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The value of novel ecosystems: Disclosing the ecological quality of quarry lakes

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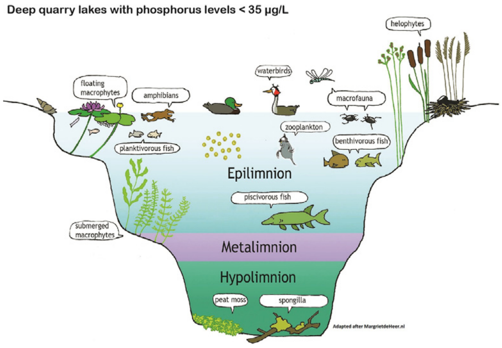
HIGHLIGHTS

- Novel ecosystems such as deep quarry lakes are underperceived ecosystems.
- We assessed ecological quality of 51 lakes in the Meuse and Rhine delta.
- Water quality of quarry lakes was higher than adjacent shallow waters.
- Quarry lakes contribute significantly to the regional macrophyte diversity pool.
- These novel lakes are a valuable part of the anthropogenic landscape.

GRAPHICAL ABSTRACT



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ABSTRACT

Intense sand and gravel mining has created numerous man-made lakes around the world in the past century. These small quarry lakes (1–50 ha) are usually hydrologically isolated, often deep (6–40 m) and stratify during summer and in cold winters. Due to their small size, these deep man-made lakes are usually not included in the regular monitoring campaigns, e.g. as required for the European Water Framework Directive (WFD). Therefore, not much is known about the ecological functioning of these novel ecosystems. During two summers, we determined the macrophyte diversity and measured a range of physico-chemical and biological parameters in 51 quarry lakes in the catchment area of the rivers Meuse and Rhine. We compared the results of this campaign to the chemical and macrophyte sampling as performed for the WFD in the immediate surrounding shallow standing waters. Alpha (local) and beta diversity (regional), and local contribution to beta diversity were calculated for the whole region of which beta diversity was further partitioned into a true species replacement and richness difference component. Quarry lakes contain higher water quality reflected by lower nutrient and chlorophyll-*a* concentration compared with shallow water bodies. Additionally, quarry lakes contribute significantly to the regional macrophyte diversity pool by harboring distinctly different macrophyte communities (beta diversity – replacement). Specifically quarry lakes with a total phosphorus concentration in the water column below 35 μg P/l contribute most to beta diversity among quarry lakes.

Novel ecosystems such as deep quarry lakes are often perceived as less valuable ecosystems, with strong implications regarding their management. Our results show that quarry lakes are in general of better

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chemical and biological quality compared with shallow standing waters. We therefore call for a more integrated assessment of the quality of quarry lakes and corresponding management strategy of these waters by water managers.

1. Introduction

Gravel and sand are a much sought after good due to their essential role in the construction of roads, buildings and concrete (USGS, 2015). These resources can be found not only in alluvial fans and beach deposits but also in (former) stream beds of rivers. Mining activities have resulted in the creation of numerous gravel or sand quarry lakes throughout the world. For example, in a small country such as the Netherlands, at the nexus of Rhine and Meuse delta in Western Europe, over 500 quarry or gravel pit lakes can be found (CBS and RIVM, 2018).

Sand or gravel quarry lakes are usually located near the site where the mining material is needed and construction is taking place, and are thus novel aquatic ecosystems in an urbanized landscape (Higgs, 2017). Quarry lakes are often deep, as a result of maximizing the amount of to be mined sand or gravel per surface area. Additionally, often located near or in residential areas, man-made quarry lakes are in many instances the primary aquatic system people interact with. In most catchments the often deep quarry lakes are outnumbered by shallow lakes, but they can provide similar, or even additional, ecosystem services such as swimming water, or fishing grounds for certain fish species (Mollema and Antonellini, 2016). However, due to their artificial origin and their young age, the natural values of these lakes are ill-known and underperceived (Blanchette and Lund, 2016). Additionally, the ecosystem services provided by deep lakes are not always visible outside the local community, which adds to the low perceived value of novel ecosystems by water management and science. The type and manner of construction of these lakes has numerous morphological and chemical consequences for the resulting lake ecosystem and surrounding landscape (Mollema and Antonellini, 2016). Limnological research has focused mostly on shallow lakes, the most abundant lake type in the world (Verpoorter et al., 2014), and iconic deep lakes such as the Great Lakes (USA), Lough Neagh (Ireland) or Lake Baikal (Russia) (e.g. (Bunting et al., 2007; Hampton et al., 2008; O'Beirne et al., 2017). But in-depth research towards understanding small deep lakes is still lacking.

1.1. Morphology and hydrology of quarry lakes

Quarry lakes are usually small (<50 ha), are often isolated from other surface waters, and are deep enough for stable stratification to occur (Miller et al., 1996; Schultze et al., 2011b; Younger and Wolkersdorfer, 2004). The lack of a marsh zone and the small littoral zone distinguish deep quarry lakes from natural shallow and deep lakes. Located in areas with high sand deposition such as deltas, they are often the only deep and stably stratifying aquatic ecosystems to be found in the surrounding landscape (Castagna et al., 2015a). Gravel quarry lakes are created when sand or gravel are mined at or below the water table, after which they fill up with rain- and groundwater through seepage. As a result of maximizing the amount of sand mined per surface area, quarry lakes can be up to 60 m deep. Quarry lakes which have been established in a lake or river will usually have an in- and outflow, however, most quarry lakes are hydrologically isolated from other surface waters (Mollema and Antonellini, 2016). Mining has an immediate effect on the groundwater flows surrounding these new lakes, resulting in a strong influence of ground water on the lake itself (Castagna et al., 2015b; Muellegger et al., 2013). The quality of the groundwater thus highly influences the quality of the quarry lake, as opposed to most natural lakes, which often have an in and/or outflow of surface water.

Quarry lakes are often not only deeper but also harbor much steeper lake banks than natural lakes in delta areas (Blanchette and Lund, 2016). This results in a relatively small littoral zone and often a missing marsh zone, which has direct consequences for the whole lake ecosystem as the exchange between the littoral and pelagic is limited (Sollie et al., 2008). Quarry lakes therefore resemble asteroid or crater lakes in morphology (Blanchette and Lund, 2016). Water quality varies among quarry lakes based upon geological subsoils and catchment interaction, i.e. hydrological connections with ground- and surface-waters, and thus range in their pH and trophic states (Castagna et al., 2015a; Miller et al., 1996; Younger and Wolkersdorfer, 2004). Some quarry lakes contain high concentration of toxic substances such as heavy metals due to the specific material that was mined at the location. Examples of quarry lakes in the USA, Australia and Canada can contain lethal concentrations of copper, zinc, iron, oil or uranium (Blanchette and Lund, 2016). In this paper, we focus on quarry lakes which originate from sand and gravel mining in fluvial planes. As opposed to the heavily polluted quarry lakes that result from metal mining, sand and gravel lakes may potentially contain good quality water.

1.2. Diversity of quarry lakes

Due to the creation of new and unique niches, deep quarry lakes can be important stepping stones for aquatic diversity in an urbanized landscape. Macrophytes play an important role in structuring aquatic diversity and ecosystem functions, through providing substrate, food and shelter, and affecting water and sediment chemistry, biogeochemical cycles and productivity (Jeppesen et al., 1998; Scheffer, 1998; Wetzel, 2001). Submerged macrophytes are very important for the stabilization of the aquatic ecosystem. Their presence stabilizes the clear water state in shallow water, as they compete for nutrients and light with phytoplankton and periphyton (Scheffer, 1998). Both the abundance and macrophyte species determine the strength of the stabilization effect and are important factors in determining the ecological quality of a lake. The presence of aquatic macrophytes is influenced by geomorphology, biotic interactions and environmental conditions (Gasith and Hoyer, 1998; Jeppesen et al., 1998). The importance of water depth, bank slope, temperature and transparency on macrophyte growth and colonization in natural lakes has been researched thoroughly (Canfield et al., 1985; Dale, 1986; Duarte and Kalff, 1986). All of these factors, i.e. depth, temperature (thermal stratification), transparency and bank slope differ significantly between natural shallow lakes and quarry lakes. Therefore, quarry lakes may potentially have a distinct different macrophyte community structure compared with natural shallow waters, providing the good quality habitat needed for macrophyte communities which require these specific circumstances.

One way of determining the diversity of submerged macrophytes in and across lakes whether they are natural or man-made is by calculating the alpha, beta and gamma diversity (Whittaker, 1960). Alpha diversity represents the local-lake level-diversity, whereas beta diversity describes the spatial differentiation in diversity among lakes. Gamma diversity describes the total diversity at a regional level (Whittaker, 1972). By calculating the local contribution to beta diversity per lake, we can determine which lakes harbor unique macrophyte communities on a regional scale. The species diversity reflects and is determined by surrounding land use, impacting the lake habitat conditions. To exemplify, agricultural practices will result in surplus fertilizer ending up in the adjacent surface waters. The added nutrients have a distinct eutrophying effect, directly resulting in changing macrophyte communities (Alahuhta et al., 2013). Moreover, the species composition and diversity in a lake may also be influenced by the diversity in surrounding lakes through dispersal between them (Alahuhta and Heino, 2013).

Although numerous of these man-made lakes are present throughout the world, few countries monitor the ecological quality or water quality of these systems. Historically, quarry activities and their planning and monitoring do not go beyond the mining stage, resulting in lakes which are not optimally formed to provide any ecosystem service, ranging from recreation to nature hotspot. Nowadays, a clear vision as how to manage and use these lakes is required and needed because quarry lakes are not merely unused relics from past mining, but often fulfill multiple functions (recreation, amenity, nature). Therefore, a good understanding of the ecology, functioning and value of deep quarry lakes is required.

Due to their small size (<50 ha), quarry lakes are so-called 'non-WFD' lakes and are not subject to the mandatory monitoring required of lakes appointed in the Water Framework Directive (WFD, 2006/118/EC) (Altenburg et al., 2013; EU, 2006). Additionally, quarry lakes are overlooked in the European Natura 2000 legislation and Habitats Directive (EC 92/43/EEC; EU, 1992), although these lakes can provide possible stepping stones of biodiversity in highly urbanized areas (Teurlincx et al., 2019).

1.3. Aims and hypotheses

In this paper, we aim at unveiling biodiversity patterns of macrophytes in deep man-made sand quarry lakes at a regional scale to improve evidence-based water management. As deep quarry lakes are fed by nutrient poor ground water, we expect that the macrophyte diversity in deep quarry lakes is higher than the macrophyte diversity in shallow stagnant water systems in the same region. We focused on quarry lakes ranging from 87 to 20 years old, so macrophytes would have ample time to colonize. Specifically, we tested the following hypotheses:

(1) Quarry lakes have a higher water quality, as reflected by lower total phosphorus and total nitrogen concentration in the water column, higher clarity (Secchi depth) and lower chlorophyll-*a* concentration.

(2) This higher water quality allows deep quarry lakes to have a higher macrophyte (alpha) diversity than shallow stagnant water systems in the same region.

(3) Due to their higher water quality, macrophyte communities in deep quarry lakes contribute disproportionately more to the regional diversity than shallow standing water bodies.

2. Material and methods

2.1. Study area

We tested our hypotheses by sampling man-made quarry lakes that could thermally stratify during summer in the province of Noord Brabant (5081 km^2), the Netherlands. In this area, multiple anthropogenic stressors such as land use, eutrophication and habitat fragmentation compromise the services these aquatic systems can provide. Our study area represents one of Europe's most affected areas for agricultural pollution as 62% of the land surface is devoted to agriculture (Meinardi et al., 2005; Rozemeijer and Broers, 2007; Vermooten et al., 2006). Thirteen (13%) of the province surface area is assigned to intensive agricultural practices and 8% of the province is assigned as residential area, resulting in on average 506.6 people/km^2.

Of the 184 man-made lakes in the province, 144 are deeper than six meters allowing for stable thermal stratification of the water column during summer. Of these, 51 lakes were selected for sampling (Fig. 1) using a fuzzy modeling clustering method based upon surrounding landscape, Pleistocene subsoil type and geological subsoil type, seepage maps, surface area, depth, connections to surface waters and age (function 'Fanny', cluster package v2.0.7-1; Maechler et al., 2018; R Core Team, 2018). This fuzzy clustering approach based upon landscape scale parameters would allow the results of this study to be extrapolated to the province of Noord Brabant. Only one of the lakes had a direct surface inlet/outlet compared to 50 hydrologically isolated lakes. The lakes differed in age between 20 years and 87 years, with an average of 43 years ± 13 years. As per Dutch legislation, mining activities have to take place within a period of 10 years after permission is granted. Over this period of 10 years, mining can be stopped and re-started depending on demand of gravel and sand. The recorded age is the age when permission was granted, with the actual age potentially being younger. Of the 51 lakes, 49 were thermally stratified during sampling, of which the epilimnion comprised the upper 2 to 5 m depending on lake size. The 2 lakes that were not thermally stratified during sampling were among the relatively shallowest lakes sampled (mean depth of 3.5–3.7 m).

2.2. Sampling

The selected quarry lakes were sampled for various water quality parameters and macrophyte community characteristics. Sampling was done following a snapshot approach (Mantzouki et al., 2018) in the summer (May–September) of 2014 (23 lakes) and 2015 (28 lakes).

2.2.1. Water and sediment quality

Prior to sampling a bathymetric map of the quarry lake was created using a Lowrance Elite5 echosounder, which also allowed for the identification of the deepest point and the depth of the thermocline. At the deepest point of the quarry lake, water samples were taken at each meter using a water sampler (UWITEC 5 l). Subsequently, water samples were pooled according to their depth into epilimnion, hypolimnion and full water column samples, and filtered over a pre-washed 0.45 μm glass microfiber filter (Whatman® GF/F; GE Healthcare GmbH, Germany) and stored at −20 °C upon arrival in the lab for nutrient and chlorophyll-*a* analysis. Additionally, the filtrate of each pooled fraction was returned to the lab in dark bottles and stored at −20 °C for subsequent analysis of dissolved nutrients. Analysis of particulate organic carbon (C), nitrogen (N), and phosphorus (P) in the water samples was done from filters which were dried at 60 °C overnight, and stored dry and dark until analysis. Using a hole puncher, 4 × 3 mm subsamples were taken from the GF/F filters (~9.4%). These subsamples were thereafter folded together into a pewter cup (Elemental Microanalysis, Okehampton, UK) and analyzed for particulate C and N on a FLASH 2000 NC elemental analyzer (Brechbuhler Incorporated, Interscience B.V., Breda, The Netherlands). The remainder of the filter was combusted in a Pyrex glass tube at 550 °C for 30 min. Subsequently, 5 ml of persulfate (2.5%) was added and samples were autoclaved for 30 min at 121 °C. Chlorophyll-*a* analysis was done from additional GF/F filter from which after defrosting, the chlorophyll-*a* was extracted using ethanol according to Nusch (1980). This entails a single 5 ml 83% ethanol extraction for 10 min at 80 °C in the dark. Afterwards, the samples were centrifuged at 1600*g* for 5 min at 4 °C and stored in amber glass vials. Using high-performance liquid chromatography (column Agilent Hypersil ODS 25 cm, 5 mm, 4.6 × 250 mm at 40 °C; carrier methanol/acetone 70/30% (v/v), flow of 1.1 ml/min) chlorophyll-*a* concentration (eluted at ca. 6 min) was determined per sample.

Temperature-, oxygen-, pH-, total dissolved salts-, and ambient light (PAR)-profiles were made at the deepest point of the quarry lake using a Hydrolab® DS5 multiprobe.

Sediment samples were taken at the same location using an UWITEC sediment corer, with cores of 60 cm long and an inner diameter of 60 mm. The sediment cores were sliced and divided into 4 fractions: (1) the organic top layer (as determined by the color and the texture of the sediment) (2) first 5 cm of the sediment core, (3) 5–10 cm and

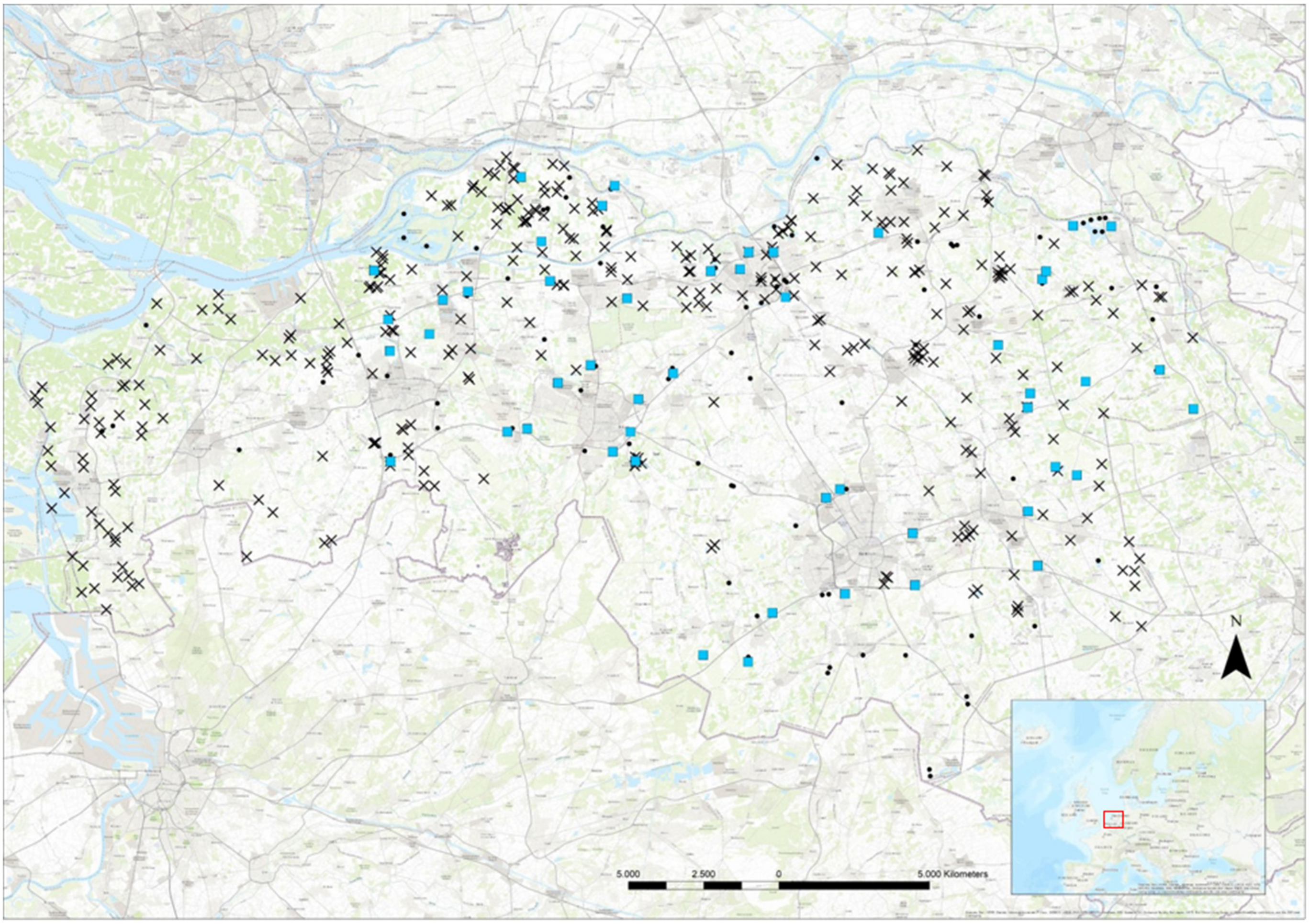

Fig. 1. Overview map of the 184 man-made lakes located in the study area, the province of Noord-Brabant, the Netherlands (black dots), the 51 deep (>6 m) man-made lakes that have been selected as field sites 2014–2015 (blue squares) and still standing shallow waters with macrophyte data between 2000 and 2016 (crosses).

(4) 10–15 cm. The fractions of three sediment cores were combined and stored directly in a vacuum bag before transport at 4 °C to the laboratory. Pore water was extracted of each sediment fraction using a rhizon® sampler (0.15 μm). Concentrations of dissolved nutrients PO_4^{3-} (Henriksen, 1965), NO_2^-, NO_3^- (Kamphake et al., 1967) and NH_4^+ (Grasshoff and Johannsen, 1972) of both pore water- and water samples were determined on a QuAAtro39 Auto-Analyzer (SEAL Analytical Ltd., Southampton, U.K.). In addition, dissolved iron (Fe), sulphur (S), calcium (Ca), zinc (Zn), magnesium (Mg), and manganese (Mn) were measured in the water sampled using an Inductive Coupled Plasma – Optical Emission Spectrometer (ICP-OES) with axial and radial view (iCAP 6500 ICP-OES Duo (Thermo Scientific).

2.2.2. Macrophyte vegetation

The aquatic vegetation of 51 lakes with a max. depth of >6 m was snapshot sampled between May and October (2014 and 2015). The submerged and floating macrophytes were quantified following Oldorff et al. (2015). In short, this method uses scuba diving along a 100 m transect perpendicular to the shoreline towards the deepest part of the lake as a way of recording macrophyte occurrence. In each lake, the location of the dive was determined based on the bathymetric map (see above) and based upon accessibility and representation of the location in relation to the whole lake. A team of at least two scuba divers surveyed each side (~2.5 m) of the 100-m transect line for macrophyte species composition and abundance (Tansley, 1935), and noted water depth at fixed distances from the shore line at 2, 5, 10, 20, 50 and 100 m, resulting in 500 m^2 area surveyed. If macrophyte species were not identifiable under water, the plant was taken to the lab, stored in 70% ethanol and identified as soon as possible using van de Weyer and Schmidt, 2011a, 2011b). Tansley scales were converted to percentage (%) coverage following Beers et al. (2014). Although this method focuses on quantifying submerged species abundance in the littoral and profundal zone, the presence of floating and emergent macrophytes along the 100 m transect line was also quantified. The presence of filamentous algae was recorded but excluded from further analysis.

2.3. Other datasets used

Shallow water bodies in the province of Noord-Brabant were used as a comparison to the sand and gravel quarry lakes in this study. Only standing water bodies were selected for comparison, consisting of shallow lakes and small to bigger canals, resulting in 332 stagnant shallow water bodies to compare to the 51 sampled deep sand or gravel quarry lakes (Fig. 1).

2.3.1. Water quality

The dataset containing chemical parameters was downloaded from waterkwaliteitsportaal.nl, which collects, manages and provides access to Dutch data collected for the WFD. Data was collected according to national WFD methodology (Altenburg et al., 2012). We calculated the summer mean values (May until September) of the selected chemical parameters (i.e. total nitrogen and total phosphorus) found at Water Framework Directive (WFD) sites between 2011 and 2016. Mean values per parameter per year were calculated before calculating a mean over the period 2011–2016.

2.3.2. Macrophyte vegetation

The macrophyte data for shallow water bodies was provided by the regional water authorities Rivierenland, Brabantse Delta, De Dommel and Aa en Maas upon request. At these WFD sites, a comprehensive macrophyte survey is carried out every three years, of which macrophyte data collected between 2000 and 2016 was analyzed. Macrophyte diversity was inventoried using standardized methods according to national WFD methodology (Beers et al., 2014). The supplied vegetation data was further subsampled to contain only helophyte and hydrophyte species based upon their Ellenberg value for moisture ($F > 9$: Hill et al., 1999).

2.4. Biodiversity indicators

Using macrophyte presence-absence data, we calculated the local (alpha) and regional (gamma) diversity based on species occurrences for the entire region of Noord Brabant. The additive beta-diversity, a measure of the differences between communities, was calculated as suggested by Jost (2007). Furthermore, we partitioned the β component into two additive components, a component of 'true species replacement' (β_{repl}) and a 'richness difference' component (β_{rich}) using the approach proposed by Podani and Schmera (2011) (Teurlincx et al., 2018). These β_{repl} and β_{rich} partitions were calculated from a Jaccard-based multi-site β-diversity index (Ensing and Pither, 2015). Next, we repeated these calculations for two subsets of the data, one containing only the deep lakes, and the other containing only the shallow water bodies in the region.

To estimate and visualize the degree of complementarity between shallow standing water and quarry lakes we calculated the relative contribution of each water body to the total, richness difference and replacement partition of beta diversity. The local contribution to beta diversity (LCBD index: as per Legendre and De Cáceres (2013) is a relative measure of the degree to which a site (here shallow standing water or quarry lake) contributes to the overall beta-diversity of the region. LCBD values for the different components of beta diversity were calculated based on a Jaccard index using the method and scripts supplied by Legendre (2014). We scaled these values between −1 and 1 for interpretation purposes, making all negative values indicative of less than average contributions to the region and all positive values reflecting above average contributions of beta diversity to the region. For illustration purposes, average LCBD values were rescaled by multiplying by the number of sites within the entire data set and expressed as a percentage to indicate increase or decrease of beta diversity of the given data set relative to the regional diversity.

Finally, we also zoomed in to potential predictors of macrophyte diversity patterns in the deep quarry lakes. We estimated the relationship between LCBD scores per quarry lakes as a dependent variable and explanatory variables lake age, surface area, average depth and the level of dissolved oxygen, pH, conductivity, P and N compounds, S, Fe, Ca, Mn, Mg, Zn, Secchi depth, light extinction and turbidity in the water column, as well as phosphate and dissolved nitrogen concentrations in the pore water of the sediment and the thickness of the organic layer using linear regression (see below).

2.5. Statistical analysis

To test for significant differences in physical-chemical characteristics of shallow waters vs. deep quarry lakes, we used *t*-tests with unequal variance (Dunnett, 1980). Additionally, we tested for significant differences between the biodiversity metrics of macrophyte diversity between deep quarry lakes versus shallow standing water bodies. Alpha diversity was tested using a generalized linear model with Poisson distribution and a log-link function. Community differences (beta diversity) on occurrence data of macrophytes was tested using a multivariate GLM with a binomial distribution and a complementary log-log link function (R package mvabund). LCBD values were compared between shallow water bodies and deep quarry systems using a linear model.

In addition, the LCBD score was calculated for each lake using only macrophyte abundance data as collected during the field campaign. Using linear models, these LCBD scores were tested against the explanatory variables (see Section 2.3; R package stats). Next, we rescaled the LCBD scores per quarry lakes against the average overall LCBD scores for the sampled quarry lakes (above average as 1, below average as 0), and used a generalized linear model to find the relationship with total phosphorus concentration in the water column. This limit value can then be used as a first approximation to determine whether a quarry lake may contain a macrophyte community of high or low value for the region. The model fit was tested against a null model using an ANOVA Chi-square test (R package stats). All analyses were carried out in R 3.6.1 using the stats (R Core Team, 2018), vegan (Oksanen et al., 2017), mvabund (Wang et al., 2012) and ggplot2 (Wickham, 2009) library and the custom code supplied by Legendre (2014).

3. Results

3.1. Physico-chemical data

The surface area of the quarry lakes varied from 1.26 to 63.19 ha and the quarry lakes maximum depth varied between 6.1 and 33.3 m (Table 1). Nutrient concentrations in the quarry lakes were generally low (mean total phosphorus (TP) concentration 0.042 mg P/l and total nitrogen (TN) concentration 0.61 mg N/l), which was significantly lower than the TP and TN concentration found in shallow surface waters ($p < 0.0001$; Table 1). This pattern also holds for inorganic phosphorus (PO_4) and nitrate (NO_3), but no significant difference was found for the ammonium (NH_4) concentration between both water types (Table 1). In addition to nutrient concentrations, deep quarry lakes also had significantly lower chlorophyll-*a* concentrations and higher Secchi readings compared with shallow surface waters in the same region. TN:TP ratio and chlorophyll-*a*:TP ratio in quarry lakes was significantly higher, and respectively lower, compared with shallow standing waters (Table 1). In quarry lakes, generally higher concentrations of TP and TN were found in the hypolimnion compared to the epilimnion ($p < 0.001$, data not shown).

Table 1
Mean and median values of the investigated variables in shallow surface waters (2011–2016) and gravel quarry lakes (2014–2015) and results of test for difference in mean values (unequal variances *t*-test), ns = non-significant.

Variable	Unit	Shallow surface waters (n = 204–382)		Quarry lakes (n = 51)		Difference (*p*-value)	
		Mean	Median	Mean	Median		
Area	ha			17.94	13.45		
Mean depth	meter			7.8	7.4		
Max depth	meter			33.3	17.0		
pH		7.4	7.4	7.6	8.3	0.458	ns
TP	mg/l	0.241	0.135	0.042	0.014	<0.001	***
PO_4	mg/l	0.107	0.022	0.013	0.000	<0.001	***
TN	mg/l	3.54	2.64	0.61	0.41	<0.001	***
NO_3	mg/l	1.67	0.75	0.24	0.07	0.001	***
NH_4	mg/l	0.34	0.11	0.28	0.02	0.500	ns
ChlA	μg/l	27.4	8.9	1.6	0.7	0.001	***
Secchi	meter	0.7	0.6	4.1	3.9	<0.001	***
TN:TP	mg/mg	14.8	21.2	51.0	15.4	0.009	**
ChlA:TP	μg/mg	113	63	67	53	0.017	*

*** <0.001.
** <0.01.
* <0.05.

3.2. Macrophyte diversity

In total 166 macrophyte species were found in the region of Noord-Brabant (Fig. 2A), including emerged, submerged and floating species. In shallow surface water bodies on average 10.6 macrophyte species per site were found, significantly more than the 7.6 species found in sand and gravel pit lakes ($p < 0.001$, GLM). A total of 78 floating or submerged macrophytes species were found in the 51 sand and gravel quarry lakes. The most common species was *Phragmites australis* (found in 21 lakes), followed by *Elodea nuttallii* (15 lakes), *Potamogeton pusillus* (11 lakes), *Juncus bulbosus* (9 lakes) and *Chara globularis* (8 lakes). In 31 of the 51 quarry lakes, charophytes were found including relatively rare species for the Netherlands: *Chara contraria*, *Nitella opaca*, *Tolypella prolifera* and *Nitellopsis obtusa*. Other rare macrophyte species found included *Luronium natans*, *Baldellia repens*, *Myriophyllum alterniflorum*, *Elatine hexandra* and *Najas marina*. Macrophytes were found up to 18.9 m water depth. In shallow water bodies a total of 144 species were found of which *Phragmites australis*, *Lemna minor*, *Glyceria maxima*, *Elodea nuttallii* and *Nuphar lutea* were most common. Of the 144 species, 38 species are considered to be relatively rare to very rare in the Netherlands, including five *Chara* species, *Tolypella prolifera*, *Nitella opaca* and *Nitella mucronata*. Other rare macrophyte species include *Potamogeton filiformis*, *Lobelia dortmanna* and *Najas marina* (Supplement 1).

Alpha diversity accounted for 25.2% of the total regional diversity. Beta diversity was thus found to be the major component of the total regional diversity, contributing 74.8%. In the region of North Brabant, both shallow as well as quarry lakes showed little similarity in macrophyte community composition, resulting in a 54.9% contribution of the replacement component to the beta diversity (Fig. 2B). In quarry lakes specifically, replacement accounted for 64.4%, contributing significantly more unique species to the region compared with shallow standing waters ($\beta_{\mathrm{repl}} = 53.0\%$). The local contribution of quarry lakes versus shallow standing water bodies to regional beta diversity differs between both types of water bodies ($p = 0.001$; GLM).

Quarry lakes contribute relatively more to the total LCBD of the region ($p < 0.001$; multivariate GLM). Separating the LCBD score for both water bodies into a true species replacement contribution ($p < 0.001$; GLM) and a species richness contribution to the LCBD score ($p = 0.065$; GLM), it becomes apparent that quarry lakes contribute more unique species to the regional diversity, although they may contain fewer species in general than shallow standing waters (Fig. 3).

3.3. Predictors of macrophyte diversity in deep lakes

The possible relationship of different physical-chemical characteristics of the water and sediment quality of quarry lakes to their macrophyte community (LCBD) was tested using linear regression analysis. We tested lake age, surface area, average depth and the level of dissolved oxygen, pH, conductivity, P and N compounds, S, Fe, Ca, Mn, Mg, Zn, Secchi depth, light extinction and turbidity in the water column, as well as phosphate and dissolved nitrogen concentrations in the pore water of the sediment and the thickness of the organic layer. Of all parameters tested, total phosphorus ($p < 0.001$), phosphate in pore water ($p = 0.012$), thickness of organic top layer of the sediment ($p < 0.001$) and chlorophyll-*a* ($p < 0.001$) showed a significant relationship with macrophyte diversity. These explanatory variables are all related to the eutrophication status of the quarry lake (Fig. 4). Additionally, the higher the average depth of the lake, the more the lake contributed to the overall quarry lakes LCBD score ($p < 0.001$).

We rescaled the LCBD abundance scores from the quarry lakes to their overall average score in order to find a limit value for the total phosphorus (TP) concentration in the water column. This limit value can then be used as a first approximation to determine whether a quarry lake may contain a macrophyte community of high or low value for the region. Hence, we tested these rescaled values using a generalized linear model against the TP concentration in the water column. Our analysis shows that if the TP concentration in a deep quarry lake exceeds 100 μg P/l (i.e. 16% of the lakes), the lake is likely not to contribute any unique species to the regional species pool as reflected by a relative LCBD score close to zero (tested against null model, $p < 0.001$, Fig. 5). As shown in Fig. 5, if the TP concentration in the quarry lake is below 35 μg P/l, the quarry lake will likely contribute unique species to the regional pool as reflected by a high relative LCBD score. Quarry lakes with a TP concentration of between 35 and 100 μg P/l, can either contain a below average, average or above average macrophyte species community (Fig. 5).

4. Discussion

Quarry lakes are novel ecosystems created by anthropogenic activities and they are often located in a landscape in which these deep systems are unique. In this study we compare the macrophyte diversity quantified during a snap-shot sampling campaign using scuba diving

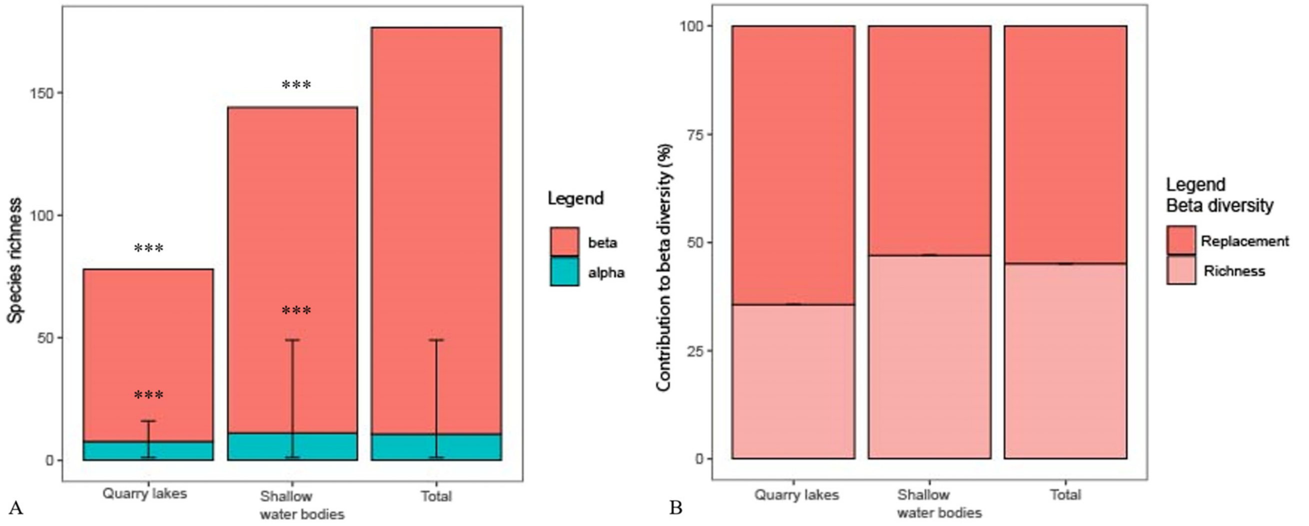

Fig. 2. (A) Macrophyte species richness in quarry lakes and shallow standing water bodies, and both water types combined (total) in the Province of Noord-Brabant, the Netherlands. Average number of macrophyte species per water body (alpha) differs significantly between quarry lakes and shallow standing water bodies ($p < 0.001$ GLM) as do their contribution to regional diversity (beta; $p = 0.001$ multivariate GLM). (B) The replacement partition of the total beta diversity was found to be larger for quarry lakes than for shallow standing water bodies (11.4% larger). Macrophyte communities of shallow standing water bodies ($n = 332$) were sampled in summer 2000–2016, quarry lakes ($n = 51$) were sampled in summer 2014–2015.

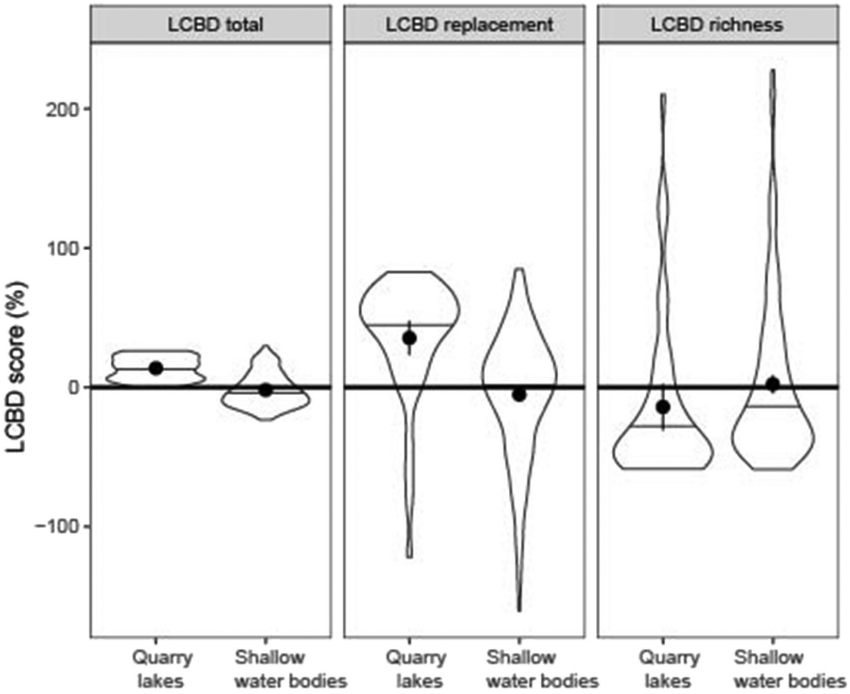

Fig. 3. Local contribution to beta-diversity (LCBD) scores of macrophyte communities in quarry lakes and shallow standing water bodies in the region of Noord-Brabant, the Netherlands. Violin plots show the differences in total (A), replacement (B) and richness (C). LCBD scores between shallow versus quarry lakes scaled to the average overall LCBD of the region (set to 0, in percentage (%)). Quarry lakes contribute more (LCBD total > 0; $p < 0.001$) and more unique 'quarry' species (LCBD replacement >0; $p < 0.001$) to the total regional diversity pool compared with shallow standing water bodies. In contrast, the average richness partition of the LCBD seems to be higher for shallow standing waters than for quarry lakes (LCBD richness; $p = 0.065$).

with the macrophyte diversity found in standing waters by the Water Framework Directive (WFD) sampling campaign in the same region.

As expected, the quarry lakes had a higher water quality than shallow lakes, as reflected by lower total phosphorus and total nitrogen concentration in the water column, higher clarity (Secchi depth) and lower chlorophyll-*a* concentration. In contrast to our expectation, deep quarry lakes had a lower macrophyte (alpha) diversity than shallow stagnant water systems in the same region. However, as expected, the quarry lakes contributed more unique macrophyte species to the regional pool compared with shallow water bodies (beta diversity). The high-quality waters of quarry lakes in the delta area of the Meuse and Rhine river are likely beneficial to the occurrence of these unique macrophyte species. Most likely, the large contribution of good quality groundwater to their water budget results in relatively oligotrophic quarry lakes in a landscape dominated by land use impacted eutrophic (shallow) water systems. In addition, the large depth of quarry lakes may aid to keep the nutrient conditions low, especially during the growth season by means of the accumulation of nutrients in the

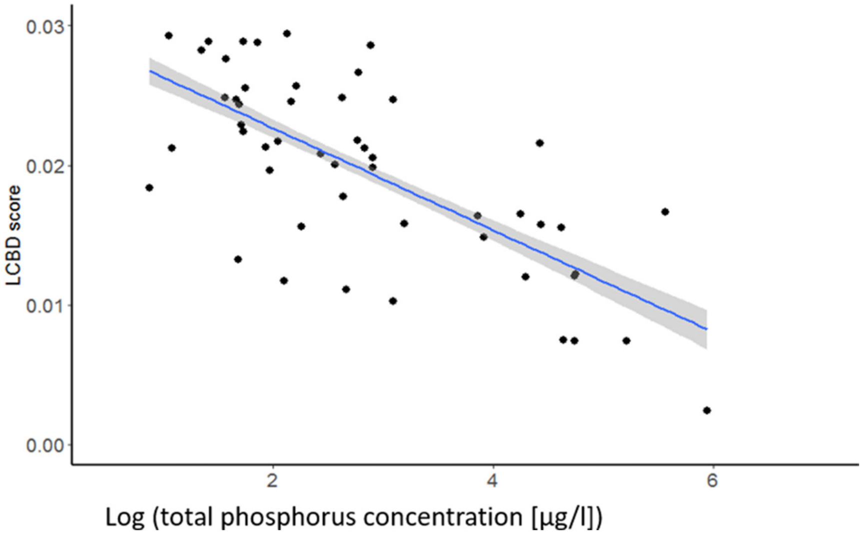

Fig. 4. Relationship between local contribution of beta diversity (LCBD) of 51 quarry lakes calculated from abundance data of their macrophyte community, and their total phosphorus concentration in the water column (in µg/l) assessed by linear regression (blue incl. standard error in grey; $R^2 = 0.5$; $p < 0.001$).

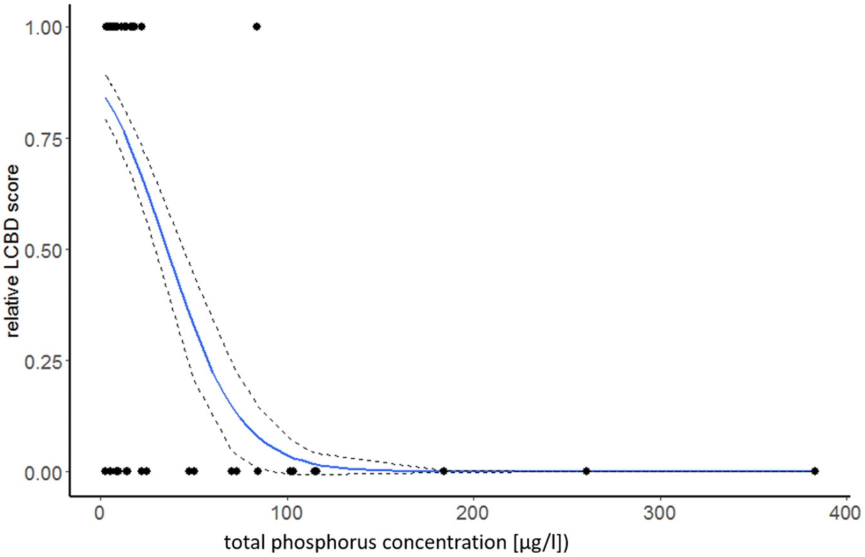

Fig. 5. Relationship between local contribution of beta diversity (LCBD) of quarry lakes calculated from abundance data of their macrophyte community rescaled to the average LCBD score of the 51 quarry lakes against their total phosphorus concentration in the water column (µg/l) as assessed by generalized linear model.

hypolimnion (Castagna et al., 2015a; Søndergaard et al., 2003). In this study we indeed found higher concentrations of total phosphorus and total nitrogen in the hypolimnion compared with the epilimnion ($p < 0.001$).

4.1. Intrinsic value of deep-man made quarry lakes

Our study shows that most quarry lakes in this region have a good chemical and biological quality; they have low nutrient concentrations, clear water and are in a significantly better state than the shallow standing waters in the same province. Based upon our chlorophyll-*a*, TP, TN and Secchi depth measurements 33 out of 51 quarry lakes would achieve a good ecological state as required by the European WFD, as for lakes with a mean depth of >3 m the limit values in the Netherlands are: chlorophyll-*a* 10 µg/l, TP 0.03 mg/l, TN 0.9 mg/l and Secchi 1.7 m. Our results are in agreement with the results of a similar study by Søndergaard et al. (2018) in which 35 gravel quarry lakes were compared to 854 natural lakes in Denmark. They concluded that quarry lakes are generally nutrient poor systems compared with natural lakes and in general add a positive element in an agriculture dominated landscape.

This study therefore supports the conclusion as made by Søndergaard et al. (2018), Mollema and Antonellini (2016) and Blanchette and Lund (2016) that quarry lakes can be valuable ecosystems.

The nutrient poor conditions of the quarry lakes can partially be explained by their depth as lakes with a large hypolimnion are less susceptible to eutrophication than fully mixed shallow water bodies (Welch and Cooke, 2005). In deeper, stably stratified systems, nutrients in the form of precipitating particles, algae and other organisms sink through the metalimnion and are trapped in the hypolimnion. These nutrients are only available for organisms that can transfer this thermal barrier or after mixing of the water column, which occurs at the end of the growing season. Other influencing factors include age; quarry activities started at the sampled lakes between 1933 and 2000, which makes the quarry lakes substantially younger than most shallow water bodies. Quarry lakes thus resemble pioneer conditions which have yet to accumulate nutrients in this landscape dominated by agricultural practices. However, no relationship between age and nutrient concentration among the 51 quarry lakes was found ($R^2 = 0.025$, $p = 0.27$). Quarry lakes might retain their low-nutrient conditions for years if external nutrient loading is poor (Søndergaard et al., 2018). Moreover, the connection to the groundwater system, and the quality of groundwater, is of much more importance in quarry lakes compared with other water bodies due to the relatively small contribution of surface water to their overall water budget. The quality of the groundwater therefore has a disproportionate influence on the quality of the quarry lake (Castagna et al., 2015a). Unfortunately, in a dense populated area such as the province of Noord Brabant, good groundwater quality is not guaranteed. Decades of intensive agricultural practices eutrophied not only surface waters but also most (shallow) groundwater systems (Visser, 2009). Consequently, the fate of most of these quarry lakes is that without change in land use they eventually will become more eutrophic. Additionally, precipitation, run-off from adjacent land, the presence of water birds and the input of leaf litter can add even more nutrients to the ecosystem pushing quarry lakes into more eutrophied ecosystem states. This is exemplified in two small quarry lakes in the region, Lake Rauwbraken (Lürling and van Oosterhout, 2013) and Lake De Kuil (Waajen et al., 2016) that developed cyanobacterial blooms after decades of good water quality. Additionally, groundwater abstraction has aided the spread of polluted groundwater by diffusion towards the well. Adding groundwater quality measurements, which will differ from quarry lake to quarry lake, to this study would be a next to further substantiate our findings. However, water quality also seemed to be influenced by the dominant ecosystem service the quarry lake was providing. Some of the quarry lakes in our study were used for sport fishing, and those lakes displayed higher nutrient and chlorophyll-*a* concentrations in the water column, and lower macrophyte diversity and LCBD (data not shown). Alternatively, the water quality determines the dominant ecosystem service. More productive water with more fish are more attractive to fisherman, clear, less productive water is more attractive to scuba divers. However, the impact of human activities on the lake, such as using boilies or fish fodder to attract fish, can greatly influence water quality and limit the provisioning of other ecosystem services by the lake.

Quarry lakes are created as a by-product of the mining process, and the practical implementation of lake design only comes into play at the very end of the mining activity. Currently, the emphasis in the design of the quarry lake is focused on physical and chemical characteristics such as bank stability preventing erosion and prevention of pollution of the lake by quarry activities (Klapper and Geller, 2001). The need for diverse microhabitats and landscape connectivity for optimal ecosystem development is completely lacking (Blanchette and Lund, 2016). However, this does not mean that established quarry lakes do not hold value for the regional diversity as is shown in this study. Isolated quarry lakes in the delta region of the Rhine and Meuse contain much lower nutrient concentrations (TP and TN), lower chlorophyll-*a* concentrations and contribute relatively more to the regional macrophyte species pool (LCBD) than stagnant shallow waters in the same region. Including the requirements for optimal ecosystem development in quarry lakes design, might further increase the value of these man-made systems. In some cases, the requirements of some components of the ecosystem (e.g. helophyte zone) are included in the design, but this can be further extended by including other zones (deeper parts) and communities. Before current established quarry lakes are to be changed to improve their ecosystem services (e.g. for the regional biodiversity), a system analysis is needed to determine whether the desired changes will actually improve the quarry lake ecosystem at all (Lürling et al., 2016). Understanding the nutrient status of water and sediments of the quarry lake through knowledge of water and nutrient fluxes into and out of the lake is paramount to determine the value of the system (Nürnberg, 1984, 1988).

The steep, highly mobile banks and the absence of riparian vegetation, characteristic of many quarry lakes, deprive the lake of nutrients and habitat complexity (Blanchette and Lund, 2016). These characteristics create an ecosystem with relatively less macrophyte species compared with surrounding more natural waters (Fig. 2A). However, the macrophyte species found in the quarry lakes are distinctly different and often rarer species, taking optimal advantage of the low nutrient conditions. In this study, 19 macrophyte species were found that are labelled “quite rare” to “rare” to “very rare” in the Dutch Red List species list (Nat, 2006; NDFF Verspreidingsatlas, 2020; Siebel et al., 2005, 2013; Sparrius et al., 2014). Of these Red List species, 8 were charophytes, a group of macro-algae highly valued by European water managers (Poikane et al., 2018). As the occurrence of this group has declined rapidly in Dutch waters (Simons and Nat, 1996), quarry lakes can thus provide a new habitat for these species. This is demonstrated by the fact that in 31 out of 51 quarry lakes, 1–5 charophyte species were recorded. Moreover, *Chara* species were found up to 9 m deep in clear quarry lakes, and up to 16.8 m deep for *Nitella* and *Nitellopsis* species. Thus, specifically the deeper parts of the quarry lakes offer good quality habitat for these rare charophytes. The maximum depth at which macrophytes were found overall was 18.9 m, much further than the 6 m assumed previously by Dutch water managers (Altenburg et al., 2013).

The sampling strategy used in this study, i.e. scuba diving, differed substantially from the strategy used by the Dutch water managers following the WFD, by using a rake (Beers et al., 2014). Using a rake to assess the macrophyte community in a lake has positive and negative aspects compared with scuba diving. Although a larger area of the lake can be covered using a boat and rake, macrophytes tend to fall from the rake while reeling it in over large depths, or macrophytes might just be too low in density or small in size to be caught by the rake at all (e.g. Wingfield et al., 2006). Scuba diving allows for a littoral close up view of the macrophyte community which increases the chance of finding macrophytes in low density situations or as small individuals. Raking is the worldwide accepted method for sampling macrophyte communities and is proven to be reliable in shallow systems (i.e. Kissoon et al., 2013), but scuba diving has been identified as more precise (Melzer, 1999) and for deeper systems indispensable (Birk et al., 2010). We used the macrophyte sampling data of WFD sites (sampled every 3 years) from 2000 to 2016 sampled via the raking method, and compared this with the results from the snapshot sampling using scuba diving in the quarry lakes. Even though the shallow standing water bodies were sampled 3–6 times during this time period and all species ever encountered were included in the analysis, the macrophyte community in quarry lakes was distinctly different from the shallow standing waters in the region (Figs. 2B and 3).

By calculating the local contribution to beta diversity (LCBD), and its replacement and richness component, among quarry lakes and in relation to surrounding shallow water bodies we show that quarry lakes add significantly to regional macrophyte diversity. Overall species richness in the region of Noord Brabant is predominantly determined by beta diversity, of which quarry lakes contribute more to the region compared to the shallow standing water bodies (Fig. 4). Determining which aspects of quarry lakes add to the high LCBD replacement score, resulted in finding an indicative threshold for total phosphorus (TP) concentration for quarry lakes contributing unique species to the regional species pool (Fig. 5). Below a TP concentration of 35 μg/l, quarry lakes are likely to contribute significantly more to the diversity of the region. Quarry lakes with a TP concentration of over 100 μg/l, are very unlikely to contribute to the regional species pool. These cut off values could be used as a first guideline in assessing the possible nature value of a quarry lake outside our sampling scheme. The LCBD methodology thus proves to be useful not only to determine ecological quality (similar to the WFD) as it proves that quarry lakes contain a diverse macrophyte community, but also for nature conservation targets (similar to Nature 2000), as it identifies the most valuable quarry lakes in the region.

4.2. Managing deep quarry lakes

As quarry lakes are firmly embedded in urbanized areas, pressures on these systems directly derive from anthropogenic activities. Similar to natural waters, eutrophication is an important pressure (Vitousek et al., 1997). In addition, since most quarry lakes are hydrologically isolated, polluted groundwater can be a major issue for the water quality of the lakes (Muellegger et al., 2013; Nixdorf et al., 2005; Søndergaard et al., 2018). Beneficial uses, or ecosystem services, that quarry lakes can provide, range from biodiversity hotspot, aquaculture, drinking water supply, irrigation and various ways of recreation to the storage of harmful substances (Mccullough and Lund, 2006). Quarry lakes are very unlikely to be able to provide all these services adequately at the same time. Water managers together with stakeholders will have to decide which services should be prioritized over others. Depending on the demands by stakeholders and changing environmental conditions, the provision of ecosystem services will change over time, which calls for more adaptive management potentially in a dynamic fashion, depending on the required service at the time and the quarry lakes responding to changing conditions (Blanchette and Lund, 2016; Cross et al., 2014).

Because quarry lakes are man-made, they are often not regarded as ‘nature’, which has resulted in numerous instances of dumping of building materials and household garbage but also of contaminated sediments resulting from anthropogenic activities elsewhere (e.g. shoaling; Schultze et al., 2011a). Quarry lakes are increasingly exploited to store dredging material under the hypothesis of improving habitat and water quality (Bolleboom et al., 2010). Generally, the ecological quality of the deep quarry lake before shoaling is regarded as low, as deep eutrophied systems can display anoxic conditions and have the potential to create low oxygen conditions after turnover. As monitoring in deep waters of the quarry lakes is not mandatory, evidence contradicting the view of deep anoxic waters is scarce (Altenburg et al., 2013). Therefore, shoaling is very often regarded as a method to improve water quality by removing the anoxic hypolimnion and decreasing the chance of cyanobacteria blooms which can benefit from stratification (Bolleboom et al., 2010). Fortunately, more and more evidence emerges that contradicts the under perceived values of quarry lakes.

The high intrinsic value of quarry lakes as demonstrated in this paper, shows that quarry lakes can be diversity hotspots in this region of the Meuse and Rhine delta. To remain regional hot spots, water managers are challenged not only by people with economic goals (“shoalers”), but also by future pressure scenarios such as climate change and the continuing changes in land use surrounding the lakes.

5. Conclusions

- Quarry lakes contain a better water quality (lower nutrient concentrations) than surrounding shallow standing water bodies in the delta region of the Meuse and Rhine.

- Quarry lakes contain a macrophyte community distinctly different from communities in shallow standing water bodies in the same region (beta diversity — replacement).
- Quarry lakes contribute significantly to the regional macrophyte species pool made up of shallow still standing waters (LCBD), acting as possible regional hot spots.
- Quarry lakes with a total phosphorus concentration in the water column of <35 μg/l contribute most to the regional diversity. When TP concentration of the quarry lake exceeds 100 μg/l, the likelihood of contributing to the regional species is very small. These TP concentration threshold values can be used as a first indicator of the potential nature value of a quarry lake.
- Quarry lakes are a distinct and important part of the landscape and should no longer be regarded as suboptimal ecosystems by water managers.
- Managing quarry lakes to fulfill their full potential asks for a different approach than described currently in Dutch WFD. The deeper parts of the quarry lakes should be integrally taken along in determining the state of the quarry lake ecosystem.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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