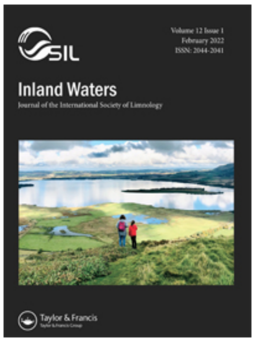


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# Serving many masters at once: a framework for assessing ecosystem services delivered by quarry lakes

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**ABSTRACT**
Globally the number of relatively deep, isolated lakes is increasing because of sand, gravel, or clay excavation activities. The major excavation areas are located within the delta of rivers, and thus the deep freshwater ecosystems formed upon excavation, called quarry lakes, are unique to the landscape. They are embedded in a landscape comprised of shallow, naturally formed lakes. Given that quarry lakes are by definition novel ecosystems, water managers face difficulties in optimally managing them to deliver ecosystem services using existing frameworks designed for natural ecosystems. All lakes in delta areas are subject to similar pressures such as urbanization and eutrophication, leading to shifts in biodiversity and ecosystem functioning, and ultimately changing the ecosystem services the systems can provide. We propose a framework to enable water managers to assess the provision of ecosystem services by quarry lakes based on their ecological quality. For each ecosystem service we determined threshold values of ecological quality based on available scientific literature, an extensive field survey of 51 quarry lakes in the Netherlands, or expert knowledge. To illustrate the usefulness of our approach, we applied our framework to a lake before and after a rehabilitation focused on improving the nutrient status of the waterbody. Assessing ecosystem services under varying levels of ecological health is important to initiate action from legislators, managers, and communities.

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## Introduction

Globally the number of relatively deep, isolated lakes is increasing yearly because of sand, gravel, and clay excavation activities (Mollema and Antonellini 2016). Because the depositions of these materials are located within the delta areas of rivers, the resulting deep freshwater ecosystems are unique to these landscapes; they are embedded in a landscape composed of shallow, naturally formed lakes and rivers (Castagna et al. 2015). Water managers in these delta areas are therefore relatively uninformed about the characteristics of these novel deep ecosystems. Because managers are responsible for the water quality in their region, understanding these novel ecosystems in the context of the wider landscape is key to informing appropriate management measures. The lack of understanding of the ecological functioning of novel quarry lakes and their role in the landscape can lead to a mismatch between the demand and the realizable supply of a wide suite of ecosystem services (Mouchet et al. 2014). To support better management of these novel ecosystems, we propose a framework to enable water managers to assess the ability of a specific quarry lake to provide specific ecosystem services, based on their ecological quality.

Although most limnological research focuses on large shallow lakes (Verpoorter et al. 2014) or large deep lakes (e.g., Bunting et al. 2007, Hampton et al. 2008, O'Beirne et al. 2017), fresh waterbdodies <0.01 km$^2$ are the most abundant waters in the world (Downing et al. 2006). Moreover, these small freshwater ecosystems continue to be created through excavation of sand, gravel, and clay as building materials. In low-lying (delta) areas, these quarries, or mining pit locations, fill up with surface, ground, and rain water and thus create novel freshwater ecosystems (Higgs 2017). These young lakes may provide oligotrophic conditions that are relatively rare in a world where global change has drastically

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impacted freshwater ecosystems (Woodward et al. 2010). A combined effect of climate change, urbanization, and eutrophication has already pushed many small lake ecosystems toward a nutrient-enriched phytoplankton-dominated state (Peeters et al. 2007). Hence, man-made quarry lakes may potentially serve as refuges for species that require oligotrophic conditions, assuming dispersal is not limiting (Søndergaard et al. 2018).

Man-made quarry lakes created by excavation activities are different from natural lakes in various ways. Maximizing the efficiency of the excavation activity leads to deep lakes with steeper slopes, large hypolimnia relative to epilimnia, and a lack of large shallow and marsh zones compared to most naturally formed lakes (Blanchette and Lund 2016). All lakes that thermally stratify for longer periods, including quarry lakes, concentrate precipitated organic material in their hypolimnion (see Hansson et al. 1994 for an example for phytoplankton). After decomposition of this material in the bed sediment, the resulting nutrients are locked within the hypolimnion by the thermocline. This nutrient-focusing effect aids the characteristically clear water of deep lakes in the summer by starving the algae in the epilimnion of nutrients (Wetzel 2001). Because quarry lakes are often located in low-lying (delta) areas, they become the only deep, and thus stably stratifying, systems in a landscape composed of shallow waterbodies (lakes, rivers, canals).

Quarry lakes also differ in their hydrological connectivity with surrounding waterbodies, often being hydrologically isolated from other surface waters. This distinguishes quarry lakes from similarly sized naturally formed lakes, leading to a different distribution of dominant water sources to the lake (i.e., rain and groundwater) and relatively high water residence time (e.g., Waajen et al. 2016). This lack of connection will also impact transport of energy, substances, and organisms from upstream waterbodies (Teurlincx et al. 2019). Diagnosing and tackling water quality issues of quarry lakes therefore requires a different frame of reference than is generally applicable to shallow lakes or large deep lakes (Welch and Cooke 2005).

The Water Framework Directive (WFD, 2000/60/EC; EU 2000) dictates water managers to achieve a "good status" of all European waters by 2027. However, most small lakes (<50 ha) are designated as "non-WFD" waterbodies, and the monitoring of these systems is not mandated (WFD, 2006/118/EC; EU 2006a, Altenburg et al. 2013). Similarly, non-European alternatives to the WFD such as the Clean Water Act (USEPA 2018) do not mandate monitoring of these waters. Quarry lakes are often located close to the project that requires the building material, such as roadworks or residential areas, that is, in locations where people interact with freshwater ecosystems. Despite the lack of government-mandated monitoring of these small waters, the vested interest of citizens provides local water managers with a rationale for maintaining good water quality in these types of lakes to safeguard ecosystem services provisioning.

For local residents and communities, small quarry lakes can provide numerous ecosystem services after mining activities are completed (Castagna et al. 2015). Many models aim to identify, characterize, and value ecosystem goods and services (e.g., Carpenter et al. 2009, Bagstad et al. 2013). The European Environment Agency (EEA) together with international partners provided a Common International Classification of Ecosystem Services (CICES) in 2013 and published an updated version (5.1) in 2018 (Haines-Young and Potschin 2018). We use the CICES system to identify and describe all possible ecosystem services a quarry lake can provide (Haines-Young and Potschin 2018).

To connect ecosystem quality and the provisioning of ecosystem services directly, it is important to first determine meaningful thresholds where a decrease in quality will result in an unacceptable loss of service provision. However, thresholds are inherently difficult to determine because various disciplines such as ecologists, economists, or water managers define thresholds differently. The ecologist would define a threshold as a point at which small changes in environmental conditions produce large, and sometimes abrupt, responses in ecosystem state or function (Groffman et al. 2006). However, for the economist, water managers, or other researchers in the social science disciplines, the threshold would be a point at which small changes in environmental conditions produce substantial improvements in the management outcome, which takes into account the value judgment of stakeholders and the underlying behavioral changes (Martin et al. 2009).

In some instances, ecological and socioeconomic thresholds will not be aligned, complicating policy decisions. For example, the definition of thresholds for provisioning and regulating biotic services may likely be rooted in ecological thresholds, whereas ecosystem services related to cultural, direct, in situ, and outdoor interactions will be closer to a societal (utility or decision) threshold (Martin et al. 2009). These 2 thresholds may or may not be the same and require modeling across disciplines, and the differences can impact policy decisions.

We developed a framework that can be used by scientists and water managers to link ecological responses to anthropogenic stressors in the context of ecosystem service provision in quarry lakes. The framework was developed by (1) compiling a list of the potential ecosystem services that quarry lakes may provide following the CICES approach; (2) determining ecosystem functioning thresholds related to ecosystem service provision in quarry lakes using a combination of literature review, expert judgment, and empirical data from 51 quarry lakes in the Province of Noord-Brabant, the Netherlands; and (3) demonstrating the usefulness of our approach through application of the framework using a restoration case study, Lake De Kuil, the Netherlands.

## Materials and methods

### Identifying ecosystem services provided by quarry lakes

We adopted the CICES (Haines-Young and Potschin 2018) system to identify and describe ecosystem services provided by quarry lakes. The CICES system, developed under the United Nations Statistical Division (UNSD; Haines-Young and Potschin 2018), was designed to help measure, account for, and assess ecosystem services. CICES version 5.1 was developed after the results of the 2016 survey by the EEA were available and further specified after several workshops organized by the EEA and UNSD (Haines-Young and Potschin 2018). Both biotic and abiotic ecosystem services are addressed and classified according to the contributions that an ecosystem can provide to human well-being. When identifying services that can be provided by quarry lakes, services from all sections and division groups of the CICES classification system were applicable. Depending on the service in question, environmental variables have been identified and thresholds set for either littoral zone (e.g., macrophyte biomass) or pelagic zone (e.g., fish biomass). Environmental variables have been chosen to directly coincide with the service each describes (e.g., fish biomass for aquaculture). However, some services required a selection of environmental variables to accurately define the suitability to provide the service. Suitability for recreation not only requires visibility to be adequate but also demands low cyanotoxin concentrations, low fecal contamination, and other considerations. We describe the environmental variables we chose to include (and sometimes the factors we did not include) in the results section.

### Determining ecosystem functioning thresholds related to ecosystem service provision in quarry lakes

We determined the threshold values for a range of parameters for identified each ecosystem service (e.g., minimum benthivores fish biomass needed in a quarry lake to be suitable for sport fishing) based on published peer-reviewed literature, a field campaign covering 51 quarry lakes in the Province of Noord-Brabant (the Netherlands), and expert judgement. Peer-reviewed literature used to determine the threshold values for ecosystem services provided by quarry lakes was found suitable if studies were from stratifying aquatic systems (e.g., to determine thresholds for fish biomass) or if the ecosystem service was provided by the littoral zone; literature from (small and large) shallow lakes was acceptable as well. Details of the quarry lake field campaign are described in the Seelen et al. (2021) and more in detail in the Supplemental Material. In short, we performed a snap-shot sampling campaign in 51 quarry lakes deeper than 6 m in the Province of Noord-Brabant. The campaign entailed chemical measurements of the water column and sediment, including nutrient and chlorophyll *a* (Chl-*a*) measurements, and an extensive vegetation survey.

In practice, the threshold values we propose in this study are the minimum or maximum concentration, biomass, cover, or amount of a certain water quality parameter a quarry lake must exhibit to support the provision of a given service. Thresholds needed to preserve ecosystems for future generations (so called bequest value) could theoretically be determined for different organism groups such as bacteria, algae, macrofauna, and fish, but here we focus on macrophytes. Macrophytes play an important role in structuring aquatic diversity (including other species groups such as fish and macrofauna; Warfe and Barmuta 2004) and ecosystem functions by providing substrate, food, and shelter and affecting water and sediment chemistry, biogeochemical cycles, and productivity (Jeppesen et al. 1998, Scheffer 1998, Wetzel 2001).

Some ecosystem services remain difficult to quantify. We therefore chose to quantify these services per parameter as "the more, the better": the amount of suspended solids captured by macrophytes (CITES code 2.1.1.2), the amount of carbon and nutrients buried in the sediment (2.2.4.2), and the filtering capacity for external nutrients by the littoral zone (2.2.5.1).

### Case study Lake De Kuil

To exemplify our approach, we applied our framework to determine the ecosystem services in quarry Lake De Kuil in Breda, the Netherlands, a deep quarry lake with many potentially competing stakeholder interests. This quarry lake is 6.7 ha with a maximum depth of 9 m and has been researched thoroughly by Waajen et al. (2016). Data from 1992–2008 and 2009–2014 were used to assess the potential services De Kuil can provide. In 2009, internal P-loading of the lake was reduced through a "Flock & Lock" method (Lürling and van Oosterhout 2013) to reduce cyanobacterial blooms. An application of lanthanum bentonite and iron(III) chloride (18–22 May 2009) resulted in a significant improvement in water quality and a reduction in cyanobacteria abundance; mean summer concentrations of total phosphorus (TP) decreased from 0.05 mg/L (1992–2008) to 0.02 mg/L (2009–2014) and Chl-*a* from 16 µg/L (1992–2008) to 6 µg/L (2009–2014; Waajen et al. 2016). This technological restoration measure was successful in reducing the occurrence of cyanobacterial blooms. We utilized available monitoring data (1992–2014; Waajen et al. 2016) to conduct a before–after assessment of the wider ecosystem service benefits associated with the internal loading control in Lake De Kuil using the framework described earlier and in more detail below.

Lake de Kuil is used for a variety of provisioning services such as sportfishing (1.1.6.1), regulation, and maintenance services such as habitat for WFD (2.2.2.3), cultural services such as environment for scientific research (3.1.2.1), and hiking (3.1.1.2) and swimming (6.1.1.1). De Kuil is situated within the province of Noord-Brabant. While not included in the sampling campaign described in the Supplemental Material and in Seelen et al. (2021), this quarry lake is located in the study area of the snapshot sampling campaign. Although vicinity is not a prerequisite, its location makes it an ideal case to evaluate the usefulness of our framework.

## Results

We identified services from all sections and division groups of the CICES classification system to be potentially supplied by quarry lakes (Table 1). The number for the specific CICES ecosystem service (Table 1) is provided in the text.

**Provisioning (biotic) services** include aquatic animals for nutrition, material, or energy such as aquaculture. For quarry lakes we defined this service to specifically address the culturing of fish as food (i.e., professional fishponds; 1.1.4.1). Additionally, quarry lakes can produce wild edible plants that can be harvested such as *Typha* species and *Mentha aquatica* (1.1.5.1). Helophytes found around quarry lakes, such as common reed (*Phragmites australis*), can be used as a building material, for example to thatch roofs (1.1.5.2). Finally, quarry lakes can provide raw materials for the production of food as a harvestable surplus, such as sport fishing for trout (*Salmo trutta*) or carp (*Cyprinus carpio*; 1.1.6.1).

**Regulation and maintenance (biotic)** services include the transformation of biochemical inputs to the ecosystem (2.1.1.2) and regulation of physical, chemical, and biological conditions (2.2.2.3, 2.2.4.2, 2.2.5.1, 2.2.6.12). Macrophytes can filter carbon from incoming water and help reduce a product of anthropogenic origin through a living process (2.1.1.2). The regulation of physical, chemical, and biological conditions includes the maintenance of habitats to sustain populations and iconic species targeted by the WFD (2000/60/EC; 2.2.2.3), but also burial of carbon and nutrients (nitrogen and phosphorus) in the lake's sediment (2.2.4.2). Additionally, water and atmospheric conditions can be regulated by the vegetated banks of the quarry lakes, which capture nutrients (2.2.5.1) and act as a net carbon sink (2.2.6.1).

**Cultural**, direct, in situ, and outdoor interactions with quarry lake ecosystems provide opportunities for nature interactions (wildlife watchers, hikers, and birders; 3.1.1.2), science (3.1.2.1), and education, including citizen science (3.1.2.2). Quarry lakes also provide habitat for rare species such as charophytes, which people seek to preserve for future generations (3.2.2.2).

**Abiotic provisioning services** that quarry lakes offer include water for drinking (4.2.1.1), irrigation (4.2.1.2), and hydropower (4.2.1.3).

**Abiotic cultural services** include recreation such as kayaking, swimming, diving, and boating (6.1.1.1).

The thresholds for ecosystem services provisioning of quarry lakes we identified were based on published peer-reviewed literature, a field campaign covering 51 quarry lakes in the Province of Noord-Brabant, and expert judgement (Tables 2–6). The tables summarize the thresholds of the identified CICES ecosystem services a quarry lake can provide but are intended to act as a "living" document as future research continues to supply data for adjusting and further specifying threshold values. Here we describe the underpinning of thresholds per group of ecosystem services in detail. The numbers for the specific CICES ecosystem services (Tables 2–6) are also listed in the text.

## Provisioning biotic services associated with fish and plants

### *Aquaculture and sports fishing*

The average total fish biomass in 17 deep quarry lakes in the Netherlands has been observed to be 100 kg/ha (Van Emmerik and Verpsui 2012, Puts and Droog 2016), which we assumed is the natural carrying capacity of an average quarry lake and thus used this value to assess the suitability of a lake to provide the service

**Table 1.** Overview of identified ecosystem services of quarry lakes based upon CICES framework (Haines-Young and Potschin 2018).

| Section | Division | Group | Class | Code |
|---|---|---|---|---|
| Provisioning (biotic) | Biomass | Reared aquatic animals for nutrition, materials, or energy | Animals reared by in situ aquaculture for nutritional purposes | 1.1.4.1 |
| | | Wild plants (terrestrial and aquatic) for nutrition, materials, or energy | Wild plants (terrestrial and aquatic, including fungi, algae) used for nutrition | 1.1.5.1 |
| | | | Fibers and other materials from wild plants for direct use or processing (excluding genetic materials) | 1.1.5.2 |
| | | | Wild animals (terrestrial and aquatic) used for nutritional purposes | 1.1.6.1 |
| Regulation and maintenance (biotic) | Transformation of biochemical or physical inputs to ecosystems | Mediation of wastes or toxic substances of anthropogenic origin by living processes | Filtration/sequestration/storage/accumulation by microorganisms, algae, plants, and animals | 2.1.1.2 |
| | Regulation of physical, chemical, biological, conditions | Lifecycle maintenance, habitat, and gene pool protection | Maintaining nursery populations and habitats (including gene pool protection) | 2.2.2.3 |
| | | Regulation of soil quality | Decomposition and fixing processes and their effect on soil quality | 2.2.4.2 |
| | | Water conditions | Regulation of the chemical condition of freshwaters by living processes | 2.2.5.1 |
| | | Atmospheric composition and conditions | Regulation of chemical composition of atmosphere and oceans | 2.2.6.1 |
| Cultural (biotic) | Direct, in situ, and outdoor interactions with living systems that depend on presence in the environmental setting | Physical and experiential interactions with natural environment | Characteristics of living systems that enable activities promoting health, recuperation, or enjoyment through passive or observational interactions | 3.1.1.2 |
| | | Intellectual and representative interactions with natural environment | Characteristics of living systems that enable scientific investigation or the creation of traditional ecological knowledge | 3.1.2.1 |
| | Indirect, remote, often indoor interactions with living systems that do not require presence in the environmental setting | Other biotic characteristics that have a non-use value | Characteristics or features of living systems that have an option or bequest value | 3.2.2.2 |
| Provisioning (abiotic) | Water | Surface water used for nutrition, materials, or energy | Surface water for drinking | 4.2.1.1 |
| | | | Surface water used as a material (non-drinking purposes) | 4.2.1.2 |
| | | | Freshwater surface water used as an energy source | 4.2.1.3 |
| Cultural (abiotic) | Direct, in situ, and outdoor interactions with natural physical systems that depend on presence in the environmental setting | Physical and experiential interactions with natural abiotic components of the environment | Natural, abiotic characteristics of nature that enable active or passive physical and experiential interactions | 6.1.1.1 |

**Table 2.** Overview of potential provisioning (biotic) ecosystem services (CICES system) that can be supplied by quarry lakes and their defining parameters. Per parameter threshold values are categorized as making a quarry lake unsuitable, moderately suitable, or suitable to supply the corresponding ecosystem service. — represents not required for that service.

| Ecosystem service: Provisioning (biotic) | Suitability | Fish biomass kg/ha | Shoot and root biomass (DW) $g/m^2$ | Helophyte shoot biomass (DW) $g/m^2$ | Piscivore fish biomass kg/ha | Benthivore fish biomass kg/ha | Width littoral zone m | Macrophyte cover % | Plant nuisance: vegetation-free water column m |
|---|---|---|---|---|---|---|---|---|---|
| 1.1.4.1 Professional fishing - fishponds | unsuitable | <10 | — | — | — | — | — | — | — |
| | moderately suitable | 10–100 | — | — | — | — | — | — | — |
| | suitable | >100 | — | — | — | — | — | — | — |
| 1.1.5.1 edible plants (helophytes and macrophytes) | unsuitable | — | <50 | — | — | — | — | — | — |
| | suitable | — | >50 | — | — | — | — | — | — |
| 1.1.5.2 Common reet production for roof thatching | unsuitable | — | — | <2500 | — | — | — | — | — |
| | suitable | — | — | >2500 | — | — | — | — | — |
| 1.1.6.1 Sportfishing for piscivores fish species | unsuitable | — | — | — | <0.02 | — | >5 | >75 | <0.5 |
| | moderately suitable | — | — | — | 0.02–0.7 | — | 2–5 | 50–75 | — |
| | suitable | — | — | — | >0.7 | — | <2 | <50 | >0.5 |
| 1.1.6.1 Sport fishing for benthivores fish species | unsuitable | — | — | — | — | <30 | >5 | >75 | <0.5 |
| | moderately suitable | — | — | — | — | 30–250 | 2–5 | 50–75 | — |
| | suitable | — | — | — | — | >250 | <2 | <50 | >0.5 |

**Table 3.** Overview of potential regulation and maintenance ecosystem services (CICES system) that can be supplied by quarry lakes and their defining parameters. Per parameter threshold values are categorized as making a quarry lake unsuitable, moderately suitable, or suitable to supply the corresponding ecosystem service. — = not required for that service.

| Ecosystem services: Regulation and maintenance | Suitability | FW macrophyte biomass to reduce suspended solids | FW macrophyte biomass to reduce cyanobacteria | Macrophyte cover % | Carbon burial $g/m^2/d$ | Phosphorus burial $g/m^2/d$ | Nitrogen burial $g/m^2/d$ | Reduction phosphorus load % | Reduction nitrogen load % | Carbon production and respiration of quarry lake $g/m^2/d$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 2.1.1.2 Particle capture between macrophytes | unsuitable | <20 | <20 | — | — | — | — | — | — | — |
| | moderately suitable | 20–200 | 20–200 | — | — | — | — | — | — | — |
| | suitable | >200 | >200 | — | — | — | — | — | — | — |
| 2.2.2.3 Maintenance of habitats for Water Framework Directive | unsuitable | — | — | <30 | — | — | — | — | — | — |
| | moderately suitable | — | — | 30–60 | — | — | — | — | — | — |
| | suitable | — | — | >60 | — | — | — | — | — | — |
| 2.2.4.2 Carbon, nutrient (P + N) burial in lake sediment | unsuitable | — | — | — | <0 | <0 | <0 | — | — | — |
| | suitable | — | — | — | >0 | >0 | >0 | — | — | — |
| 2.2.5.1 Reduction of nutrients by littoral zone | unsuitable | — | — | — | — | — | — | <20 | <20 | — |
| | moderately suitable | — | — | — | — | — | — | 20–50 | 20–50 | — |
| | suitable | — | — | — | — | — | — | >50 | >50 | — |
| 2.2.6.1 Net carbon sink | unsuitable | — | — | — | — | — | — | — | — | <0 |
| | suitable | — | — | — | — | — | — | — | — | >0 |

**Table 4.** Overview of potential cultural (biotic) ecosystem services (CICES system) that can be supplied by quarry lakes and their defining parameters. Per parameter threshold values are categorized as making a quarry lake unsuitable, moderately suitable, or suitable to supply the corresponding ecosystem service. — = not required for that service.

| Ecosystem service: Cultural (biotic) | | Suitability | Fish biomass kg/ha | Width littoral zone m | Plant biomass littoral zone g $DW/m^2$ | Total phosphorus water column µg/L | Visibility m |
|---|---|---|---|---|---|---|---|
| 3.1.1.2 | Hikers | unsuitable | — | >2; <0.1 | — | — | <0.5 |
| | | moderately suitable | — | 0.1–1 | — | — | 0.5–1.5 |
| | | suitable | — | 1–2 | — | — | >1.5 |
| | Birders | unsuitable | <67 | — | <73 | — | <1.5 |
| | | moderately suitable | — | — | — | — | 1.5–5 |
| | | suitable | >67 | — | >73 | — | >5 |
| 3.1.2.1 | Environment in which scientific research can be done | | — | — | — | — | — |
| 3.1.2.2 | Environmental education and citizen science | | — | — | — | — | — |
| 3.2.2.2 | Habitat for rare species (Red List species) | unsuitable | — | — | — | >100 | — |
| | | moderately suitable | — | — | — | 35–100 | — |
| | | suitable | — | — | — | <35 | — |

**Table 5.** Overview of potential cultural (abiotic) ecosystem services (CICES system) that can be supplied by quarry lakes and their defining parameters. Per parameter threshold values are categorized as making a quarry lake unsuitable, moderately suitable, or suitable to supply the corresponding ecosystem service. — = not required for that service.

| Ecosystem service: Cultural (abiotic) | | Suitability | Width littoral zone m | Macrophyte cover % | Cyanotoxin concentration (microcystin) µg/L | *E. coli* cfu/100 mL | Intestinal enterococci cfu/100 mL | Visibility m | Plant nuisance: vegetation-free water column m |
|---|---|---|---|---|---|---|---|---|---|
| 6.1.1.1 | Shallow recreation | unsuitable | >50 | >50 | >50 | >1800 | >400 | <0.5 | 0 |
| | | moderately suitable | 5–50 | 10–50 | 10–50 | — | — | 0.5–1.5 | 0–0.5 |
| | | suitable | <5 | <10 | <10 | <1800 | <400 | >1.5 | >0.5 |
| | Deep recreation | unsuitable | >50 | >50 | >50 | >1800 | >400 | <0.5 | 0 |
| | | moderately suitable | 5–50 | 10–50 | 10–50 | — | — | 0.5–1.5 | 0–1 |
| | | suitable | <5 | <10 | <10 | <1800 | <400 | >1.5 | >1 |

**Table 6.** Overview of potential provisioning (abiotic) ecosystem services (CICES system) that can be supplied by quarry lakes and their defining parameters. Per parameter threshold values are categorized as making a quarry lake unsuitable, moderately suitable, or suitable to supply the corresponding ecosystem service. — = not required for that service.

| Ecosystem service: Provisioning (abiotic) | | Suitability | Cyanotoxin concentration (microcystin) µg/L | Turbidity NTU | *E. coli* cfu/100 mL | Intestinal enterococci cfu/100 mL | Volume of inflow to quarry lake $m^3$/d |
|---|---|---|---|---|---|---|---|
| 4.2.1.1 | Drinking water | unsuitable | >1 | >1 | >0 | >0 | — |
| | | moderately suitable | — | 0.2–1 | — | — | — |
| | | suitable | <1 | <0.2 | 0 | 0 | — |
| 4.2.1.2 | Irrigation | unsuitable | >20 | — | >1000 | — | — |
| | | suitable | <20 | — | <1000 | — | — |
| 4.2.1.3 | Hydropower | unsuitable | — | — | — | — | <3285 |
| | | suitable | — | — | — | — | >3285 |

"professional fish pond" (1.1.4.1). Below a fish biomass of 10 kg/ha (1% of average yield of common carp in aquaculture), aquaculture is assumed to no longer be economically feasible (Menezes et al. 2017).

Sport fishing is a popular pastime for many people (Schramm et al. 1991). Based on the differences in ecological requirements of benthivorous or piscivorous fish, this service has been split into 2 parts: sport fishing for piscivorous fish (clear water fishing; 1.1.6.1) or sport fishing for benthivorous fish (turbid water fishing; 1.1.6.1). Fishing for piscivorous fish species (including pike and trout) requires a minimum density of 0.02 kg/ha, and ideally 0.7 kg/ha, based on the fish yield of pike fisheries in Europe (Dill 1993). Fishing for benthivorous fish species (bream, carp) requires a higher density of at least 30 kg/ha but ideally >250 kg/ha (Van Emmerik and Verpsui 2012). Sportfishing at quarry lakes is often only permitted from the shoreline, thus requiring a relatively small helophyte zone (preferable <2 m, maximum 5 m) and low cover in the shallow zone by macrophytes (<50%) to cast and prevent snagging the hook on aquatic vegetation (Verhofstad and Bakker 2017). Macrophytes were considered a nuisance for sport fishermen when <0.5 m of the upper layer of the water column (i.e., <50 cm below the water surface) was devoid of vegetation. These parameters were added to the minimum fish biomass requirements to determine the suitability of a quarry lake to provide sport fishing services (1.1.6.1; Table 2).

### *Macrophytes for food and roof thatching*

The helophyte border around lakes can provide habitat for edible macrophyte species. One of the most popular food sources is the rhizomes of *Typha* (Liptay 1989, Gott 1999). We assumed a person is willing to search and dig 5 m$^2$ for a meal of 0.5 kg fresh weight (FW), making a minimum of 50 g/m$^2$ dry weight (DW) of root biomass sufficient to warrant non-commercial harvest for food (1.1.5.1). Thatching a roof with common reed (*Phragmites australis*) has been a proven way of building for hundreds of years. For an average roof of 100 m$^2$, 25 kg common reed per m$^2$ with a 10% moisture content is needed (Long and Oelofson 1978). For a quarry lake to supply this service, the helophyte zone should offer at least 2500 g/m$^2$ DW shoot biomass (Long and Oelofson 1978; 1.1.5.2; Table 2).

## Regulating biotic services associated with plants and their specific functions

### *Macrophytes reduce sediment resuspension and nutrient input*

Submerged macrophytes can reduce particle resuspension in a lake by trapping carbon (sediment particles) from the water column, preventing it from reentering the lake ecosystem. With a FW biomass of at least 20 g/m$^2$, but ideally >200 g/m$^2$, sediment resuspension was greatly reduced in a large shallow lake (James et al. 2004; 2.1.1.2.). We copied these thresholds to quarry lakes because the density of macrophytes in the littoral zone to reduce particle resuspension induced by wind does not discriminate between lake types.

As nutrients (carbon, nitrogen, phosphorus) enter the quarry lake system, they can be retained in the ecosystem. If nutrient burial takes place in the lake sediment, nutrient pollution is removed from the surrounding landscape. A net burial of these nutrients is beneficial in a world where eutrophication has polluted waterbodies and terrestrial systems (Radbourne et al. 2017; 2.2.4.2).

Additionally, water quality can be regulated by the vegetated banks of the quarry lakes by the capture of incoming nutrients. Reducing incoming nutrients by 20% (threshold for moderately suitable), or even over 50% (suitable), has proved possible in shallow lakes (Sollie et al. 2008a, 2008b; 2.2.5.1). Climate regulation by the sequestration of carbon in the sediments of quarry lakes is possible, although no concrete threshold value for the amount of carbon sequestered to be considered “better” could be found. We defined quarry lakes with a net carbon sequestration as suitable for supplying this service and a net release of carbon into the atmosphere as unsuitable (Mendonça et al. 2017; 2.2.6.1; Table 3).

### *Macrophyte populations*

Quarry lakes can provide habitat for numerous macrophyte species and can thus contribute to sustaining regional macrophyte populations. The field campaign in 51 quarry lakes provided the threshold values for this ecosystem service. The percentage cover of macrophytes up to their maximum growth depth in each quarry lake was converted to the cover for the whole lake. Twelve quarry lakes had a total cover of 0–30% on their sediment surface, 7 quarry lakes a cover of 30–60%, and 32 quarry lakes a cover of >60%. The bin cut off value for cover was chosen based on the average number of macrophyte species and number of Red List species per bin. Quarry lakes with up to 30% cover contained on average 5.5 species and 1.1 Red List species; quarry lakes with 30–60% cover contained 7.9 macrophyte species and 1.4 Red List species; and quarry lakes with >60% cover contained on average 8.2 macrophyte species and 1.7 Red List species (Supplemental Material; 2.2.2.3). The threshold value for moderately suitable was set at 30% cover and suitable at (>) 60% cover (Table 3).

## Cultural, direct, in situ services and outdoor interactions

### *Recreation surrounding quarry lakes*

Wildlife watchers can enjoy the surroundings of quarry lakes by hiking alongside its shores. We assumed that to be enjoyable, the hiker would like to see the water, and, if so, see into the water (Seelen et al. 2019). Therefore, a threshold value for the helophyte border width of 5 m was set and water clarity of at least 0.5 m Secchi depth (expert judgement; 3.1.1.2). Birdwatchers are more interested in specific fish-eating birds such as the great crested grebe (*Podiceps cristatus*). A suitable habitat for these birds should provide a minimum fish population of 81 kg/ha/yr per bird (Bon and Ogunja 1988, Ulenaers and van Vessem 1994). Birders interested in macrophyte-eating species such as Eurasian coot (*Fulica atra*) require a minimum DW macrophyte biomass of 73 g/m$^2$ for 10 birds during the year (Driver 1984). Both fish-eating as well as macrophyte-eating birds can dive up to 5 m (Ingram et al. 1942); hence we assumed an ideal water clarity from 5 m and deeper (Secchi depth) (3.1.1.2).

For scientists and citizen scientists to make optimal use of a quarry lake, no specific requirements of the ecological system itself are needed. Rather, the opportunity to research and learn from the ecosystem is sufficient, leading to no threshold being set for these functions (3.1.2.1 and 3.1.2.2; Table 4).

### *Red List (macrophyte) species in quarry lakes*

A characteristic of a living system that can supply a bequest value includes the provision of habitat for rare macrophyte species. Quarry lakes with a TP concentration of <35 μg/L are likely to contain species unique in the regional species pool (data from field campaign quarry lakes 2014–2015). Quarry lakes with a TP concentration >100 μg/L are unlikely to harbor any Red List species (Seelen et al. 2021; Supplemental Material; 3.2.2.2; Table 4).

### *Recreation in and on quarry lakes*

Recreation on and in water requires visibility, low cyanotoxin (e.g., microcystin), no fecal contamination (e.g., low *Escherichia coli* and intestinal enterococci concentrations), and the absence of nuisance vegetation. Macrophytes were considered a nuisance for shallow recreation (swimming, kayaking, etc.) when <0.5 m of the water column was free of vegetation (Verhofstad and Bakker 2017). Maximum concentrations of microcystin for swimming have been determined to be 50 μg/L, preferably <10 μg/L, by the World Health Organization (WHO 2006). Maximum concentrations of other cyanotoxins have not been determined to date; therefore, we identified the thresholds for cyanotoxin to be equal to the maximum concentrations of microcystin as set by WHO (2006). *E. coli* and intestinal enterococci are human pathogens used as indices of fecal pollution in recreational water (EU 2006b, WHO 2006). The European Union has set a maximum amount of colony forming units (cfu) per 100 mL for both indicators, which if surpassed calls for a warning to be issued for recreationalists. For *E. coli* the maximum concentration is 1800 cfu/100 mL, whereas the maximum concentration of intestinal enterococci is 400 cfu/100 mL. Minimum transparency (Secchi depth) has been set at 1.5 m so swimmers are able to see their toes. For recreation purposes that require a larger vegetation-free water column (such as larger boats), the threshold value was set to 1 m of vegetation-free water needed to keep vegetation from becoming a nuisance (Verhofstad and Bakker 2017; 6.1.1.1). If the size of the littoral zone is <5 m (defined as the zone with an average depth of 1.5 m), nuisance caused by plants was considered negligible (Table 5).

## Abiotic provisioning services of water in quarry lakes

### *Drinking water, irrigation, and hydropower*

Suspended particles, *E. coli*, intestinal enterococci, and cyanotoxin (microcystin) concentrations could pose a risk in water to be used as drinking water. The concentrations of these pollutants should be below the threshold values outlined by the WHO and European Union (EU 1998, Falconer et al. 1999, WHO 2017; 4.2.1.1) at 1 NTU (turbidity as measure for suspended particles), 0 cfu/100 mL (*E. coli*), 0 cfu/100 mL (intestinal enterococci), and 1 μg/L (microcystin) respectively. Other nonbiological pollutants such as heavy metals, pesticides, or harmful disinfection byproducts should be removed in the production of drinking water as well; these guidelines are readily available via EU (1998) and WHO (2017) but were not specified in this study. Where these thresholds are exceeded, water industries must ensure that sufficient treatment is conducted to meet regulatory thresholds, a costly process that requires advanced removal techniques (Hijnen et al. 2006).

For water to be suitable for irrigation on crops intended for human consumption, the maximum cyanotoxin (microcystin) concentration is 20 μg/L (WHO recommendation; Falconer et al. 1999), whereas the maximum concentration of *E. coli* (as indicator for fecal contamination) is 1000 cfu/100 mL (WHO recommendation; Blumenthal et al. 2000; 4.2.1.2).

Hydropower requires a minimum amount of water to reach the lake. We assumed a stable water level is preferable and therefore calculated a minimum input of 3285 m$^3$/d to generate a maximum output of 25 kW, which is considered the smallest economically viable hydropower system (Renewables First 2019; 4.2.1.3; Table 6).

**Preliminary application of the ES framework using a restoration case study – Lake De Kuil, Netherlands**

Our before and after intervention comparison shows that controlling internal loading in De Kuil has increased the number of ecosystem services this quarry lake can suitably provide (Table 7). By reducing the nutrient (P) levels in the water column, the lake has become more suitable for recreation, as a habitat for rare species, and as irrigation water, but also for sport fishing for benthivorous fish. The increase in suitability for sport fishing is unexpected because decreasing the TP concentration in the lake will support a smaller benthivorous community (Yurk and Ney 1989). The increased benthivorous fish biomass could be due to stocking (although no evidence of this is known at the local water authority) or the increase in habitat because the hypolimnion is no longer oxygen depleted during stratification.

## Discussion

In this study we identified the potential ecosystem services a quarry lake can provide (Table 1) and identified the threshold values associated with the parameters determining whether a lake can provide that service (Tables 2–6). We showed the usefulness of this

**Table 7.** Overview of ecosystem services of Lake De Kuil in 2 time periods: 1992–2008 and 2009–2014, corresponding to before and after addressing internal P loading issues using a Flock & Lock method in 2009 (Waajen et al. 2016). DW = dry weight.

| CICES CODE | Ecosystem service | 1992–2008 | 2009–2014 |
|---|---|---|---|
| 1.1.4.1 | Professional fishing - fishponds | moderately suitable (10–100 kg/ha) | suitable (>100 kg/ha) |
| 1.1.5.1 | Edible plants (helophytes and macrophytes) | unsuitable (<50 g DW/m$^2$) | unsuitable (<50 g DW/m$^2$) |
| 1.1.5.2 | Common reed (*Phragmites australis*) production for roof thatching | unsuitable (<2500 g DW/m$^2$) | unsuitable (<2500 g DW/m$^2$) |
| 1.1.6.1 | Sport fishing for piscivorous fish species | suitable (fish biomass >0.7 kg/ha; width littoral zone <2 m; cover macrophytes unknown; plant nuisance >0.5 m) | suitable (fish biomass >0.7 kg/ha; width littoral zone <2 m; cover macrophytes unknown; plant nuisance >0.5 m) |
| | Sport fishing for benthivorous fish species | unsuitable (fish biomass <30 kg/ha; width helophyte zone <2 m; cover macrophytes unknown; plant nuisance >0.5 m) | moderately suitable (fish biomass 30–250 kg/ha; width helophyte zone <2 m; cover macrophytes unknown; plant nuisance >0.5 m) |
| 2.1.1.2 | Suspended solids (carbon) capture between macrophytes due to settlement (reduced water flow) | not assessed | not assessed |
| 2.2.2.3 | Maintenance of habitats for Water Framework Directive | not assessed | not assessed |
| 2.2.4.2 | Carbon, nutrient (P + N) burial in lake sediment | not assessed | not assessed |
| 2.2.5.1 | Reduction of nutrients (phosphorus and nitrogen) by littoral zone | not assessed | not assessed |
| 2.2.6.1 | Net carbon sink | not assessed | not assessed |
| 3.1.1.2 | Hikers | suitable (width helophyte zone 1–2 m; visibility <1.5 m) | suitable (width helophyte zone 1–2 m; visibility <1.5 m) |
| | Birders | unsuitable (fish biomass <67 kg/ha; >73 g/m$^2$ DW macrophyte biomass; visibility 1.5–5 m) | moderately suitable (fish biomass >67 kg/ha; >73 g/m$^2$ DW macrophyte biomass; visibility 1.5–5 m) |
| 3.1.2.1 | Environment in which scientific research can be done | suitable | suitable |
| 3.1.2.2 | Environmental education and citizen science | suitable | suitable |
| 3.2.2.2 | Habitat for rare species (Red List Species) | moderately suitable (total phosphorus concentration water column 35–100 µg/L) | suitable (total phosphorus concentration water column <35 µg/L) |
| 4.2.1.1 | Drinking water | unsuitable (microcystin concentration >1 µg/L; turbidity >1 NTU; *E. coli* >0 cfu/100 mL; intestinal enterococci >0 cfu/100 mL) | unsuitable (microcystin concentration >1 µg/L; turbidity >1 NTU; *E. coli* >0 cfu/100 mL; intestinal enterococci >0 cfu/100 mL) |
| 4.2.1.2 | Irrigation | unsuitable (microcystin concentration >20 µg/L; *E. coli* >1000 cfu/100 mL) | suitable (microcystin concentration <20 µg/L; *E. coli* <1000 cfu/100 mL) |
| 4.2.1.3 | Hydropower | unsuitable (inflow volume <3285 m$^3$/d) | unsuitable (inflow volume <3285 m$^3$/d) |
| 6.1.1.1 | Shallow recreation | moderately suitable (width littoral zone <5 m; macrophyte cover unknown; microcystin concentration 10–50 µg/L; *E. coli* <1800 cfu/100 mL; intestinal enterococci <400 cfu/100 mL; visibility >1.5 m; plant nuisance >0.5 m) | suitable (width littoral zone <5 m; microcystin concentration <10 µg/L; *E. coli* <1800 cfu/100 mL; intestinal enterococci <400 cfu/100 mL; visibility >1.5 m; plant nuisance >0.5 m) |
| | Deep recreation | moderately suitable (width littoral zone <5 m; microcystin concentration 10–50 µg/L; *E. coli* < 1800 cfu/100 mL; intestinal enterococci <400 cfu/100 ml; visibility >1.5 m; plant nuisance >1 m) | suitable (width littoral zone <5 m; microcystin concentration <10 µg/L; *E. coli* < 1800 cfu/100 mL; intestinal enterococci <400 cfu/100 mL; visibility >1.5 m; plant nuisance >0.5 m) |

approach by determining the ecosystem services that quarry lake De Kuil can provide, before and after application of a rehabilitation plan (Table 7). Additionally, the threshold values of a suite of water quality parameters per ecosystem service can be used to optimize the ecology of a lake to supply a distinct service or multiple services. Working toward a defined threshold involves creating the desired ecological quality or trophic state for a service to be optimally supplied.

### Which services can coexist, and which are mutually exclusive?

Quarry lakes can provide a suite of ecosystem services. Often, all these possible services cannot be provided simultaneously because the competing interests and potential conflicts of the demands cannot be fulfilled by the lake's finite resources (Barbier et al. 2008, Sharmina et al. 2016). For instance, in these relatively small lakes, nonconsumptive services such as recreation cannot coincide with consumptive uses such as aquaculture. Larger quarry lakes have the potential to supply more services as their size allows the optimization of various different, potentially conflicting, ecosystem services. Heterogeneity in space and time concerning the demand and supply of ecosystem services is possible but will especially be dependent on the nutrient status (i.e., trophic state of the lake).

Water managers can utilize the thresholds as management goals to determine which ecosystem services a system can readily supply, which services are within management reach, and which services are mutually exclusive. An example of services that at first glance are mutually exclusive but could coexist if the quarry lake is large enough is the maintenance of habitats for the WFD (2.2.2.3) and recreation (6.1.1.1.) The suitability of both services is based on the percentage cover by macrophytes in the potentially habitable area. Whereas the WFD would ideally require a cover of >60%, a cover >50% is considered a nuisance by sportfisherman, boaters, and swimmers (Supplemental Material; Verhofstad and Bakker 2017). However, large quarry lakes offer multiple spatially separated locations in which macrophyte cover can be manipulated, or differs naturally, to allow the coexistence of both services.

While most threshold values are not spatially explicit, the local or regional delivery and desire of services may be. Moreover, provisioning of services may be considered in a spatial context, with managers striving for combining services within lakes where possible but also striving for optimal regional service delivery. Our current framework is inherently scale-independent and may be applied within lake regions and also across lakes to make such management and planning decisions.

### Next steps for quarry lakes

Our framework helps identify the ecosystem services a quarry lake can provide and the ecological requirements of these quarry lakes needed to fulfil the ecosystem services demanded of these systems. This step is important because quarry lakes are unique systems in a landscape otherwise dominated by shallow waterbodies (delta areas) and diversify the services provided by freshwaters in a region. The resulting heterogeneity in the landscape aids the biodiversity of freshwater ecosystems under anthropogenic pressure. Compared to quarry lakes, the biodiversity of submerged macrophytes in shallow waterbodies contained more diverse macrophyte communities, but quarry lakes contained macrophyte species that were not found in the shallow waterbodies in the same region. Quarry lakes thus contributed significantly to the regional diversity via their local contribution to beta diversity (Legendre and De Cáceres 2013, Seelen et al. 2021). Comparing the diversity of ecosystem service delivery of quarry lakes to their surrounding waterbodies allows more informed water management decisions and policy (Seelen et al. 2021).

In this study we focused on the diversity of macrophytes as a proxy for a biodiverse quarry lake ecosystem, but including similar databases of algae, zooplankton, and (rare) fauna would be useful to further identify and specify specific thresholds for biodiversity in quarry lake systems. Results of quarry lake research can be found in general in "grey" literature such as conference proceedings or technical reports in (peer reviewed) mining industry journals. Currently, the much-needed scientific studies on (deep) quarry lakes ecology are missing, yet they remain essential to understanding these unique novel ecosystems and the ecosystem services they can provide (Blanchette and Lund 2016).

In densely populated (delta) areas such as the Netherlands, quarry lakes are often the primary freshwater ecosystem for human interaction, emphasizing the social aspect of ecosystem services demand. By recognizing quarry lakes as complex socioecological systems, with clear feedback loops between the ecosystem and the humans interacting with the ecosystem, managers could tailor their actions accordingly. More specifically, human perception and behavior should be considered when designing management plans for quarry lakes, but also the dependency of supply and demands of ecosystem services on the ecological functioning of a quarry lake. The ecological and social carrying capacity of a (quarry lake) ecosystem can vary and influence the need of water managers to intervene in ecosystem degradation. Unfortunately, the link between ecosystem service demand and ecological quality (or ecological state) is often not linear, or even positive, and can differ depending on user needs. For example, good water quality attracts recreationalists to enjoy the lake, but increased use of the lake (and its surroundings) leads to more nutrient input (e.g., sediment resuspension) and contaminates (e.g., dog, human or horse feces), which in turn reduce water quality and thus hamper recreational opportunities. This challenge complicates water management decisions as trade-offs can present themselves in choosing either ecosystem quality or prioritizing single ecosystem services, such as recreation. The ratio between supply and demand of ecosystem services, as well as spatial–temporal variation and their dynamics in a lake, should therefore be assessed and researched (Venohr et al. 2017). Only then is it possible to manage for optimal provisioning of ecosystem services as well as achieve a good quality ecological status. Thus, an integrated management approach among ecosystems, stakeholders, and water managers is needed in which continuous assessments, including feedbacks, are considered.

## From diagnosis to scenario analysis

We provided a semiquantitative way to assess which ecosystem services a quarry lake can provide (Tables 2–6). The information is intended to be an organic document that will be adjusted when new insights arise. Thresholds themselves, or the assumptions made to determine them, are subject to change as scientific research is conducted and/or management targets change. Some ecosystem services are yet to receive a threshold value (for instance carbon burial, although research is in progress; e.g., Anderson et al. 2019), and methods to assess them are bound to move forward from a more conceptual to an assessable value. Formalizing this approach into a computational model framework will improve useability and improve the possibility of linking to existing ecosystem models (e.g., Couture et al. 2018). To use the framework to not only retroactively diagnose the impact of ecological changes on ecosystem services, as shown here for lake De Kuil, but also to forecast future impacts on ecosystem services such linkage is imperative (Couture et al. 2018). In a changing world, where we are increasingly confronted with new and previously unknown pressures on lake ecosystems, quantifying impacts on lake ecosystems and the services they can provide is essential (Carpenter et al. 2009, Sanon et al. 2012, Janse et al. 2019).

Using our framework in the context of (future) scenario analysis requires linking it to the wide range of existing ecological models developed to assess water quality of lake ecosystems and understanding and predicting their response to various (environmental) cues. Lake ecosystems can be modeled with a wide range of mathematical complexity, from a few equations (e.g., Nürnberg 2004), to intermediate complexity with short run times (e.g., PCLake+; Janssen et al. 2019), to frameworks that allow a high level of detail and simulate complexity on a spatial scale (FABM: Bruggeman and Bolding 2014; Delft3D-WAQ/ECO: Los 2009). Models that include key lake food web components and ecological feedback mechanisms are suitable for determining lake ecological state and calculating the parameters used in Tables 2–6 (see Janssen et al. 2015 for an extensive review on a wide range of aquatic ecosystem models and their properties). To be useful for our application, these models will need to explicitly model at least the interplay between the littoral and (stratified) pelagic zone and the effect on key ecosystem properties. If applicable, these models may then also be used to improve the threshold values by running exploratory scenarios across environmentally relevant gradients where both ecological state as well as the associated services are assessed.

## From tables to computer model

To formalize our framework in a computational model we suggest coupling process-based models, as described earlier, to a Bayesian Belief Network (BBN; e.g., Barton 2006, Bagstad et al. 2013, Landuyt et al. 2013, Villa et al. 2014, Grizzetti et al. 2016, Couture et al. 2018), a multivariate statistical model that allows a probabilistic modeling approach. The network consists of multiple nodes connected to each other via statistical dependencies (i.e., cause–effect relations). Bayesian networks have the distinct capability to retain uncertainty throughout the network and are thus highly suitable to assess the capacity for providing an ecosystem service and ecosystem state with a measure of uncertainty (Varis and Kuikka 1999, Moe et al. 2016; Supplemental Fig. S1). When formalized in a BBN, integration between ecological outcomes and services becomes explicit and communicable to a wide audience. Both the temporal and spatial dimension of this approach is flexible. Process-based model scenarios may be generated on a daily basis, which could be useful in the context of assessing the risk on deterioration of bathing water quality under different scenarios such as heatwaves (e.g., Jöhnk et al. 2008), but also on decadal time spans to assess carbon sequestration potential (e.g., Tranvik et al. 2009). In addition, the output may be generated at different levels of spatial scales, much akin to multidimensional use of aquatic ecosystem models (e.g., Janssen et al. 2017, Bruce et al. 2018). Through the inherent flexibility of the coupling of a process-based model to a BBN, this approach is well suited to a wide range of management relevant questions ranging from efficacy of local restoration measures to impacts of large-scale changes in legislation.

### *Toward integrated assessment and prediction of ecology, water quality, and ecosystem services*

Assessing ecosystem services under varying levels of ecological quality is important to initiate action from legislators, managers, and communities. When valued services become endangered, they are likely to care more (Seelen et al. 2019), thereby promoting environmental stewardship to preserve or improve the ecological quality of the water system. However, environmental management is reliant on actions linked to ecosystem and human response, which comprises a complex network of environmental, economic, and social factors unique to each site. Conflicts should be expected between community groups that expect diverse services from the lakes. There is a need to consider net ecosystem gains using the approach outlined in this paper to aid managers in best meeting the needs of the community. This approach is scalable from a habitat to national scale.

## Conclusions

We identified a comprehensive list of ecosystem services that may be provided by quarry lakes. We proposed threshold values per ecosystem service to link ecosystem state indicators with ecosystem service provisioning. Management of quarry lakes is important to improve water quality, which can result in net ecosystem service gains. We demonstrated this ability through a restoration case study in Lake De Kuil, the Netherlands, where services such as professional fishing, sport fishing for benthivorous fish species, opportunities for birderwatchers, water quality for irrigation, and recreation opportunities in and on the water were improved following the control of internal P loading. Our current approach is semiquantitative. We envision extending this approach with process modeling and BBN to inform better management of these novel ecosystems to optimize net ecosystem service provision from habitat to national scales.

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