted time) has grown in popularity in recent years (Sforzi *et al.* 2018). The data from these events can be submitted to national databases and used for research purposes (Tweddle *et al.* 2012). With a number of bioblitzes having been carried out in Edinburgh, the area surrounding Blackford Pond has great potential as a candidate for this kind of citizen science activity. Involving people in their local environment with such activities is an opportunity to further the research on biodiversity already carried out at the site and to encourage community involvement with the space (Hassall 2014).

It should be noted that the samples from the pond have been regularly used as demonstration materials in various educational courses at RBGE (e.g. MSc in Biodiversity) and The University of Edinburgh (e.g. 'Biology, Ecology and the Environment' course). The ecosystem services provided by the pond in relation to academic research and education are unlikely to have been reflected in the estimates of the pond's economic value using contingent valuation, and should therefore be addressed by further studies. There are, however, very subtle interesting trade-offs with some other ecosystem services. For example, the installation of reedbeds to improve water quality caused inconvenience in collecting mud for teaching and research materials (David Mann, personal communication). Furthermore, alterations of the trophic status of the pond may also cause problems for investigation of epipelic diatoms. Considering that the site has been proposed for designation as an Important Plant Area for algae (Brodie & John 2004; Brodie *et al.* 2007) any further management measures should be carefully considered in that respect.

4.5. Trade-offs and the importance for environmental management

Possible management priorities, on the basis of our research, may relate to improvements in water quality and also conservation measures to promote *Rhodocybe gemina* and other uncommon fungi occurring at the site. The latter aspect would link well with addressing the issue of fungal conservation lagging behind the conservation of other taxa both in Scotland and worldwide (Newton *et al.* 2003). The relative paucity of mycorrhizal fungi records (only four species) certainly suggests a call for more plantings of native trees and shrubs characterised by ectomycorrhizal associations. It should be noted, however, that although endomycorrhizal tree species (currently common on the site) do not host ectomycorrhizal partners, they nonetheless provide habitat for some saprotrophic fungi and associated invertebrates; for example, *Rhodocybe gemina* at this site appears to be associated with sycamore. Furthermore, both sycamore and ash provide very different microhabitats for characteristic suites of lichens – see, e.g., Thor *et al.* (2010), with a variety of trees important for tree-scale species turnover of epiphytes (Ellis 2012). There is, therefore, an obvious trade-off.

The current management emphasis of the pond and the surrounding area is on higher plants. However, this appears to be beneficial for the overall biodiversity of the site. This reflects the important ecological roles of plants as regards primary production, provision of substrates, habitat structure and microclimate. The composition of the plant community has profound influences on the overall biological diversity and ecosystem functioning. It is as yet unclear how much of this influence may be apportioned to native and introduced plant species. That is an acknowledged issue which corresponds to a knowledge gap existing in the contemporary research on urban ecology (Aronson *et al.* 2017) and should, therefore, be addressed by further studies.

Biodiversity, amenity, water quality and flood resilience benefits are the most important among ecosystem services of GI and BGI (CIRIA 2019a, 2019b; Fenner *et al.* 2019; O'Donnell *et al.* 2020). These benefits are interlinked and to some extent can be expected to correlate. In particular, our results show the importance of the variety of available habitats and the ecotone effect, resulting from the proximity of the pond and the adjacent GS, for the high values of biodiversity and amenity of the site. However, trade-offs between multiple benefits are not uncommon (Fenner 2017). The research presented here discusses some of these trade-offs and contributes to their improved understanding. This is beneficial for practical management not only of ponds, but also of other natural and artificial lentic and slow-flowing systems, as well as a wider range of GI objects. Trade-offs between specific ecosystem services categories are also taken into account in the NCPT calculations.

Further studies should examine in detail the potential trade-offs of the biodiversity, water quality and flood resilience provided by a pond with such ecosystem services as carbon capture and air quality, which may be expected to decrease because of the reduction in vegetation cover due to the pond's presence. A detailed account of flora and phytoplankton provided here (and often missing in considerations of carbon capture in non-marine settings) will be of relevance in that respect.

4.6. Further implications

It is noteworthy that multiple benefits of the pond manifest across a range of scales. For example, most of the biodiversity, flood resilience and water quality benefits are local, mainly on the micro- and mesoscale. However, the benefits for scientific research and education are, arguably, on the global scale. This follows from a regular use of the site by RBGE and Edinburgh University students (including international students) who benefit from this nature-based laboratory, and is also evidenced by a large number of peer-reviewed publications (see Section 4.4).

The pond will also help to alleviate urban heat island effect, and contributes to the overall resilience to climate change. The detailed consideration of all the multiple benefits associated with ecosystem services across a range of scales is paramount for the emerging framework of NBS valuation, and this paper provides important information in that respect (Raymond *et al.* 2017; Huthoff *et al.* 2018).

Additionally, the account of biodiversity and other ecosystem services given here is of relevance to the wider BGC framework. Urban ponds are an important component of BGI, which is becoming a common part of modern cities (Brears 2018; D'Arcy *et al.* 2018). Previous research has demonstrated that ponds (together with associated GS) are characterised by a better ecological quality than such BGI features as detention basins and swales (Miró *et al.* 2018), and are important both in residential and industrial settings (Krivtsov *et al.* 2021a, 2021c). There are, however, concerns regarding pollution and eutrophication of these systems. In particular, they may harbour cyanobacteria capable of producing toxins harmful to human and animal health (Codd 1984), which is more probable in conditions of elevated temperatures and low flow (Krivtsov *et al.* 1999b, 2000). The simultaneous consideration of hydrology, water chemistry and biodiversity presented in this paper provides information helpful for anticipating such conditions (Krivtsov *et al.* 2021a, 2021b), thus making it easier to design appropriate case-specific mitigation measures.

5. CONCLUDING REMARKS

This study has provided valuable information on taxonomic richness and ecological interactions of higher plants, bryophytes, lichenised and non-lichenised fungi, algae, protozoa, zooplankton, vertebrate animals and aquatic macroinvertebrates. The relatively high biodiversity value of the site has been implicated as one of the important causal prerequisites of its high amenity value. The study has also provided a thorough analysis of the site's hydrology and flood resilience benefits. This comprehensive combination provides an important basis for holistic environmental management which should take into account conservation requirements of various biological groups in the overall context of ecosystem services. The presence of rare, uncommon and declining species highlights the importance of managed urban habitats for a range of organism groups, even when sites are not managed primarily for those groups.

A summary overview of interactions among ecosystem services and the trade-offs considered in this paper is given in Figure 11. Although the focus of this paper has been primarily on the biodiversity, water quality and flood resilience benefits of this semi-natural location, it can also be seen that the site provides a number of other ecosystem services, such as social and cultural benefits, including physical and mental wellbeing, and

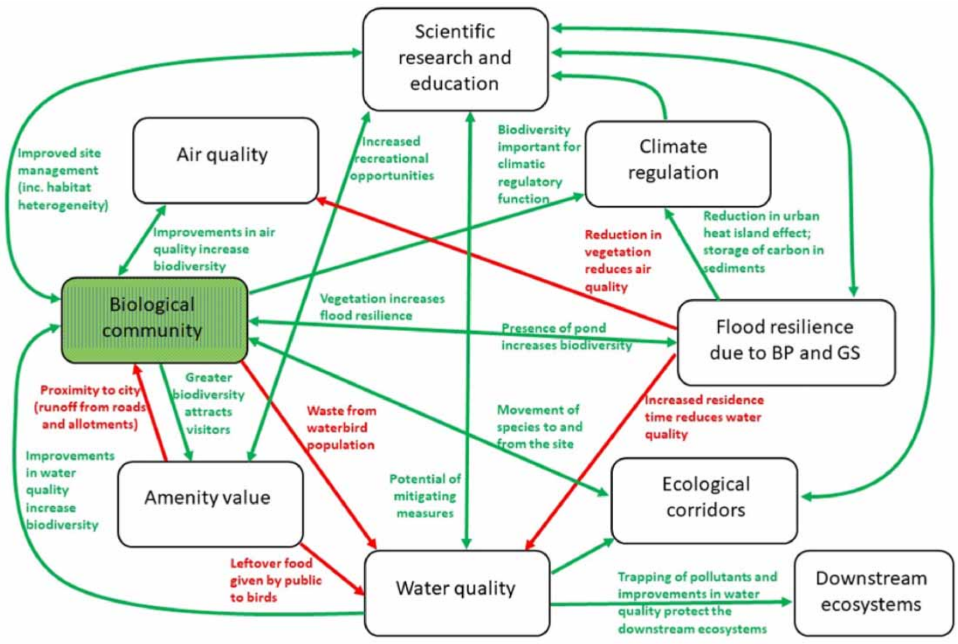


Figure 11 | Flowchart showing the main links between the ecosystem services provided by the Blackford pond (BP) and associated green space (GS). Green arrows and text show positive links and red arrows and text show main negative links (trade-offs). The biodiversity of the pond and GS is also driven by the habitat heterogeneity due to the interzonal effect. Note that some links and components (e.g. management trade-offs between mycorrhizal and lichenised fungi and between water quality and research) have been omitted to keep the chart readable – see text for further details.

educational opportunities through its role as an accessible GS. This reinforces the importance of BGI in urban areas and illustrates that when considering the ecosystem services provided by a site it is necessary to consider the different benefits in tandem, as they are interconnected.

Overall, our study contributes towards a better understanding of the ecology and overall functioning of GI and BGI, helping to increase appreciation of their benefits and promote further implementation.

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CONFLICT OF INTEREST

The authors declared none.

DATA AVAILABILITY STATEMENT

Data available for scientific cooperation. Biodiversity data are being deposited in relevant databases. All relevant data are included in the paper or its Supplementary Information.

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