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Gravel pit lakes in Denmark: Chemical and biological state

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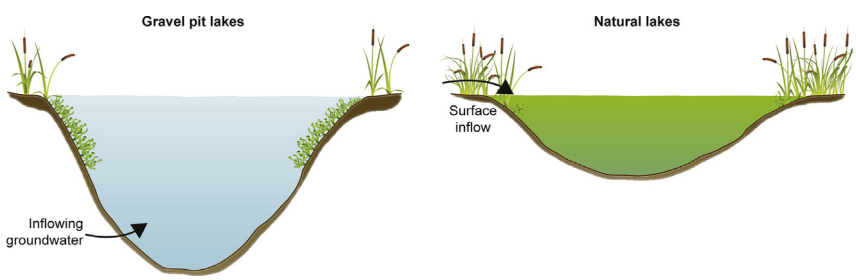
HIGHLIGHTS

- 35 Danish gravel pit lakes with an area between 0.2 and 13 ha were studied.
- The lakes were nutrient poor and with clear water compared with natural lakes.
- Submerged macrophytes were abundant and fish present in most gravel pit lakes.
- Gravel pit lake may be a way to increase biodiversity and high quality lakes.

GRAPHICAL ABSTRACT



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ABSTRACT

Mining of gravel and sand for construction purposes is big business and gravel pit lakes have become increasingly common all over the world. In Denmark, hundreds of gravel pit lakes have been created during the past decades. We investigated the chemical and biological status of 33–52 gravel pit lakes and compared the results with data from similar-sized natural Danish lakes. The area of the lakes ranged from 0.2 to 13 ha and their age from 0.5 to 26 years. Generally, the gravel pit lakes were clear with low nutrient concentrations, the median concentrations of total phosphorus and total nitrogen being 0.023 mg/l and 0.30 mg/l compared with 0.115 mg/l and 1.29 mg/l, respectively, in natural lakes. Correspondingly, median chlorophyll *a* was 5 μg/l in the gravel pit lakes and 36 μg/l in the natural lakes. Submerged macrophytes were found in all gravel pit lakes, with particularly high cover in the shallow ones. Most gravel pit lakes were deeper than the natural lakes, which may restrict the area potentially to be covered by submerged macrophytes, with implications also for the biological quality of the lakes. Fish were found in most of the gravel pit lakes, roach (*Rutilus rutilus*), perch (*Perca fluviatilis*) and rudd (*Scardinius erythrophalmus*) being the most frequently observed species. Fish stocking was common and included also non-native species such as carp (*Cyprinus carpio*) and rainbow trout (*Oncorchynchus mykiss*). Compared with the natural lakes, fish species richness and catch per gillnet were overall lower in the gravel pit lakes. Groundwater-fed gravel pit lakes add importantly to the number of high-quality lakes in Denmark and with an optimised design and by avoiding negative side effects, they can be positive for both nature and society.

1. Introduction

Worldwide, enormous amounts of sand and gravel are mined for industrial or construction purposes (USGS, 2015; Mollema and Antonellini, 2016). In 2013, the European demand for sand and gravel generated an estimated annual turnover of € 15 billion and employment for about 200,000 people (UEPG, 2017). In Denmark, between 18 and 35 million m^3 sand and gravel are mined every year, corresponding to 0.0004–0.0008 m^3 per m^2 or about 6 m^3 per person. When sand and gravel are mined below the water table, new lakes appear after the excavation. In some parts of Denmark, up to 50 lakes between 1 and 15 ha have been created in this way within small areas (Appendix: Fig. A1).

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The creation of pit lakes may impact the landscape and environment in a number of ways. On the negative side are potential impact on groundwater quality and interactions with the wider catchment (Miller et al., 1996; Blanchette and Lund, 2016). In areas with groundwater abstraction, dredging for sand and gravel poses a potential risk to the groundwater quality as the protective soil cover is removed, exposing the groundwater to the atmosphere (Muellegger et al., 2013). Pesticides and other pollutants originating from runoff from adjacent farmland to surface water or produced in the lakes (such as microcystins from cyanobacteria) may eventually adversely affect drinking water sources. Gravel pit lakes may also lead to increased freshwater loss because surface water evaporation is larger than the evapotranspiration from replaced vegetated land (Mollema and Antonellini, 2016). Finally, digging for gravel and sand can conflict with nature conservation plans by damaging existing terrestrial areas of significant nature value. On the positive side, pit lakes provide habitats for a number of organisms, thereby increasing the overall biodiversity in the agricultural or urban areas where digging is usually performed (Mollema and Antonellini, 2016), providing important refuges for wildlife such as birds (Santoul et al., 2004). Further, if properly managed, gravel pit lakes may, by reducing nitrate and phosphate concentrations, improve the groundwater quality in areas where agricultural land use has led to increased nutrient concentrations (Weilhartner et al., 2012). Finally, gravel pit lakes can be used for a number of recreational purposes such as boating, angling and swimming (Emmrich et al., 2014; Zhao et al., 2016; Blanchette and Lund, 2016). Based on a study of a pit lake area with nine lakes resulting from lignite mining located south-east of Berlin, Germany, the annual non-market recreational benefits of good water quality were found to be significant, amounting to between € 10.4 and 16.2 million (Lienhoop and Messner, 2009).

Although gravel pit lakes are becoming an increasingly common freshwater lake type, they have received limited scientific attention, preventing the development of advanced remediation strategies after the cease of mining (Soni et al., 2014; Zhao et al., 2016; Blanchette and Lund, 2016). Potentially, the creation of gravel pit lakes is a win-win situation; digging of gravel below the water table allows a more complete extraction and sometimes its use closer to the place of excavation, in this way minimising transport, construction expenses and CO_2 emission while simultaneously creating valuable freshwater ecosystems.

We investigated the chemical and biological state of a subset of Danish gravel pit lakes established during the past two to three decades. We used an extensive sampling program at 35 sites to present a general picture of gravel pit lakes. We further compared the chemical and biological quality of these lakes with natural Danish lakes to document to which extent gravel pit lakes add to the overall number of high quality Danish lake ecosystems. Although ample literature exists on natural lakes and some on gravel pit lakes, the two lake types have rarely been compared. As we had no or only limited information about the interaction between gravel pit lakes and groundwater, this aspect was not included.

We hypothesised that mainly groundwater-fed gravel pit lakes formed on nutrient poor soils would be nutrient poor and have good ecological quality, adding positively to the nature value of an agriculture-dominated landscape.

2. Methods

2.1. Study lakes

The general sampling program included 35 gravel pit lakes established for sand and gravel mining during the past 0.5 to 26 years in three regions of Denmark (Appendix: Table A1 and Fig. A2). None of the lakes had direct surface inlets or outlets, and the water level was relatively stable throughout the year. In two lakes (Nim 9 and Nim 10), sand was mined down to a clay layer, and direct connection to the groundwater therefore seems unlikely; rather they depend on water inflow from the catchment through surface runoff or drainage. During sampling, the water level in Nim 9 and Nim 10 was high and parts of nearby areas were flooded.

Many of the gravel pit lakes were thermally stratified (first 25 lakes mentioned in Table A1). The epilimnion comprised the upper 2 and 6 m depending on lake size (see further details in Søndergaard and Lauridsen, 2017). In some analyses, we divided the lakes into deep and shallow defined as lakes with maximum depths >10 m and from ≥1 to 3 m, respectively, to avoid significant differences in maximum depth. Inclusion of shallow lakes with maximum depth < 1 m would make the data set biased towards significantly lower maximum depth in the natural lakes.

2.2. Sampling and chemical analyses

The gravel pit lakes were sampled once during summer (6 June–17 August 2016) for physical, chemical and biological (submerged macrophytes and fish) variables. Physical-chemical samples were taken from a boat from a central location in the lake as surface samples (0–0.5 m) using a core sampler, and the analyses included Secchi depth, chlorophyll *a* (Chl), pH, alkalinity, colour and concentrations of total phosphorus (TP), phosphate (PO_4), total nitrogen (TN), nitrite + nitrate (NO_3) and ammonia (NH_4). Temperature, pH and Secchi depth were measured *in situ*. Samples for determination of Chl and dissolved nutrient fractions were taken and filtered on the same day, whereas samples for calculation of alkalinity, TN and TP were frozen at −18 °C until analyses. All samples were stored in clean acid-rinsed glass bottles that were kept dark and cold in the field until freezing in the laboratory. In some of the samples, nitrogen concentrations were below the limit of detection. Therefore, in our data presentation and analyses, we used 0.03 mg/l for TN below 0.05 mg/l, 0.005 mg/l for NO_3 below 0.01 and 0.001 mg/l for NH_4 below 0.001 mg/l. All chemical variables were analysed according to standard procedures (see Søndergaard et al., 2005a).

2.3. Submerged macrophytes

Presence and abundance (species + cover) of submerged macrophytes were recorded at 13–90 positions (average 44) in each lake using water glasses or a rake depending on lake size and depths where macrophytes could colonise. Cover was divided into: no plants, 0–5%, 5–25%, 25–50%, 50–75% and 75–100%. The species/taxa list was supplemented with visual observations along the shore, but the species list is not necessarily complete.

Submerged macrophyte sampling was conducted once in each lake between 30 June and 10 August. Mean macrophyte cover for the whole lake or in the littoral zone (i.e. areas with depths below 3 m) was calculated as a percentage of the lake area as a whole or of the littoral zone. Mean cover for all positions at each 1 m depth interval (0–1 m, 1–2 m, 2–3 m, etc.) was used to calculate the mean of all depth intervals for the whole lake and the littoral zone.

2.4. Fish

Fish were monitored using 42 m long multiple mesh-sized gill nets with 14 different mesh sizes (from 6.25 mm to 75 mm) once in each of 33 lakes between 6 June and 17 August. The number of nets was one in lakes <5 ha, two in lakes between 5 and 10 ha and three in lakes >10 ha. The nets were set at one or more random positions perpendicular to shore in the late afternoon and retrieved after 18 h. Carp (*Cyprinus carpio*) often avoid survey nets and were thus not always caught despite visual observation.

Quantitative measurements of the total fish stock and the individual species were expressed as catch per unit effort of weight (CPUE-weight) and catch per unit effort of number (CPUE-number). In each lake, one