Links between ecological and human wealth in drainage ponds in a fast-expanding city, and proposals for design and management

Abstract

Sustainable Drainage Systems (SuDS) are engineering solutions for managing storm water, and they can also provide blue spaces that equitably benefit the health and wellbeing of urban dwellers. The main objectives of this study were to test whether affluent neighbourhoods have SuDS with better ecological quality in one of Europe's fastest developing cities, and to investigate whether designable or manageable habitat characteristics of the SuDS, and the adjacent terrestrial area, are related to ecological quality. We estimated SuDS ecological quality by dimension reduction of five biotic and abiotic ecosystem components through performing a Principal Coordinate Analysis. Then we regressed SuDS ecological quality against socio-economic descriptors of the neighbourhood. We next applied non-parametric Kruskal–Wallis tests and probabilistic co-occurrence analysis to assess associations between habitat characteristics and ecological quality of SuDS. Our data showed that more affluent neighbourhoods have SuDS of higher ecological quality. We identified thresholds for some easily designable and manageable habitat characteristics of SuDS clearly linked to their ecological quality. There was strong co-occurrence of habitat characteristics, with aggregation of features linked to poor and good ecological quality, in SuDS designed as detention basins/ swales or ponds respectively. Our results can be applied to the design and management of SuDS to foster good ecological quality irrespective of the neighbourhood. This study will be valuable for building and managing SuDS in a nature-based way, thus providing more socially equitable access to high-quality urban blue space.

Keywords: Blue spaces; Habitat design and management; Socio-economic equality; Stormwater ponds; SuDS ecological quality; Urban ponds.

1. Introduction

The world's human population is increasing and as it does so a greater proportion of people are living in cities (United Nations, 2014). For example, in Europe, 9% of land is classified as urban (Scalenghe & Marsan, 2009). Whilst urban expansion is clearly a threat to biodiversity (e.g. Beninde, Veith, & Hochkirch, 2015), when effectively managed, urban green (parks and gardens) and blue (coast, ponds, lakes, canals and rivers) spaces can provide valuable wildlife habitats (Aronson et al., 2017; Hill et al., 2016). Green and blue spaces can be especially important when the surrounding countryside has been degraded by intensive agriculture (Colding & Folke, 2009; Deutschewitz, Lausch, Kuhn, & Klotz, 2003). Such spaces can also contribute to habitat networks, which can connect populations, enabling movement of genes and individuals (Van der Ryn & Cowan, 1996)(xxx, 2015 masked for blind review). Furthermore, blue and green spaces offer opportunities to bring urban dwellers into contact with nature (Folke et al., 2011).

Several studies (Irvine, Warber, Devine-Wright, & Gaston, 2013; Mitchell & Popham, 2008; Triguero-Mas et al., 2015) have shown wellbeing and health benefits to people living close to urban green space, though not necessarily urban blue space. Specifically, exposure to green space has been linked to a better self-perceived general and mental health, and to all-cause mortality i.e. all of the deaths that occur in a population, regardless of the cause (van den Berg et al., 2015). Urban blue spaces, have been reported to be drivers of emotional restoration, and to enhance physical and mental health of city-dwellers (Völker & Kistemann, 2011; White et al., 2010). On the other hand, high-quality and easily accessible green spaces also contribute to reducing social and age-related inequalities (Aspinall et al., 2010; Shanahan, Lin, Gaston, Bush, & Fuller, 2014). Furthermore, access to urban green spaces has been found to break the usual link between socioeconomic and health inequality (Mitchell & Popham, 2008; Mitchell, Richardson, Shortt, & Pearce, 2015). Biodiversity plays a central role in the observed benefits for people, with health benefits positively linked to species richness of green spaces (i.e. plants and birds richness; Fuller, Irvine, Devine-Wright, Warren, & Gaston, 2007), although the relationship with plant diversity is unclear, possibly due to people being unable to distinguish different species (Dallimer et al., 2012). Indeed, it has been suggested that the qualities (atmosphere, comfort, safety, attractiveness, maintenance, naturalness, etc.) of urban green and blue spaces may be equally or more important than the quantity for human health and wellbeing (Francis, Wood, Knuiman, & Giles-Corti, 2012; van Dillen, de Vries, Groenewegen, & Spreeuwenberg, 2012). In addition, cumulative accessibility opportunity indicators of green spaces, which take all the green space within a certain distance into account, are more consistently positively related to health than residential proximity ones (Ekkel & de Vries, 2017). These multiple benefits are of great interest to policy makers and to government agencies charged with nature and environmental protection (Hansen & Pauleit, 2014; Wade & McLean, 2014).

One class of urban blue space is Sustainable Drainage Systems (SuDS): storm water management solutions that reduce flood risk and diffuse pollution, through a series of processes which mimic natural drainage processes rather than hard engineering approaches (Woods-Ballard et al., 2015). SuDS have been seen as a way of helping countries achieve their obligations under the European Union’s Water Framework

Directive (European Council, 2000) and Scotland was one of the early adopters of the approach, with SuDS being mandated in all new developments with more than two new premises since 2003 (Scottish Parliament, 2003). SuDS might be designed as detention basins, "landscaped depressions that are normally dry except during or immediately following storm events", swales, "shallow, flat-bottomed vegetated open channels" or as ponds, "a permanent pool of water that provide[s] attenuation and treatment of surface water runoff" (Woods-Ballard et al., 2015). Several researchers have suggested that SuDS can benefit wildlife by providing habitats, connecting wildlife populations and bringing urban dwellers into contact with nature (Hill et al., 2016; Parris, 2016; Woods-Ballard et al., 2015)(xxx 2015 masked for blind review). As artificial features, all aspects of SuDS and their immediate surroundings are under the control of planners and designers. The decision to make a pond rather than a detention basin and how to design that pond, e.g. with shallow sides, with planting of shrubs etc, are made at the design stage and are subject to oversight by local, and at times national government (Woods-Ballard et al., 2015). Ongoing management, including grass-cutting, clearing reeds and management of water levels is controlled by local authorities, water companies, residents' associations, local communities or a combination of these groups. Therefore, there is an opportunity for SuDS to be planned and managed as an integrated means of reducing flood risks, improving opportunities for biodiversity, and promoting human wellbeing and health (Charlesworth & Booth, 2016).

Given the potential importance of SuDS to urban ecosystems we sought to evaluate possible links between urban economic circumstances, and the habitat characteristics of SuDS. The study had two objectives: (i) test the hypothesis that affluent neighbourhoods have SuDS with better ecological quality, as defined in Section 2.2, (perhaps because developers make a higher level of investment in expensive neighbourhoods), and (ii) investigate whether designable or manageable habitat characteristics of the SuDS and the adjacent terrestrial area are related to ecological quality.

2. Methods

2.1. Study area and data survey

We based the study on 34 SuDS constructed between 2002 and 2012 and located in newly-developed residential areas of the city of Inverness, Scotland, UK (57°28'N 4°13'W; Fig. 1; Table A1 in Appendix A). As one of western Europe's fastest growing cities since 2000, Inverness in the Scottish Highland region of the UK, is a good study area for SuDS, with the population of the greater Inverness area increasing by 17% between 2003 and 2013, when it reached 79,415 (National Records of Scotland, 2016). Most of this recent expansion took place under a legislative regime promoting SuDS, and they can be found in a wide variety of neighbourhoods from low-priced and social housing through to more expensive developments. In addition, many of the SuDS are part of a long-term biodiversity monitoring project (xxx, 2015 masked for blind review).

Originally all 40 SuDS in the city were surveyed, but six of them were excluded from the current study as they are not in residential areas. Of the 34, 20 were designed as ponds, and the other 14 as detention basins/ swales. Studied SuDS had surface areas ranging from 0.0054 to 0.1644 ha, with a median of 0.02145 ha, and altitudes from 38 to 165 m.a.s.l. with a median of 74 m. We surveyed each SuDS at least four times in 2015 between late winter and late summer to record habitat characteristics (see Table 1 for a list of variables and sections below for a detailed survey description). Twelve of the SuDS had also been surveyed four times per year from 2010 to 2013 for a previous study (xxx, 2015 masked for blind review). We collected field data for both the SuDS and the adjacent terrestrial area within approximately 500 m of the edge of the SuDS, this distance being based on known movement distances of British amphibians (Baker, T., Buckley, Gent, & Orchard, 2011). Specific data collected and methods used are detailed in the sections below.

2.2. Ecological quality

Ecological quality of freshwater and marine ecosystems can be evaluated using multimetric indices based on several biotic (e.g. macrophytes, diatoms, amphibians, fish, macroinvertebrates or nematodes) and abiotic (e.g. concentration of pollutants) ecosystem components (e.g. Borja, Franco, & Perez, 2000; Clarke, Wright, & Furse, 2003). Patterns of variation in taxonomic richness (number of species or other taxa; e.g. macrophytes, macroinvertebrates, amphibians) are often highly correlated, and have been extensively used to assess ecological quality of ponds (e.g. Ilg & Oertli, 2016; Noble & Hassall, 2015). Following these lines, we assessed SuDS ecological quality as a measure obtained by the dimension reduction of five ecosystem components (Table 1) that have previously been used to assess the ecological quality of ponds: Of these components, three related to the pond itself: richness of amphibian species, of general macroinvertebrate groups and of macrophyte species (e.g. Menetrey, Sager, Oertli, & Lachavanne, 2005; Walker, Wijnhoven, & van der Velde, 2013). The other two components related to the adjacent terrestrial area (whether green or constructed): richness of terrestrial habitats and degree of urbanization (e.g. Villaseñor, Driscoll, Gibbons, Calhoun, & Lindenmayer, 2017) (xxx 2017 masked for blind review).

We surveyed amphibian species and macroinvertebrate taxa or general groups, at least four times in the 2015 breeding season, from late winter to late summer. Of the

SuDS, twelve had also been surveyed from 2010 to 2013 four times per year during the breeding season. For amphibian survey we used four techniques following the British National Amphibian and Reptile Recording scheme (NARRS) protocol: egg searching, dip netting, torching/flash-lighting, and trapping (ARG-UK, 2013; Griffiths & Langton, 2003). Egg searching involved looking for frog- and toad-spawn (March/April) and folded leaves containing newt eggs (May to August), among the submerged vegetation. Dip netting was carried out from the shore using a net with a 2 mm mesh, sweeping all the accessible perimeter of ponds and including all habitats present. Torching (Cluson Clulite CB2, 1 million C/P) was conducted from shortly after dusk to shortly after midnight, walking around the entire pond perimeter. Trapping was carried out using up to 20 46×21×21 cm funnel traps for each pond (4 mm nylon mesh with 6 cm diameter openings at each end, see Madden & Jehle, 2013). Funnel traps were installed amongst aquatic plants shortly before sunset and checked within 10 hours. Trapping was not carried out in SuDS near to houses, to avoid the risk of tampering or vandalism. All surveying followed Scottish Natural Heritage guidance, to ensure welfare of both target and non-target species, and the disease and non-native species control measures advised for amphibian field workers (ARG-UK, 2008).

We assessed macroinvertebrate community both during amphibian survey and by dip-netting the different habitats found in the pond in proportion to their coverage. The total sampling time for each site was three minutes of netting plus a further minute of shore visual searching in line with the UK National Pond Survey protocol (Biggs et al., 1998). Eleven macroinvertebrate taxa were identified in the field and then returned to the pond. Macroinvertebrates were identified to high-level taxa: adult pond skaters (Family Gerridae), adult back-swimmers (Family Notonectidae), beetle adults and larvae (Order Coleoptera), larvae of dragonflies (Order Odonata), mayflies (Order

Ephemeroptera), caddisflies (Order Trichoptera) and gnats (Order Diptera), and adult leeches (Subclass Hirudinea), molluscs (Phylum Mollusca) and large crustaceans (>0.5cm) such as *Gammarus* spp. A list of vascular plants in the pond and its margins, up to maximum high water, was compiled in August 2015. Data from surveys were pooled to determine the presence or absence of amphibian, macroinvertebrate and macrophyte taxa and compute their richness at given ponds.

We characterised adjacent terrestrial habitat by estimating its composition from the water's edge to approximately 500 m into the surrounding land, as % coverage of the following categories (EUNIS alphanumeric code in brackets, European Environment Agency, 2014): rocks, intensive unmixed crops (I1.1), cultivated areas of gardens and parks (I2), mesic grassland (E2), Temperate thickets and scrub (F3.1), mixed *Pinus sylvestris - Betula* woodland (G4.4), broadleaved deciduous woodland (G1), *Pinus sylvestris* woodland (G3.4), highly artificial coniferous plantations (G3.F), recently felled areas (G5.8), surface running waters (C2), mires, bogs and fens (D), and surface standing waters (C1). We subsequently calculated the number of terrestrial habitats (the total number of categories presents in the surrounding area) as a richness value.

The degree of urbanization of the adjacent terrestrial area was estimated by adding the % of land coverage, from the water's edge to approximately 500 m into the surrounding area, of the categories (EUNIS alphanumeric code in brackets, European Environment Agency, 2014): low density buildings (J2), residential buildings of village and urban peripheries (J1.2), road networks (J4.2) – subdivided into sand/forestry road and asphalt road, and artificial concrete embankment (J4.1). This variable was square root transformed to enable it to be more simply compared with the other four ecosystem components.

2.3. Socio-economic descriptors

To accurately describe the socio-economic status of the neighbourhoods where SuDS had been constructed, we used 17 variables retrieved from Scotland's Census of 2011 (National Records of Scotland, 2016) (Table 1). We chose 17 variables from the three tables of the Scottish census that were most related to the household's economic resources: KS401SC – type of household residence (flat or detached, semi-detached or terraced house), QS407SC - number of rooms for the sole use of the household (from three to nine or more) and KS404SC – number of cars or vans belonging to the household (from zero to four or more). Flat prices in Inverness are typically much lower (averaging £109,711) than semi-detached and detached houses (averaging £168,172 and £240,9786 respectively; Registers of Scotland, 2017). The socio-economic categorizations of the 10-yearly Scotland's Census offer useful research opportunities (Clayton & Gillam, 2018), and have been used in other research areas such as health studies (e.g. Doherty, Brewster, Jensen, & Gorman, 2010; Drever, Doran, & Whitehead, 2004). To avoid diluting any association between the socio-economic characteristics of a neighbourhood and habitat characteristics of the nearby SuDS, we used census Output Areas (OA), which is the smallest geographical area for which census results are published in Scotland (minimum size = 20 residential households, target size = 50 households) (National Records of Scotland, 2016). Values for each socio-economic variable were transformed to percentages to facilitate comparison of Output Areas with different population sizes.

2.4. Design and management characteristics

In the field, we also collected data for 10 designable and manageable habitat characteristics (Table 1) that previous studies suggested were linked to the ecological quality of SuDS (xxx, 2015 masked for blind review)(Woods-Ballard et al., 2015). The characteristics can all be managed by design (e.g. height of outflow, landscaping or planting of shrubs and perennials), or management (e.g. opening of sluices, mowing regimes or clearing reeds). We grouped these characteristics into four classes: (i) hydroperiod (water level, permanent/ ephemeral and frequency of desiccation, (ii) morphology (SuDS type, predation refuge presence and slope of bank), (iii) aquatic vegetation (macrophyte surface coverage and vertical density of macrophytes), and (iv) adjacent terrestrial habitat (terrestrial habitat structure and richness of terrestrial habitat types).

We assessed the duration of the hydroperiod in the pond as either ephemeral, if the pond has just short wet periods, or permanent, if it holds water more or less all the time. We assessed water level during the survey period (amphibian breeding season), as empty, low or full. We also estimated the frequency that the pond dries up by interviewing local residents: annually (dries annually), sometimes (dry for three or more years in ten), rarely (dries no more than two years in ten, or only in drought), or never (never dries) (ARG-UK, 2010).

We assessed the type of design for each SuDS, either detention basin, swale or pond. Detention basins are "landscaped depressions that are normally dry except during or immediately following storm events," swales are "shallow, flat-bottomed, vegetated open channels", and a pond is "a permanent pool of water that provide[s] attenuation and treatment of surface water runoff" (Woods-Ballard et al., 2015). We recorded the presence or absence of predation refuge areas in the pond, generally shallow vegetated or stony areas near the shore that large aquatic predators (e.g. fish) cannot access. Other studies have shown such refuges to be important for amphibians (xxx, 2017; xxx, 2017 masked for blind review). Bank slope was estimated visually and expressed as percent coverage for the categories: shallow (<10 cm deep), flat (0-10º), slightly sloping (15-30º), moderately sloping (roughly 40º), quite sloping (50-60º), very sloping (70-80º) and vertical (roughly 90º). We assessed macrophyte surface coverage by estimating the percentage cover of submerged or emergent macrophytes, and macrophyte vertical density by estimating the percentage of the pond water column occupied by vegetation, where present.

We assessed terrestrial habitat structure as poor (structure that offers limited opportunities for foraging and shelter; e.g. amenity grassland), moderate (habitat that offers opportunities for foraging and shelter, but limited in area and does not completely surround pond) or good (extensive area of habitat that offers good opportunities for foraging and shelter completely surrounding pond; e.g. rough grassland, scrub or woodland) (ARG-UK, 2010). We recorded the number of EUNIS habitats (European Environment Agency, 2014) present in the adjacent terrestrial green area according to five categories: 1-3 habitats, 4 habitats, 5 habitats, 6 habitats or 7-9 habitats. None of the surveyed SuDS had 10 or more types of adjacent terrestrial habitats.

2.5. Statistical analyses

We made different but related numerical treatments to achieve the two objectives of the study. We first assessed SuDS ecological quality by performing a dimension reduction of the five ecosystem components described above through a Principal Coordinate Analysis (PCoA) based on Chord distance (Borcard, Legendre, & Gillet, 2011). Ecosystem components were previously standardized to zero mean and unit variance to correct their heterogeneous dimensions (Borcard et al., 2011). The type of SuDS, either swale, detention basin or pond, was used to explore the importance of the design. We next computed Spearman correlations between the first component of the PCoA with the five ecosystem components. The first component of the PCoA (PCo 1) accurately represented the general ecological quality of SuDS, hence this was used as an independent variable in further analyses (see below).

We achieved the first objective of the study by investigating the relationship between SuDS ecological quality and the socio-economic conditions of the neighbourhood (as Output Area) by regression analysis. To avoid pseudoreplication in the data, since one Output Area in the dataset had three SuDS and other seven had two SuDS, we made a multiple linear mixed model (LMM, Lindstrom & Bates, 1988) with the Output Area as a random factor. The response variable was SuDS ecological quality (PCo 1). The predictors introduced were the socio-economic descriptors of the Output Area, in addition to SuDS type, which was also included to consider the importance of design. We avoided excessive correlation within the predictor dataset by subjecting the 17 socio-economic descriptors originally chosen, together with SuDS type, to a collinearity analysis and selection procedure. We sequentially computed Variance Inflation Factor VIF for all 18 predictors and rejected the variable with the highest value until none of them was >3. We chose this threshold since a VIF value above 3 is indicative of worrisome collinearity in regression analyses (Zuur, Ieno, Walker, Saveliev, & Smith, 2009). All predictors except SuDS type were previously log(x+1) transformed to bring them closer to the normal distribution. At the end of the procedure we obtained a selected dataset of nine predictors, SuDS type and eight independent socio-economic descriptors: semidetached houses, terraced houses, and three rooms, six rooms, eight rooms, nine rooms, three cars and four cars belonging to the household. A detailed description of the nine final selected predictors is given in Table 1. Table A2 in Appendix A shows initial and final VIF values of the procedure.

We next searched the best LMM and performed a backward selection process to find the minimum combination of predictors that described most of the variance (Zuur et al., 2009). We began with all predictors, dropping the least significant at each step. We then compared the new and the previous model with a likelihood ratio test until we found significant differences, at which point we rejected this final model and took the previous one. Violation of the assumptions of normality and homogeneity in variance were checked by examining the residuals (Zuur et al., 2009). Eventually, to have a more complete view of the links between ecological and human wealth in Inverness, we computed Pearson correlation coefficients among all eight socio-economic predictors used in the LMM. The socio-economic variables 'proportion of detached houses' and 'proportion of households with one car' were also included to better illustrate the correlation structure within the entire dataset.

To achieve the second objective we investigated the associations between SuDS ecological quality (PCo 1) and designable and manageable habitat characteristics, by computing Kruskal-Wallis analyses and constructing boxplots to highlight useful thresholds. These thresholds are values above or below which there is an impact (positive or negative) on ecological quality, and which could thus be used to inform design or management of SuDS. The level of statistical significance considered was $P \leq 0.05$. Once habitat thresholds were known, we computed pairwise probabilistic co-occurrences (Griffith, Veech, & Marsh, 2016) among all categories within habitat variables. All analyses were carried out with *R* statistical software (R Core Team, 2016) using the basic functions and the packages *vegan* (Oksanen et al., 2018) to perform PCoA, *nlme* (Pinheiro, Bates, DebRoy, Sarkar, & R Development Core Team, 2017) to develop LMM, *sjPlot* (Lüdecke, 2018) and *ggplot2* (Wickham, 2009) to compute and draw marginal effects in LMM, and *cooccur* (Griffith et al., 2016) to perform co-occurrence analyses.

3. Results

3.1. SuDS ecological quality and neighbourhood wealth

The PCoA showed a clear gradient within the ecological dataset (Fig. 2a), with a first principal component (PCo 1) that represented 46.0% of the explained variance. Four of the five ecosystem components were strongly correlated with PCo 1: amphibian richness (Spearman rho= 0.83, P<0.001), macroinvertebrate richness (Spearman rho= 0.91, P<0.001), macrophyte richness (Spearman rho= 0.84, P<0.001) and urbanization (Spearman rho= –0.52, P=0.002). SuDS type also showed a relationship with PCo 1 (Fig. 2a), with SuDS designed as ponds generally having higher ecological quality than those designed as swales or detention basins.

The best LMM (R^2= 0.72) confirmed this relationship between SuDS type and ecological quality (PCo 1) (Table 2, Fig. 2b). Within the socio-economic dataset, SuDS ecological quality (PCo 1) was positively associated with the proportion of household residences with nine or more rooms (Table 2, Fig. 2b). Furthermore, the correlation structure of the socio-economic dataset (Table 3) showed that a higher number of rooms in the household residence was positively associated with other indicators of affluent neighbourhoods, such as higher number of cars belonging to the household or higher proportion of detached houses in the Output Area. In contrast, a lower number of rooms in the household residence was positively associated with other indicators of less affluent neighbourhoods, such as lower number of cars belonging to the household and lower proportion of detached houses in the Output Area.

3.2. Habitat characteristics of SuDS

Hydroperiod was a determining designable and manageable habitat characteristic for the ecological quality of SuDS. SuDS found dry during the field survey showed lower ecological quality (median PCo 1 score -0.92 [range -0.99, -0.75]; Fig. 3ai), while SuDS found with low levels or full of water had higher ecological quality (median -0.33 [-0.79, 0.91] and 0.42 [-0.94, 0.89] respectively). Also, those ephemeral SuDS which had only short wet periods generally had lower ecological quality (median -0.79 [-0.99, -0.33]; Fig. 3aii) than those which were permanently wet (median 0.42 [-0.95, 0.91]). Similarly, SuDS that dried up either annually, or three to nine years in 10, showed lower ecological quality (median -0.79 [-0.99, -0.42] and -033 [-0.79, 0.54] respectively; Fig. 3aiii). In contrast, SuDS that dried up rarely (one to two years in 10), or never, showed higher ecological quality (median -0.03 [-0.95, 0.84] and 0.81 [0.07, 0.91] respectively).

Several other characteristics of SuDS' design and construction were also important. Detention basins and swales showed lower ecological quality (median -0.76[-0.99, -0.03]; Fig. 3bi), while SuDS ponds showed higher ecological quality (median 0.62 [-0.95, 0.91]). SuDS without predation refuges showed lower ecological quality (median -0.68 [-0.99, 0.91]; Fig. 3bii), compared to SuDS with predation refuges (median 0.56 [-0.79, 0.87]). SuDS with less than 10% of slightly sloping bank (15-30º approximately) showed lower ecological quality (median -0.76 [-0.99, 0.75]; Fig. 3biii), compared to those with 10% or more (medians higher than 0.32 [-0.94, 0.91]; Fig. 3biii).

Macrophyte coverage of SuDS, both surface coverage and vertical density, was related to high ecological quality. SuDS with water surface coverage of aquatic vegetation between 20% and 85% showed higher ecological quality (medians 0.55

[0.07, 0.89] and 0.66 [-0.34, 0.87]; Fig. 3ci), relative to those with surface coverages lower than 20% or higher than 85% (medians -0.79 [-0.99, 0.91] and -0.38 [-0.79, 0.75] respectively). Similarly, SuDS with vertical density of aquatic vegetation between 10% and 85% showed higher ecological quality (medians of 0.35 [-0.62, 0.87] and 0.55 [-0.34, 0.91]; Fig. 3cii), compared to those with lower than 10% or higher than 85% (medians -0.86 [-0.99, -0.75] and -0.78 [-0.99, -0.33] respectively).

The quality and number of terrestrial adjacent habitats were also important in defining SuDS ecological quality. All the SuDS with poor terrestrial habitat structure showed lower ecological quality (median -0.68 [-0.99, 0.17]; Fig. 3di). In contrast, most of the SuDS with moderately- or well-structured adjacent terrestrial habitat showed higher ecological quality (medians 0.42 [-0.79, 0.89] and 0.66 [-0.79, 0.91] respectively). A similar although less defined pattern was found for the richness of adjacent terrestrial habitats (Fig 3dii).

Co-occurrence analyses highlighted a large degree of coincidence for habitat characteristics linked with either higher or lower ecological quality (Fig. 3). Thus, SuDS ponds showed positive co-occurrence with the presence of predation refuges, were wet throughout the survey season (whether low-level or full), had moderate values of macrophyte vertical density and surface coverage (10-20% to 85%), had a greater proportion (>10%) of perimeter with slightly sloping bank, desiccation limited to two years in 10 at most, and moderately- or well-structured adjacent terrestrial habitat. In the same manner, detention basins and swales showed positive co-occurrence with the complementary categories.

4. Discussion

Our results confirmed that ecological quality of SuDS is higher in more affluent neighbourhoods. We also established that many characteristics of the SuDS and the adjacent terrestrial area that can be included in the initial design, or enhanced through management, are associated with ecological quality.

SuDS, whilst designed as measures to control pollution and flooding, can be a good example of multi-functional features. Their creation is promoted through European legislation for new developments and, if well-designed, they can also provide ecological and social benefits (Völker & Kistemann, 2011). Previous work in Britain suggested that pond creation is one of the most space-efficient means of enhancing local biodiversity (Williams et al., 2004), and White et al. (2010) found that people demonstrated preferences for landscapes which include water features over those without. Indeed, images of built environments including water were rated as positively as natural green space. However, access to SuDS of good ecological quality may not be equitably distributed in newly-developed cities. In our case, SuDS with higher values for ecological quality were found in more affluent neighbourhoods, defined according to type of residence (detached, semi-detached etc), number of rooms and cars belonging to each household. Therefore, our results clearly show that people in lower-priced homes in Inverness have less opportunity to experience good ecological quality SuDS in their immediate vicinity. This inequality is particularly concerning, since proximity to recreational/green spaces has been linked to a reduction of the detrimental effect of social deprivation on people's health (Mitchell & Popham, 2008; Mitchell et al., 2015). Other studies have shown that poorer urban families are less likely to visit the countryside than more affluent ones (e.g. Booth, Gaston, & Armsworth, 2010). For children, having the chance to grow up in contact with nature has also been linked to improved mental health/ educational outcomes (Bingley & Milligan, 2004). Given the stated aim of the UK, other European governments and the World Health Organisation to reduce health inequalities (Bartley, 2016; reviewed in Marmot, 2005; Marmot, Allen, Bell, & Goldblatt, 2012), improving access to good quality urban blue space could be a simple measure with positive societal effects. However, three flat-dominated neighbourhoods in Inverness had SuDS of very good ecological quality (HFR, IP and WHR, Table A1 in Appendix A) which shows that, with enlightened planning, more egalitarian construction of SuDS is possible.

The ecological quality of the Inverness SuDS is largely driven by habitat quality, with previous studies showing little impact of pollutants in all but one pond (xxx 2015 masked for blind review). Many of these habitat characteristics stem from the original design, which maximizes potential benefits from the outset. Ponds clearly out-perform detention basins and swales and, where this is compatible with the engineering function, should ideally be constructed with predation refuges in the form of small shallow areas (some of them stony), a proportion of slightly sloping bank and a fine-grained bottom to allow the colonization and growth of macrophytes. The surrounding landscaping is also important, and should include several types of adjacent terrestrial habitat (grassland, bushes, woodland) with mixed autochthonous species, rather than the uniform amenity grassland seen at some sites. The combination of slightly sloping bank and rich, well-structured adjacent, terrestrial habitat provides good opportunities for foraging and shelter to the pond fauna, particularly to amphibians and adult phases of invertebrates (xxx 2017 masked for blind review).

Regular hydroperiod is linked to good ecological quality. Our results suggest that ponds which never dry out have the highest ecological quality. In contrast, other studies of both natural and created ponds found that, for amphibians at least, occasional desiccation events (c. one year in 10) are beneficial, probably because they eliminate introduced top predators, principally fish (Oldham, Keeble, Swan, & Jeffcote, 2000). Exotic fish are frequently introduced (accidentally or deliberately) into ponds (e.g. Copp, Wesley, & Vilizzi, 2005) and cause large negative impacts on amphibian and macroinvertebrate communities (Hamer & Parris, 2011; van Kleef, van der Velde, Leuven, & Esselink, 2008). Our surveys took place during the breeding season for many species, so it is perhaps unsurprising that SuDS drying out during this period tended to score less well for biodiversity than those retaining at least some water. Indeed, given the tendency of common frogs (*Rana temporaria*) to lay eggs in shallow water (Minting, 2016), these SuDS may act as population sinks, ultimately reducing reproductive success and urban population sizes of spring-breeding species.

Functional design of SuDS may include qualities that promote good ecological quality. Most of the habitat characteristics of our study sites were not randomly distributed, but co-occurred following a coincidence pattern linked with poor or good ecological quality, suggesting that one can design-in qualities associated with high ecological performance. Whilst SuDS are primarily designed for water management, rather than for societal or ecological benefits, some of the characteristics shown to benefit wildlife are also linked to their functionality. For example, gently sloping sides increase the rate of natural treatment of some pollutants (Woods-Ballard et al., 2015), and as we have shown, are linked to ecological richness. Gently sloping banks are also less of a hazard for people, particularly children, than steep sides, an important feature in residential areas.

Detention basins and swales showed a large aggregation of habitat characteristics linked to poor ecological quality, whereas SuDS designed as ponds showed coincidence of habitat characteristics linked to good ecological quality. However, there may be cases where detention basins and swales offer the best engineering solution and in such cases, design should at least attempt to incorporate as many of the favourable factors identified as possible. Furthermore, we recommend consideration of green or blue corridors of favourable habitat linking the site with a pond or ponds. Further study of gene-flow in water-dependent taxa such as amphibians would be beneficial to better understand the extent to which wildlife makes use of such corridors but the observed speed of colonization suggests that movement is significant (xxx 2015 masked for blind review).

Occasionally management work is needed to keep SuDS within good standards of ecological quality and engineering function. Ponds tend to be fairly low in their maintenance requirements but occasional thinning of vegetation to keep surface and vertical water column macrophyte densities broadly between 20% and 80% will promote good ecological quality of SuDS and reduce the likelihood of their becoming blocked and therefore failing in their primary water management function. Managing adjacent areas to favour meadow plants, rather than amenity grassland lacking species and structural diversity, could be promoted. This increased plant diversity may also lead to greater capture of excess nutrients (e.g. from garden fertilizers) before they reach the water system (Woods-Ballard et al., 2015).

There are likely to be other factors driving ecological quality. Previous studies have suggested proximity to water courses (Birx-Raybuck, Price, & Dorcas, 2010) to be an important factor in urban amphibian diversity, though the near ubiquity of streams in Inverness meant that all SuDS were within 500 m of a stream (xxx 2015 masked for blind review). The recent release of improved tools to map land under concrete suggests promising areas of study, perhaps coupled with vehicular traffic metrics (Villaseñor et al., 2017). Whilst it seems intuitively obvious that SuDS and their environs will promote greater ecological diversity than amenity grassland, we did not study the biodiversity of more imaginative uses of public space, such as urban woodlands or flower meadows. There may well be a trade-off between the social and ecological benefits of alternative land covers. However, given the legal imperative for SuDS creation, it would perhaps be more useful to consider the interactions between high-diversity green and blue space.

This study demonstrates that access to SuDS of good ecological quality is not equitably distributed in this newly-developed city. As with any study limited to one city, it would be unwise to assume that all our findings are universally applicable. However, we have also shown that the factors leading to this inequality can easily be overcome through low-cost methods of design and management. SuDS are required by European legislation for new developments, and timely investment in their design and management can enable them to fulfil a range of other ecological and social functions. This potential decoupling of economic and ecological wealth gives planners and developers an opportunity to enhance the biodiversity of urban areas with consequent benefits for citizens regardless of socio-economic status. The outputs of this study can be applied, as nature-based solutions (Nesshöver et al., 2017), to the management of constructed SuDS, and for the design of urban ponds to promote human health and wellbeing alongside biodiversity in established and expanding cities.

Appendix A. Supplementary data

Supplementary tables associated with this article can be found, in the online version, at ----------

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TABLES:

Table 1

Variables used in the numerical treatment. Abbreviations are given in brackets.

Variable type	Variable name	Description
Ecosystem components	Amphibian richness (amphrich)	Number of amphibian species present in the SuDS
	Macroinvertebrate richness (minvrich)	Number of defined macroinvertebrate taxa present in the SuDS
	Macrophyte richness (macrophrich)	Number of macrophyte species present in the SuDS
	Terrestrial habitat richness (terrich)	Number of habitats present in the adjacent terrestrial green area of SuDS (European Environment Agency, 2014)
	Urbanization (urban)	% coverage of SuDS adjacent terrestrial area occupied by human constructions, square root transformed
	SuDS ecological quality (PCo 1)	First principal coordinate for all five ecosystem components of SuDS. This is positively correlated with SuDS general ecological quality
Socio-economic indicators	Semidetached houses(SEMIDETA)	Percentage of semidetached houses in the Output Area, log(x + 1) transformed
	Terraced houses (TERRACED)	Percentage of terraced houses in the Output Area, log(x + 1) transformed
	Three rooms (ROOM3)	Percentage of household residences with three rooms in the Output Area, log(x + 1) transformed
	Six rooms (ROOM6)	Percentage of household residences with six rooms in the Output Area, log(x + 1) transformed
	Eight rooms (ROOM8)	Percentage of household residences with eight rooms in the Output Area, log(x + 1) transformed
	Nine rooms (ROOM9)	Percentage of household residences with nine or more rooms in the Output Area, log(x + 1) transformed
	Three cars (CAR3)	Percentage of households with three cars or vans in the Output Area, log(x + 1) transformed
	Four cars (CAR4)	Percentage of households with four or more cars or vans in the Output Area, log(x + 1) transformed
Habitat characteristics	SuDS type	Factor indicating if the SuDS was designed as a detention basin, swale or pond
	Predation refuge	Binary factor determined by the presence or absence of predation refuge areas in the pond
	Slightly sloping bank	% of pond perimeter with slightly sloping banks (20-30º slope)
	Water level	Factor indicating the water level in the pond during the survey period: empty, low or full
	Ephemeral/ permanent	Binary factor determined by the duration of the hydroperiod in the pond: ephemeral or permanent
	Frequency of desiccation	Factor indicating the frequency in 10 years the pond dries up: annually, sometimes (3-9) rarely (1-2) or never (ARG-UK, 2010)
	Macrophytes surface coverage	% coverage of the pond surface occupied by submerged or emergent macrophytes
	Macrophytes vertical density	% of water column occupied by aquatic vegetation
	Terrestrial habitat structure	Factor indicating terrestrial habitat structure: none, poor, moderate or good (ARG-UK, 2010)

	Terrestrial habitat richness	Factor indicating the number of habitats present in the adjacent terrestrial green area: 1-3, 4, 5, 6 or 7-9

Table 2

Model parameters for the best Linear Mixed Model (LMM) analysis of SuDS ecological quality (PCo 1) by socio-economic predictors. SuDS type, either swale, detention basin or pond, was also added as predictor to highlight the importance of design. Variables are described in Table 1. We present the two variables selected in the best model, the coefficient, standard error (SE), degrees of freedom (DF) and p-value (*P*).

Variable	Coefficient	SE	DF	*P*
Intercept	0.12	0.14	22	0.38
SuDS type: swale	–1.34	0.21	22	<0.001
SuDS type: detention	–1.05	0.15	8	<0.001
Log(ROOM9+1)	0.43	0.15	22	0.008

Table 3

Correlation structure within the socio-economic dataset. The table shows the Pearson correlation matrix of the eight socio-economic descriptors used as predictor variables in the linear mixed model (LMM) analysis. The abbreviations indicate: semidetached houses (SEMIDETA), terraced houses (TERRACED), three rooms (ROOM3), six rooms (ROOM6), eight rooms (ROOM8), nine rooms (ROOM9), three cars (CAR3) and four cars (CAR4). Variables are described in Table 1. The variables detached houses (DETACHED) and one car (CAR1) were also added to better illustrate the correlation structure. All variables were previously log(x+1) transformed. *denotes correlation significantly different from zero ($p < 0.05$).

	SEMIDETA	TERRACED	ROOM3	ROOM6	ROOM8	ROOM9	CAR1	CAR3	CAR4
DETACHED	-0.12	-0.53*	-0.63*	0.58*	0.71*	0.62*	-0.57*	0.42*	0.36*
SEMIDETA		0.45*	0.19	0.08	-0.06	-0.29	0.28	-0.23	-0.24
TERRACED			0.45*	-0.43*	-0.33	-0.15	0.48*	-0.29	-0.19
ROOM3				-0.39*	-0.4*	-0.26	0.22	-0.29	-0.19
ROOM6					0.1	0.08	-0.03	0.1	-0.05
ROOM8						0.62*	-0.65*	0.35*	0.41*
ROOM9							-0.59*	0.56*	0.42*
CAR1								-0.5*	-0.7*
CAR3									0.5*

FIGURE CAPTIONS:

Fig. 1. Map of the studied SuDS, Inverness, Highland, UK. Site codes are given in Table A1 in Appendix A.

Fig. 2. Links between ecological and human wealth. Left panel (a) shows the patterns of SuDS ecological quality as obtained in the Principal Coordinate Analysis (PCoA). The type of SuDS was used to highlight the importance of design: swale (◊), detention basin (Δ) and pond (○). The ecosystem components were added *a posteriori* in the PCoA drawing their Spearman correlations with the two axes. The scores of the first axis of the PCoA (PCo 1) were used in further analyses as indicators of the general ecological quality of SuDS (see Fig. 2b and Fig. 3). Variable descriptions are given in Table 1. Abbreviations used are: amphibian richness (amphrich), macroinvertebrate richness (minvrich), macrophyte richness (macrophrich), terrestrial habitat richness (terrich) and degree of urbanization (urban). Right panel (b) shows the estimated effect of the two significant predictor variables on SuDS ecological quality (PCo 1), as determined from the best linear mixed model (LMM). The plot shows the predicted values for the response at each category or each value from the predictor, including approximate 95% confidence intervals relative to the main estimate (error lines and contour of the shaded area). The two significant predictors selected in the best LMM were SuDS type and the socio-economic descriptor nine or more rooms per household residence (ROOM9).

Fig. 3. Relationship between SuDS ecological quality (PCo 1) with designable and manageable habitat characteristics. Boxplots are grouped in four classes: (a) hydroperiod, (b) morphology, (c) aquatic vegetation and (d) adjacent terrestrial habitat.

A notch is drawn in each side of the indicator. If the notches of two plots do not overlap this is ‘strong evidence’ that the two medians differ (Chambers, Cleveland, Kleiner, & Tukey, 1983, p. 62). The *P* values of the Kruscal-Wallis tests are shown above each chart. Sample sizes are given in parentheses below the boxplots. Plots of the same shade indicate categories of each variable that showed positive statistical co-occurrence, white indicates random co-occurrence.

FIGURES:

Figure 1

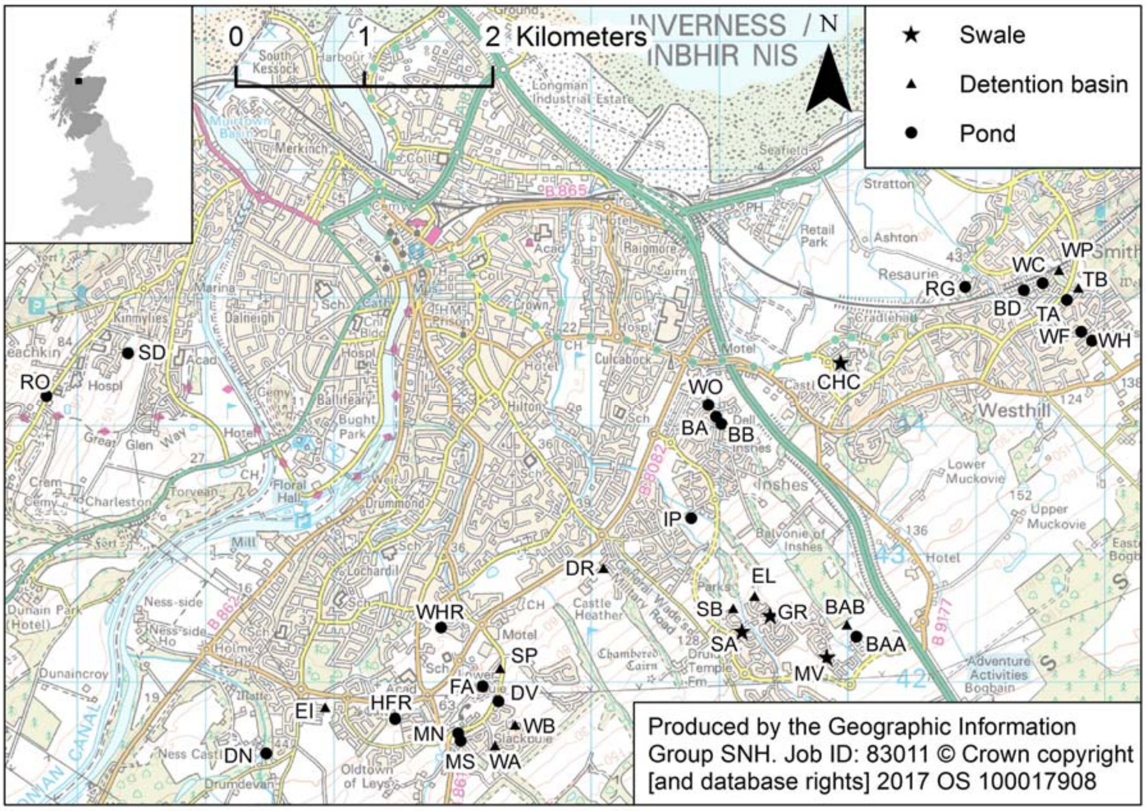


Figure 2

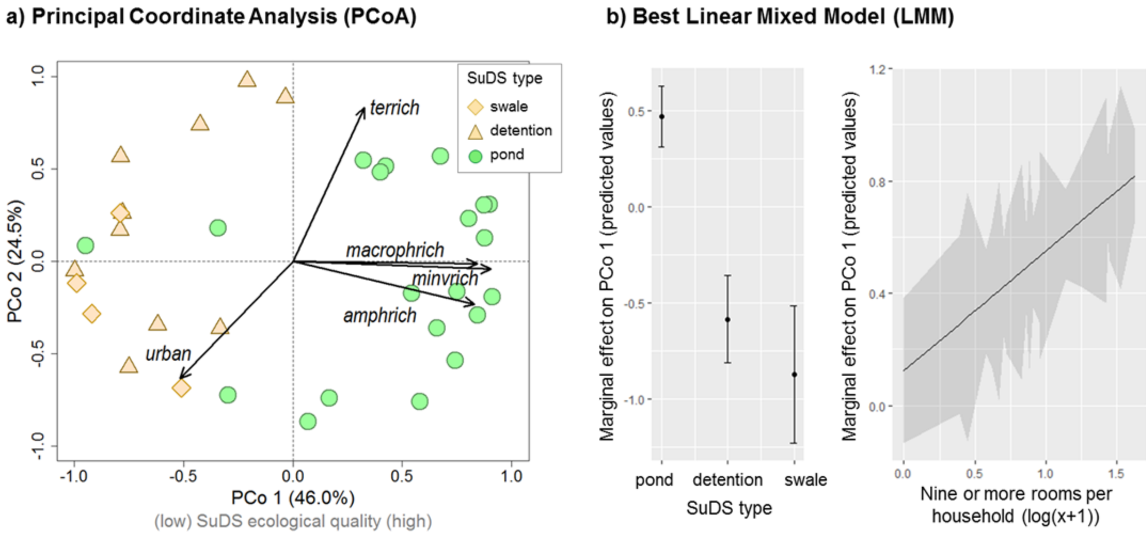
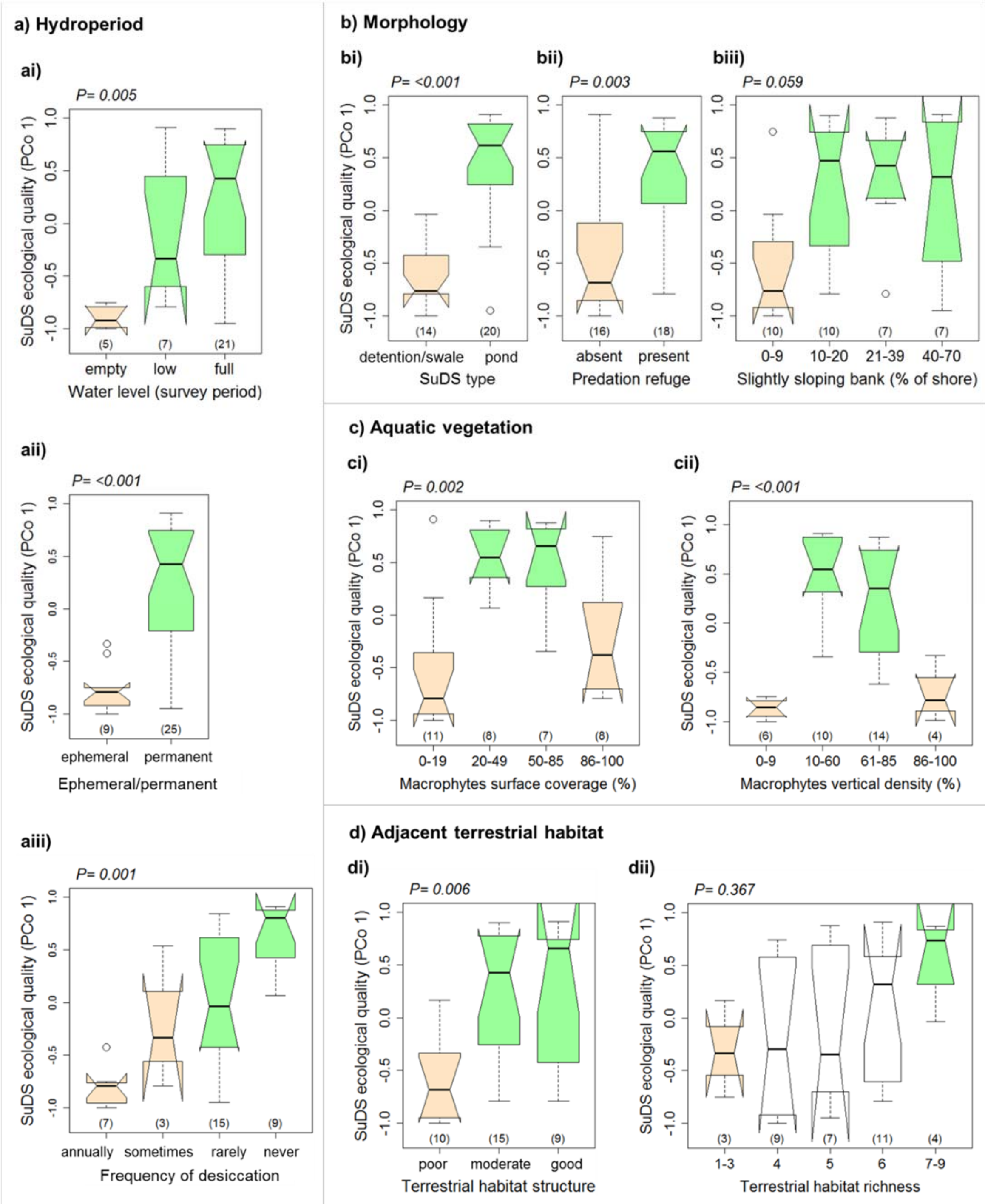

a) Principal Coordinate Analysis (PCoA)
SuDS type
swale
detention
pond
terrich
macrophrich
minvrich
amphrich
urban
PCo 2 (24.5%)
PCo 1 (46.0%)
(low) SuDS ecological quality (high)
b) Best Linear Mixed Model (LMM)
Marginal effect on PCo 1 (predicted values)
pond
detention
swale
SuDS type
Nine or more rooms per
household (log(x+1))

Figure 3


a) Hydroperiod
ai)
P= 0.005
SuDS ecological quality (PCo 1)
(5) (7) (21)
empty low full
Water level (survey period)
aii)
P= <0.001
(9) (25)
ephemeral permanent
Ephemeral/permanent
aiii)
P= 0.001
(7) (3) (15) (9)
annually sometimes rarely never
Frequency of desiccation
b) Morphology
bi)
P= <0.001
(14) (20)
detention/swale pond
SuDS type
bii)
P= 0.003
(16) (18)
absent present
Predation refuge
biii)
P= 0.059
(10) (10) (7) (7)
0-9 10-20 21-39 40-70
Slightly sloping bank (% of shore)
c) Aquatic vegetation
ci)
P= 0.002
(11) (8) (7) (8)
0-19 20-49 50-85 86-100
Macrophytes surface coverage (%)
cii)
P= <0.001
(6) (10) (14) (4)
0-9 10-60 61-85 86-100
Macrophytes vertical density (%)
d) Adjacent terrestrial habitat
di)
P= 0.006
(10) (15) (9)
poor moderate good
Terrestrial habitat structure
dii)
P= 0.367
(3) (9) (7) (11) (4)
1-3 4 5 6 7-9
Terrestrial habitat richness