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WETLANDS BIODIVERSITY AND PROCESSES

Ponds and their catchments: size relationships and influence of land use across multiple spatial scales

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Abstract The information on both the catchment land use and catchment area has the potential to be adopted into the conservation and management of ponds. There have been, however, few attempts to describe the effects of land use acting at various spatial scales on ponds and the studies were restricted to specific categories of ponds. This paper presents a study on 92 ponds distributed over a broad range of environmental conditions in Central Europe. We combined an extensive field survey and a detailed analysis of sediment and water chemistry with GIS-derived data to estimate the relationship between the area of the ponds and the area of their catchments, and to assess the relationship between pond physico-chemical conditions and land use across multiple spatial scales. Relating the area of ponds to the area of their catchments, we found a significant positive relationship ($r = 0.72$). Considering land use effects on pond conditions, catchment-scale land use was the only significant spatial extent influencing the physico-chemical conditions. Most notably, the proportion of intensively exploited land (arable land, urban areas) in the catchment scale was positively correlated with the deterioration of pond physico-chemical properties. The results of the study suggest that effective conservation of ponds cannot be achieved merely through the

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management of narrow buffer zones around them but should involve maintenance of less intensive land use within the whole catchment. Moreover, easily accessible catchment-scale GIS data could serve as a decision-support tool for cost-effective management strategies aimed at improving pond physico-chemical conditions.

Keywords Landscape management · Water chemistry · Biodiversity conservation · Buffer zones

Introduction

The role of ponds in regulating the hydrological regime, nutrients cycles as well as their supporting role for terrestrial biocoenoses have been strongly emphasized (see Céréghino et al., 2014 and references therein). Despite their small size, ponds are appreciated as biotopes markedly contributing to the local and regional aquatic biodiversity (e.g., Nicolet et al., 2004; Bilton et al., 2006) and often harboring many rare or endangered species (Oertli et al., 2002; Della Bella et al., 2005).

The considerable supply to regional diversity is an outcome of high beta diversity, which reflects large differences in community composition among individual ponds (e.g., de Meester et al., 2005; Hamerlík et al., 2014). The reasons for such heterogeneity are not clear, however, environmental variability among ponds certainly plays a substantial role. Ponds are deemed to have small catchments reflecting primarily local conditions, which make them very variable even within a small area (Biggs et al., 2005; Davies et al., 2008a; Svitok et al., 2011). However, although it is widely accepted that smaller waterbodies have smaller catchments, this a priori assumption of a positive pond area/catchment area relationship has never been tested explicitly. If true, such relationship would lead to important implications for cost-efficient strategies of biodiversity conservation. Within a small catchment it would be generally easier and cheaper to manage or mitigate activities or land use practices that affect biodiversity (Declerck et al., 2006).

Beside the effect of size, one of the major factors influencing the physico-chemical and biological properties of aquatic ecosystems is land use within their catchments (e.g., Carpenter et al., 1998; Townsend et al., 2003; Søndergaard et al., 2005; Theodoropoulos et al., 2015). In management practice, however, people sometimes face the problem of a lack of precise knowledge on catchments land use, particularly the lack of high-resolution (small scale) data on land use. The latter type of data usually needs to be acquired or confirmed in the field or based on a high-resolution geographic information system (GIS) model, which may, especially in the case of a high number of waterbodies, be time demanding or costly. A possible solution could be using the easily obtainable GIS information on catchment-scale land use without a need to specify its spatial organization. Of course, the efficiency of this approach relies on the relationship between pond conditions and land use at the whole catchment level. In general, the land use effects depend on the scale considered, vary in time and space, and show different patterns among systems of different sizes (Buck et al., 2004; Akasaka et al., 2010; Alahuhta et al., 2012; Nielsen et al., 2012). Several studies examined scale-related patterns of relations between land use and water quality in standing waters, but came to contrasting conclusions (Houlahan & Findlay, 2004; Declerck et al., 2006; Kizuka et al., 2008; Akasaka et al., 2010; Nielsen et al., 2012). For example, Declerck et al. (2006) conducted an extensive survey of farmland ponds and suggest that the most important land use effects on ponds operate at a relatively small radius (<200 m) rather than at large spatial scales. This supports the idea that zones closely adjacent to the waterbody pose a greater influence on pond conditions than distant zones. The importance of adjacent buffer zones is also reported elsewhere (e.g., Akasaka et al., 2010; Bird & Day, 2014). On the other hand, Houlahan & Findlay (2004) and Nielsen et al. (2012) found little support for the buffer zones but report effects over larger distances. Differences in waterbody types, sets of investigated parameters, and intensity of land use in the above studies make difficult to draw any general conclusion about the critical spatial scale.

We combined an extensive field survey of 92 ponds in Slovakia and a detailed analysis of their sediment and water chemistry with GIS-derived data in order to (i) test the hypothesis of a positive relationship between the area of ponds and their catchments, (ii) estimate the effect of land use in various spatial scales on the physico-chemical attributes of ponds, and specifically (iii) test the assumption that the raw GIS information on the catchment-scale land use is useful for modeling the pond physico-chemical conditions.

Materials and methods

Study area

Slovakia is a small country (approx. 49,000 km^2) with very diverse environmental conditions derived from a wide altitudinal gradient, ranging up to ca. 2550 m. The country is separated into two distinct biogeographic areas, the Carpathian and the Pannonian bioregions (Hrivnák et al., 2014). The southern part of the country is dominated by agricultural landscapes, while the northern and central regions are represented by uplands and mountains, with forest land cover prevailing.

We surveyed 92 ponds distributed over the entire territory of Slovakia (Fig. 1). Based on previous studies (Biggs et al., 2005; Oertli et al., 2005), we defined the pond as a standing waterbody of area <50,000 m^2 with the potential of the bottom being completely covered by aquatic plants, i.e., with a deep aphotic zone absent. The studied ponds span a wide range of sites, from lowland to mountain zones, across a complex gradient of different geographical and ecological conditions. Ponds of natural origin (e.g., oxbow ponds, glacial ponds), as well as artificial ponds represented by gravel and sand pits or dammed ponds, were included in our study. The basic environmental characteristics of the studied ponds are summarized in Table 1.

Physico-chemical characteristics of ponds

Data on the water and sediment chemistry were collected during extensive field works during July and the first half of August 2012 and 2013. Water samples consisting of three spatially stratified replicates were collected at each site. Water pH and conductivity were measured in the field. Water samples for other physico-chemical characteristics were filtered in the field, quickly frozen using WAECO CoolFreeze CDF-36 portable freezer, transported to the laboratory and stored at −18 °C. Concentrations of NH_4^+, NO_2^-, NO_3^-, and PO_4^{3-} were determined colorimetrically (for details see Hrivnák et al., 2013). Chemical elements were determined at Acme Analytical Laboratories, Ltd. (Vancouver, Canada) by the ICP-AES/ICP-MS method.

Sediment samples (three spatially stratified replicates) were dried at laboratory temperature, crushed, and passed through a 2-mm sieve. Sediment pH and conductivity (sediment/water ratio = 1:2.5 measured by a CyberScan PC 650 multiparameter device), and NH_4^+, NO_2^-, NO_3^-, and PO_4^{3-} contents were determined in the laboratory (cf. Hrivnák et al., 2014). Mean depth of water was derived from 10 random measurements at each pond.

The position of individual ponds was identified and digitized using ArcGIS 10.2 (ESRI Corp., Redlands, CA, USA) by analysis of orthophoto maps, terrain observation, and the 1:10,000 Basemap of the Slovak Republic. In the GIS environment, surface area was calculated for each pond. Climatic data (Total annual precipitations and Average annual temperature) for

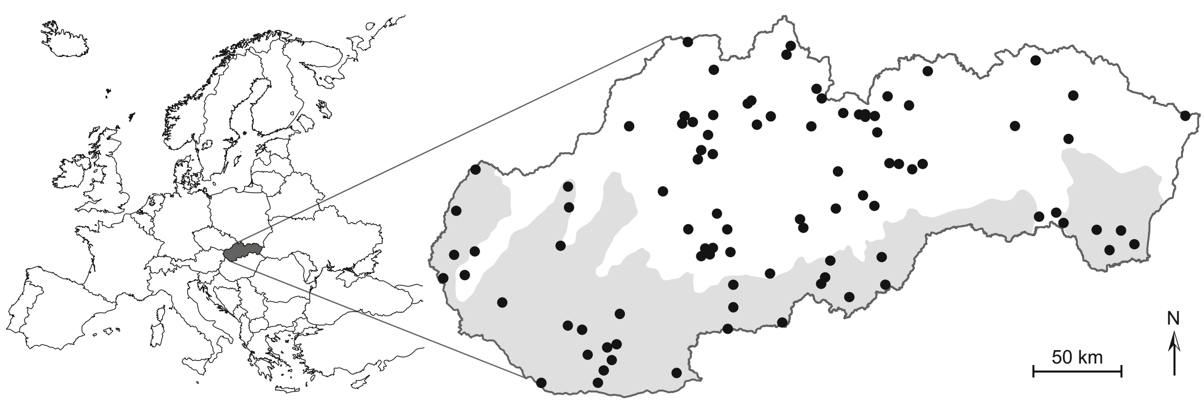

Fig. 1 Map of Slovakia with the locations of the sampled ponds (*black dots*). Bioregions of Slovakia are distinguished by color; Pannonian bioregion—*light gray* and Carpathian bioregion—*white*

Table 1 Summary characteristics of studied ponds and their catchments

Variable	Unit	Mean (SD)	Median (Q1/Q3)	Minimum	Maximum
Catchment physical structure					
Catchment area	km^2	3.54 (16.43)	0.12 (0.008/1.42)	0.0002	150.91
Average slope	degree	8.16 (7.80)	6.34 (1.11/13.87)	0.01	27.53
Average soil loss (erosion)	t $year^{-1}$	3.91 (17.89)	0.60 (0.19/2.25)	0.00	170.67
Pond topography					
Altitude	m	450 (357)	376 (163/623)	98	1651
Surface area	m^2	6,480 (8,944)	2,817 (375/8,713)	20	48,620
Average depth	cm	110 (71)	98 (63/147)	4	391
Local climate					
Total annual precipitations	mm	839 (237)	697 (593/864)	620	1794
Average annual temperature	°C	7.3 (1.8)	7.7 (6.2/8.5)	0.9	9.8
Land use					
Arable land	%	1/15/18	0/0/1	0/0/0	30/97/100
Forests and shrubs	%	64/45/39	70/45/30	0/1/0	100/100/100
Grasslands	%	22/20/25	15/11/17	0/0/0	95/98/100
Urban areas	%	6/11/7	2/5/0	0/0/0	65/70/70
Waterbodies	%	7/9/11	0/2/1	0/0/0	100/70/100

Minimum, maximum, mean, and standard deviation (SD) and median with first (Q1) and third quartile (Q3) are displayed. Proportions of land use categories are given in the following order: 10 m/100 m/catchment

each pond were obtained from the Slovak Hydrometeorological Institute and included records from the period 1961–1990, which is defined by the World Meteorological Organization as the standard normal period and statistically can best describe the climate in the 20th century (World Meteorological Organization, 2011). Raster values for each point were computed in the geographic resources analysis support system (GRASS) of the GIS environment, version 7.1, which was released under the GNU/GPL license.

Catchment properties and land use data

Land use was recorded at three different spatial scales: (i) in the immediate surroundings of the ponds (10 m); (ii) in a 100 m area adjacent to the ponds; and iii) in the whole catchment area. The 10 and 100 m radiuses, representing buffer zones of the ponds, were selected to comply with the approaches of previous studies on land use versus pond characteristics (e.g., Declerck et al., 2006). We delimited the pond edge based on botanical criteria (i.e., 10 m buffer zone beginning at the outer edge of the helophyte belt). The percentage of land use for the first scale was estimated by visual assessment of the whole 10 m buffer. Land use cover of the 100 m buffer strip was based on visual estimation along transects (20 × 100 m) perpendicular to the pond bank. Number of transects was given by pond size and ranged from 4 to 10. At the catchment scale, land use was evaluated using GIS tools (see below). The ESPRIT Ltd. Digital elevation model (DEM) with a resolution of 10 m was utilized to delineate the catchments. The DEM was derived from contour lines, streamlines data, lakes data, and spot elevation data using the Topo to Raster tool built in the ArcGIS 10.2 Spatial Analyst extension. The Topo to Raster tool is an interpolation method based on the ANUDEM program (Hutchinson, 1989; Hutchinson et al., 2011), specifically designed for the creation of hydrologically correct DEMs. The waterbodies, flow lines, and some important barriers were 'burnt' into the DEM to ensure that the modeled runoff would flow into the water bodies and that they would be retained during the catchment delineation process.

For each catchment, the following characteristics were derived using spatial analysis tools integrated in a GIS environment: catchment area, proportion of land use types, average catchment slope, average annual soil loss from the catchment (t $year^{-1}$). The percentage cover of land use types for the whole catchment area was determined by intersecting each catchment with the land cover database of the Institute of Landscape Ecology, Bratislava, Slovakia derived from the ZBGIS© (Primary Base for Geographic Information System). The minimum mapping unit of the database was 100 m^2. The average catchment slope was derived from the slope map calculated from the DEM. The long-term average annual soil loss from the catchment was estimated from the map of actual erosion (resolution 10 × 10 m), computed using the RUSLE (Revised Universal Soil Loss Equation) erosion model, which takes into account the slope factor, flow accumulation factor, soil erodibility factor, cover management factor, and rainfall erosivity factor (Wischmeier & Smith, 1978; Desmet & Govers, 1996). All these characteristics were summarized for each catchment using a zonal statistics tool (Arc GIS 10.2 Spatial Analyst extension).

Data analysis

Pond area–catchment area relationship

In order to explicitly test the widely held assumption about the positive relationship between the area of ponds and their catchments, we correlated the catchment area with the pond area. To keep the analysis as simple as possible, we used the Pearson correlation coefficient with both variables log-transformed for linearity. We applied a simple permutation test (10,000 permutations) instead of relying on the normality assumption (Manly, 1997). Confidence limits for the correlation coefficient were calculated by non-parametric bootstrap (10,000 samples) using the bias-corrected and accelerated percentile method (Efron, 1987).

Relationships between the physico-chemical conditions of ponds and land use

We investigated the relationships between the physico-chemical characteristics of pond water and sediment and the proportion of land use across three spatial extents (10 m from pond edge, 100 m and whole catchment). Redundancy analysis (RDA) on the correlation matrices of physico-chemical variables was used to relate pond conditions with land use. Separate RDAs were performed for physico-chemical data of the sediment, water, and combined dataset (water + sediment) at each spatial extent. In addition to the influence of land use, we also focused on the role of local factors that can control water and sediment conditions. A series of partial redundancy analyses (pRDA) was applied to evaluate the effects of land use on the physico-chemical conditions of ponds after accounting for the effects of catchment physical structure, pond topography, and local climate (see Table 1 for details). Partial RDAs were also used to evaluate the pure contribution of those locally specific variables to the variance in physico-chemical conditions. Associations between the matrices in RDAs and pRDAs were tested using 10,000 permutations of residuals. Variance in physico-chemical data explained by a particular group of variables was calculated in each analysis and its confidence limits were estimated by bootstrap as outlined above.

Analyses were performed in R (R Core Team, 2014) using the libraries boot (Canty & Ripley, 2014) and vegan (Oksanen et al., 2014).

Results

Pond area–catchment area relationship

A significant, positive relationship was detected between the area of ponds and their catchments (Pearson r (95% conf. interval) = 0.40 (0.17, 0.59), $P = 0.0003$). However, six small ponds with large catchments emerged as outliers in the bivariate distribution of the data (Fig. 2). When these outliers were omitted, the strength of the relationship markedly increased ($r = 0.72$ (0.62, 0.80), $P < 0.0001$).

Relationships between the physico-chemical conditions of ponds and land use

The studied ponds span a wide range of physico-chemical conditions (Table 2). For example, water conductivity ranged from 7.8 to 1803 µS cm^{-1}, water pH from 5.61 to 9.16. Phosphates in water ranged from <0.01 to 2.06 mg l^{-1}, NO_3^- from <0.01 to 12.22 mg l^{-1}, Ca from 0.31 to 149.62 mg l^{-1}, and Na from 0.17 to 205.58 mg l^{-1}.

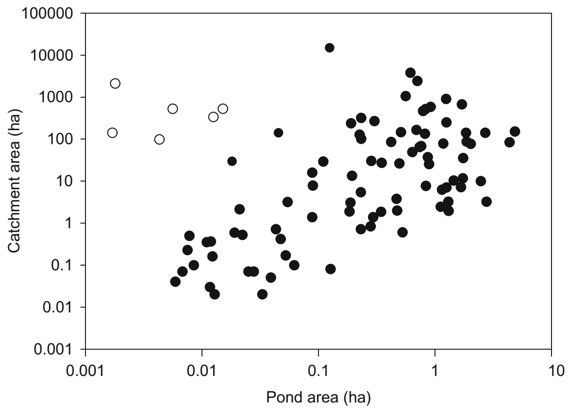

Fig. 2 Relationship between the area of ponds and their catchments. *Empty circles* represent outliers in bivariate distribution

The physico-chemical conditions of ponds were significantly related to catchment-scale land use as well as to the 100 m buffer, regardless of whether we considered sediment and water characteristics separately or jointly (Fig. 3a–c). Land use at these spatial extents explained the comparable amount of variance in pond characteristics. In contrast, land use in the near vicinity of ponds (10 m from the pond edge) did not significantly influence the physico-chemical conditions. When we accounted for the effects of other locally specific variables (physical structure of the catchment, pond topography, local climate), the significant influence of land use at 100 m extent disappeared and land use at the catchment scale remained the only significant spatial scale (Fig. 3d–f). However, as detected by the relatively low explanatory power of the models for water (explained variance: 7.2%), sediment (8.7%), and combined dataset (7.7%), these relationships should not be overemphasized. Since the pattern of spatial scale significance was consistent across all datasets, we focused more closely on pooled water and sediment data.

Land use at the catchment scale was the most relevant predictor of pond conditions followed by pond topography and local climate (Fig. 4a). Variance explained by the physical structure of the catchment was indistinguishable from the variance explained by random chance only, i.e., the pure effect of the catchment structure was non-significant.

Detailed relationships between the physico-chemical characteristics of ponds and catchment-scale land use are shown in Fig. 4b. Not surprisingly, an increasing proportion of urban structures and arable land in catchments was associated with increasing amounts of NH_4^+, PO_4^{3-}, and some metals (e.g., Co, Cu, Fe, Zn). The proportion of urban land was also positively related with sediment and water conductivity with associated ions. Water pH increased in parallel with the decreasing proportion of arable land and increasing proportion of waterbodies.

Discussion

Pond area–catchment area relationship

One widely accepted premise states that smaller waterbodies have smaller catchments (Gordon et al., 1992; Davies et al., 2008b). However, the relationship between pond area and the area of its catchment was not explicitly tested and thus we focused on this in our study. As expected, we found a significant positive relationship between pond area and catchment area, though, this relationship was rather weak ($r = 0.40$), meaning that not all small ponds have also small catchments, and vice versa. Surprisingly, some very small ponds indeed had large catchments (Fig. 2). This pattern can emerge in situations where a pond has an inflow draining large area. For example, one small dam pond of 180 m^2 had a large catchment of 0.298 km^2 due to a small stream mouthing into this pond. Suspiciously, large catchment areas calculated from the GIS model may also result from raw DEM resolution. For example, the disproportionally large catchment area of 20.97 km^2 calculated for the smallest pond (20 m^2) is clearly an artifact of our DEM resolution (10 m). In this case, DEM erroneously matched the pond with a nearby flowing stream, resulting in an unrealistically huge pond catchment area. When omitting such ponds from the modeling, the relationship improved markedly ($r = 0.72$) and allowed us to conclude that the general assumption of increasing catchment area with increasing area of waterbody is applicable also for ponds. One have to bear in mind that GIS-derived data, especially those with poor resolution, require careful checking to avoid errors in subsequent analyses.

Our finding of the positive relationship between the area of ponds and their catchments may raise a point in the discussion on the most suitable size of ponds to be

Table 2 Physico-chemical characteristics of water and sediment of studied ponds

Variable	Unit	Abbreviation	Mean (SD)	Median (Q1/Q3)	Minimum	Maximum
Water						
pH		pH	7.74 (0.72)	7.89 (7.35/8.24)	5.61	9.16
Conductivity	$\mu S\ cm^{-1}$	Cond	466 (398)	351 (181/597)	7.80	1,803
NH_4^+	$mg\ l^{-1}$	NH_4	0.44 (0.75)	0.22 (0.09/0.46)	0.01	5.86
NO_3^-	$mg\ l^{-1}$	NO_3	1.37 (2.18)	0.72 (0.18/1.55)	<0.01	12.22
NO_2^-	$mg\ l^{-1}$	NO_2	0.11 (0.14)	0.09 (0.01/0.16)	<0.01	0.80
PO_4^{3-}	$mg\ l^{-1}$	PO_4	0.41 (0.52)	0.19 (0.07/0.49)	<0.01	2.06
Ca	$mg\ l^{-1}$	Ca	36.74 (27.76)	31.79 (16.28/49.37)	0.31	149.62
Mg	$mg\ l^{-1}$	Mg	22.49 (32.07)	11.97 (5.14/22.87)	0.09	169.81
Na	$mg\ l^{-1}$	Na	19.29 (35.00)	7.06 (3.04/21.00)	0.17	205.58
K	$mg\ l^{-1}$	K	7.90 (17.41)	2.70 (1.07/7.10)	0.06	130.02
Cl	$mg\ l^{-1}$	Cl	29.61 (61.97)	5.00 (0.50/30.00)	0.50	406.00
Al	$\mu g\ l^{-1}$	Al	18.35 (58.11)	3.00 (0.50/8.25)	0.50	518.00
As	$\mu g\ l^{-1}$	As	3.18 (4.69)	1.80 (0.60/3.40)	0.25	29.80
B	$\mu g\ l^{-1}$	B	55.81 (132.99)	22.50 (14.00/53.75)	2.50	1,054.00
Ba	$\mu g\ l^{-1}$	Ba	44.21 (43.74)	32.81 (15.94/60.31)	0.75	256.65
Br	$\mu g\ l^{-1}$	Br	61.88 (155.52)	18.00 (7.00/57.25)	2.50	1,265.00
Co	$\mu g\ l^{-1}$	Co	0.16 (0.23)	0.05 (0.03/0.12)	0.01	1.20
Cr	$\mu g\ l^{-1}$	Cr	2.52 (2.80)	1.25 (0.25/4.85)	0.25	13.10
Cu	$\mu g\ l^{-1}$	Cu	2.34 (1.99)	1.65 (1.00/3.03)	0.30	15.60
Fe	$\mu g\ l^{-1}$	Fe	27.61 (50.72)	0.50 (0.50/26.25)	0.50	303.00
Li	$\mu g\ l^{-1}$	Li	10.89 (46.12)	2.20 (0.70/5.30)	0.05	337.80
Mn	$\mu g\ l^{-1}$	Mn	45.21 (138.89)	2.83 (0.18/13.96)	0.03	1,072.41
Mo	$\mu g\ l^{-1}$	Mo	0.93 (2.81)	0.20 (0.05/0.65)	0.05	22.20
S	$mg\ l^{-1}$	S	22.83 (41.76)	8.00 (4.00/19.00)	0.50	213.00
Sb	$\mu g\ l^{-1}$	Sb	0.51 (0.85)	0.26 (0.11/0.52)	0.03	6.33
Si	$mg\ l^{-1}$	Si	3.52 (4.41)	1.90 (0.65/4.58)	0.04	21.17
Sr	$\mu g\ l^{-1}$	Sr	238.17 (527.72)	142.47 (64.97/261.62)	1.29	4,894.06
U	$\mu g\ l^{-1}$	U	0.84 (2.15)	0.15 (0.05/0.56)	0.01	13.82
Zn	$\mu g\ l^{-1}$	Zn	4.34 (6.11)	1.65 (0.25/5.70)	0.25	33.00
Sediment						
pH		pH–s	6.63 (0.95)	7.02 (5.85/7.33)	4.56	8.22
Conductivity	$\mu S\ cm^{-1}$	Cond-s	835 (672)	660 (305/1197)	68	3,726
NH_4^+	$\mu g\ g^{-1}$	NH_4-s	56.61 (48.93)	40.50 (23.30/78.30)	9.10	246.00
NO_3^-	$\mu g\ g^{-1}$	NO_3-s	1.23 (1.41)	0.61 (0.18/1.86)	<0.01	7.71
NO_2^-	$\mu g\ g^{-1}$	NO_2-s	0.27 (0.42)	0.10 (0.02/0.29)	<0.01	2.22
PO_4^{3-}	$\mu g\ g^{-1}$	PO_4-s	64.95 (56.38)	44.86 (24.41/84.28)	0.02	211.46

Minimum, maximum, mean with standard deviation (SD) and median with first (Q1) and third quartile (Q3) are displayed

created or protected for diversity maintenance (Davies et al., 2008a). Management or protection of small catchments is naturally easier and cheaper than management of larger ones. Our previous results (Hamerlík et al., 2014), as well as several other studies on ponds (e.g., Gee et al., 1997; Martínez-Sanz et al., 2012) indicate that smaller ponds support diversity comparable to the diversity of large ponds. Therefore,

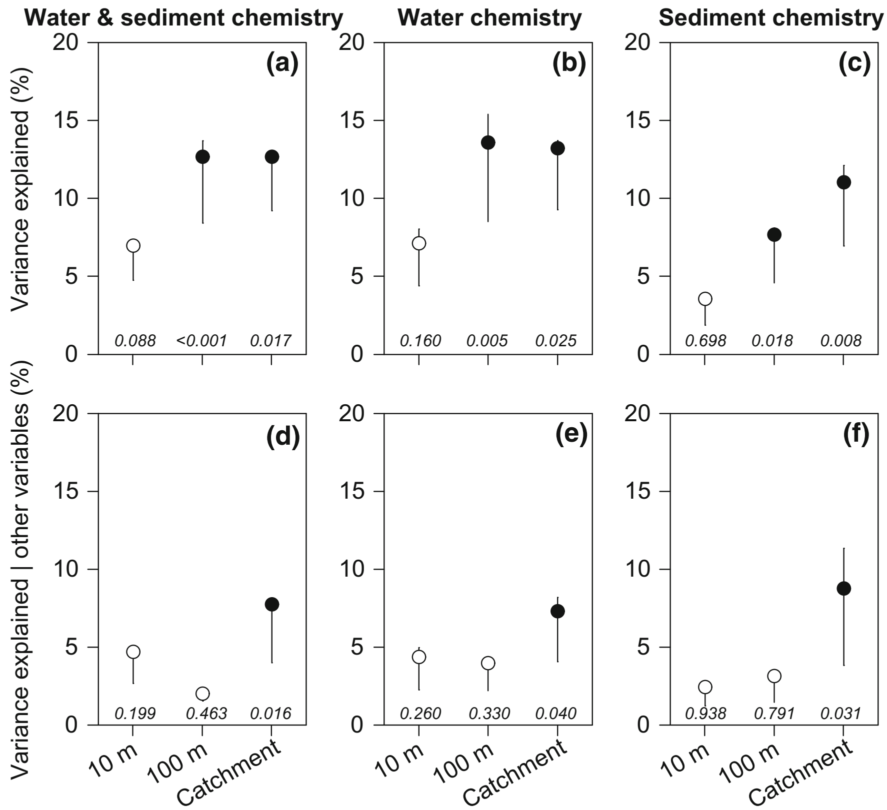

Fig. 3 Proportion of variance in the physico-chemical characteristics of ponds explained by land use at three spatial extents (10 m from pond edge, 100 m and whole catchment). Solid circles represent a significant ($P < 0.05$) association between pond conditions and land use in RDAs (**a**, **b, c**) and pRDAs (after accounting for the effect of catchment structure, pond topography and local climate) (**d**, **e**, **f**). *Error bars* denote 95% bootstrap confidence intervals. Probabilities obtained by RDAs are given at the *bottom* of the plots

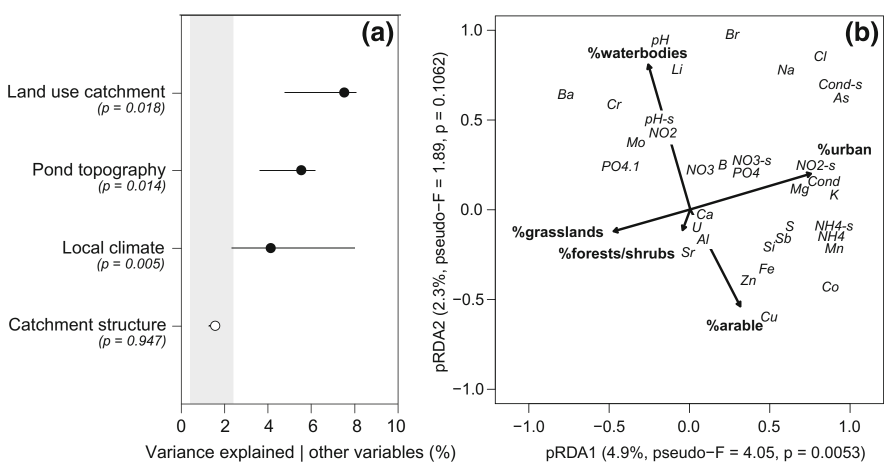

Fig. 4 Results of pRDAs on overall pond conditions (water + sediment characteristics). Proportions of variance explained purely by the given group of variables (*circles*) and its 95% confidence intervals (*error bars*) are plotted along with a 95% confidence band of variance explained by random chance only (*gray area*) (**a**). *Solid circles* represent a significant ($P < 0.05$) association between pond characteristics and the given group of variables after accounting for the effects of other variables in pRDAs (the exact probabilities are given in parentheses). Ordination plot of pRDA (**b**) illustrating the significant effect of land use on the physico-chemical conditions of ponds. Explained variances, test statistics, and probabilities are displayed for each ordination axis. The ordination scores are scaled symmetrically. Abbreviations of variable names are explained in Table 2

focusing actions on small ponds with smaller catchments appears to be a reasonable trade-off between maintaining diversity and management expenses (Williams et al., 2008).

Importance of spatial scale in relationships between pond conditions and land use

When we accounted for the effects of locally specific factors (physical structure of catchment, pond topography and local climate), catchment-scale land use appeared the only significant spatial scale in our study.

The debate on the most relevant spatial extent determining the physico-chemical or/and biological parameters of freshwaters is quite extensive, and still remains open. In accordance with our results, Houlahan & Findlay (2004) found that the effects of land use on water and sediment chemistry of wetlands can extend over large distances. Similarly, Nielsen et al. (2012) showed that catchment-scale land use had the strongest influence on water quality for Danish lakes. Several studies, however, indicated that water quality is more strongly affected by the land use of adjacent buffer zones than of the whole catchment (e.g., Alahuhta et al., 2012).

Specifically for ponds, the few available multi-scale studies concluded that land use closely adjacent to the waterbody has a greater effect on pond characteristics than larger extents (e.g., Declerck et al., 2006; Akasaka et al., 2010), emphasizing, conversely to our results, the importance of buffer zones for shaping the pond environment in agricultural landscapes. However, a direct comparison among studies can be misleading when there are differences in the nature of the waterbodies, the character of catchment land use, and the studied environmental parameters (Buck et al., 2004; Fraterrigo & Downing, 2008). All the Belgian ponds (Declerck et al., 2006) were farmland ponds providing drinking water for cattle and the 55 Japanese ponds (Akasaka et al., 2010) represented category of irrigation ponds. Farmland and irrigation ponds differ from other pond types in many aspects and can therefore be affected by land use via other mechanisms operating at different spatial scales (Declerck et al., 2006). In contrast, the 92 ponds studied here are very heterogeneous, spanning a wide range of physico-chemical conditions (from oligotrophic to eutrophic conditions) and land use patterns (from completely forested through agricultural to strongly urbanized catchments) (cf. Table 1). Moreover, we partialled out many locally specific variables, which could potentially confound the relationship between ponds physico-chemical conditions and land use. As we have shown (Fig. 3), missing control for confounding variables would lead to erroneous conclusion about the importance of buffer zones. A shift from a few basic measures of water quality to a truly multivariate response may also add to diminishing buffer-zone effect in our study. All these aspects of the study facilitate wider generalization of our results.

The price to pay for such generality is higher variability of data that may not be captured by models. For instance, our catchment-scale models explained only 7.2–8.7% of the variance in the multivariate datasets. There is a plethora of other factors (related to land use or not) that can affect the physico-chemical characteristics of studied ponds including e.g., quality and quantity of soils in catchment, subsurface flow, fish community composition and density, vegetation, or historical contingency. Covering wide range of conditions for the sake of generality is certainly reflected in relatively high error variance of our models, which may rouse a concern. However, we were primarily focused on the effect of land use and morphology as these quantities are easily derived from GIS layers with the potential to serve as early and easily obtainable proxy on the physico-chemical state of ponds. Apparently, even basic GIS data on the proportion of land use categories within the catchment may provide valuable information on the pond water and sediment physico-chemical characteristics, which could be potentially useful for conservation or management planning (cf. Davies et al., 2004).

Drivers of pond conditions

Catchment-scale land use emerged as the most significant predictor of pond physico-chemical conditions followed by pond topography and local climate, while the influence of catchment structure was negligible (Fig. 4a). Ponds with a high proportion of urban areas in their catchments were characterized by relatively high values of conductivity of both sediment and water and elevated nutrient concentrations. Nutrients as well as the concentrations of some metals in the water were also positively related to the increase of the arable land fraction (Fig. 4b). The proportion of the urban areas and arable land in catchments is widely known to be negatively associated with the water quality of lakes, reservoirs, and ponds (Jones et al. 2004; Akasaka et al., 2010) and their impact on aquatic ecosystems does not require a detailed discussion. Briefly, urban areas discharge substantial amounts of nutrients and suspended solids into aquatic ecosystems (Soranno et al., 1996; Lake et al., 2001). A high proportion of agricultural land use in the catchments of waterbodies is usually related to intensive agricultural activities leading to higher degrees of soil erosion and transport of nutrients and contaminants (e.g., some metals, Mortvedt, 1996).

Conclusions

This is the first time that an a priori assumption of the positive relationship between the area of ponds and their catchments was tested explicitly. We proved that ponds area and the area of their catchments are positively correlated and larger ponds could indeed be expected to have larger catchments. This has an important implication for cost-efficient conservation management since within a small catchment it would be generally easier and cheaper to manage or mitigate activities or land use practices.

Most of the scale-related studies on land use effect on ponds deal with the specific category of farmland or agricultural ponds. Allowing for wider generalization of our results, we sampled a range of pond types and showed that not the buffer zones but the whole catchment land use best explained physico-chemical conditions of studied ponds. The proportion of arable land and urban areas in the catchments was positively correlated with the deterioration of pond environment. It seems that the effective conservation of ponds cannot be achieved through the management of narrow buffer zones around them but should involve maintenance of less intensive land use within the whole catchments. Importantly, even basic GIS data on catchment land use may be of high value, especially in the first, planning phase of management or research when detailed field information is missing.

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Compliance with ethical standards

Ethical standards Authors declare that manuscript complies with the Ethical Standards applicable for Hydrobiologia journal.

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