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NATURE-BASED SOLUTIONS FOR A CHANGING WORLD

Perspective

Enhancing ecological integrity while preserving ecosystem services: Constructing soft-sediment islands in a shallow lake

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Abstract

1. Ecosystems are increasingly managed to provide multiple benefits to humans, which often degrades their ecological integrity. This strongly applies to aquatic ecosystems, in which engineering can enhance flood protection, drinking water supply, fisheries and recreation. Although these activities typically increase ecosystem functionality to humans, they often impair key aspects of biodiversity and natural functioning.
2. Classical restoration of such degrading freshwater ecosystems can lead to societal opposition, if returning to a former ecosystem state affects previously acquired ecosystem services. Innovative nature-based solutions are therefore needed that enhance natural values in ecosystems, without affecting existing services.
3. We present a large-scale project aiming to increase the ecological integrity of a human-modified freshwater lake while maintaining its services to humans. The freshwater lake Markermeer in the Netherlands was formed by closing off an estuary for flood protection. The ecological integrity of this lake diminished over time, likely because a declining primary productivity impaired biodiversity at higher trophic levels. This decline is associated with a lack of gradual land–water transitions, strong resuspension of fine sediments, low nutrient availability and lack of dynamics typically to be expected in a natural temperate freshwater lake. Restoring the lake to its former marine state would conflict with current ecosystem services.
4. A nature-based solution was initiated in 2016, consisting of constructing a five-island archipelago from the lake's own soft-sediments called the 'Marker Wadden'. The project aims to increase the lake's primary production by creating gradual land–water transitions, more heterogeneity in water depths and decreasing turbidity by creating shelter and deep sinks reducing fine-sediment resuspension by the wind – thus introducing currently missing elements that are typical for natural lakes. We

present the underlying ecological framework and first scientific results of this innovative ongoing project.

5. Within 4 years, the Marker Wadden project shows how forward-looking sustainable development of lake ecosystems using a rewilding approach can enhance natural processes and attract birds and fish, without conflicting with existing ecosystem services. This inspires new directions for halting and reversing the degradation of other vital ecosystems worldwide.

KEYWORDS
ecosystem multifunctionality, forward-looking restoration, land–water connections, littoral zone, Marker Wadden, nature-based solution, novel ecosystems, rewilding

1 | INTRODUCTION

Human society strongly depends on vital functions and services of natural ecosystems (IPBES, 2019; Zedler & Kercher, 2005). These include food production, fisheries, recreation, drinking water supply, energy generation and carbon storage (Clarkson et al., 2013; Zedler & Kercher, 2005). Consequently, ecosystems do not only have intrinsic natural and cultural values but are increasingly requested to provide multiple functions simultaneously, including economic returns. This can lead to ecosystem degradation by overexploitation, pollution and habitat loss (Davidson, 2014; WWF, 2020). Many of the world's freshwater lakes, estuaries and wetlands have important functions for humans, but are also increasingly scarce, used and competed for (Reynaud & Lanzanova, 2017; Schallenberg et al., 2013). Worldwide, many aquatic ecosystems are influenced by engineering for a specific, single service (e.g. damming a river to generate hydropower) that can strongly impair its ecological integrity. Engineering often homogenizes abiotic and biotic conditions, inhibits natural dynamics such as water-level fluctuations and leads to reductions in biodiversity, trophic complexity and functional diversity at each trophic level (Gibbs, 2000; Millennium Ecosystem Assessment, 2005). Consequently, many aquatic ecosystems are currently in need of sustainable nature development strategies, because their ecological integrity has eroded as a result of a wide range of simultaneous demands and associated modifications (Davidson, 2014).

Classical ecological restoration of freshwater ecosystems, which to a large degree has focused on returning degraded ecosystems to their pre-human-use conditions, is often challenging (Higgs et al., 2014; Higgs et al., 2018). Worldwide, many lakes are modified for flood protection, drinking water reservoirs or to fulfil new, desired, ecosystem functions such as energy generation or recreation (Reynaud & Lanzanova, 2017; Schallenberg et al., 2013). With classical restoration, where past modifications are undone, at least some of these new ecosystem functions to humans are unavoidably lost (Higgs et al., 2014). Furthermore, classical restoration projects that affect (part of) these desired functions mostly face complicated, long-term negotiations (Perring et al., 2015; Suding et al., 2015) – including about what should be the historical reference state of the ecosystem to return to (Higgs et al., 2014). To overcome such challenges, novel strategies for degrading ecosystems are needed that enhance their ecological integrity, while preserving their ecosystem services and socio-economic benefits (Corlett, 2016; Gulati et al., 2008; Higgs et al., 2014; Higgs et al., 2018; Martin, 2017).

Here we present a forward-looking approach to enhance the ecological integrity of the shallow lake Markermeer in the centre of the Netherlands, which is – like many freshwater lakes in the world – a human-created lake (Hogeboom et al., 2018). The large lake Markermeer was formed by the construction of two dikes and multiple land reclamations in a marine estuary, named the Zuiderzee (Figure 1a and 1b). First, a 32-km long dike (named the Afsluitdijk) was completed in 1932, which turned the main tidal estuary of the river IJssel into a 357,000-ha freshwater lake over time. The new lake IJsselmeer, still fed with fresh water by the river IJssel, experienced a drastic change in salinity, food web composition and hydrology (Cremer et al., 2009). Second, land reclamation occurred in 1942 (60,000 ha) and between 1955 and 1968 (114,000 ha). Third, a 27-km long dike (named the Houtribdijk) was completed in 1975 and divided lake IJsselmeer into two lakes: a new almost land-locked lake Markermeer (70,000 ha) in the southwest with limited riverine input (river Eem, discharge of 10 $m^3\ s^{-1}$), and the drainage lake IJsselmeer (113,000 ha) in the northeast still fed by the river IJssel (discharge of 340 $m^3\ s^{-1}$; Figure 1b; Vijverberg et al., 2011; terminology sensu Heino et al., 2021). Both lakes developed distinct ecological values and started to provide many ecosystem services to humans, including recreation, drinking water supply, fishing and water supply for agriculture (Gulati & van Donk, 2002). However, the engineering activities did not automatically introduce elements such as gradual land–water transitions, heterogeneity in water depths or water-level dynamics into these lakes that one would expect in well-functioning large lowland freshwater lakes formed by natural processes (Schindler & Scheuerell, 2002).

Both lakes initially developed towards important ecosystems for piscivorous and benthic feeding waterbirds. Benthivorous waterbirds like the common pochard *Aythya ferina*, tufted duck *A. fuligula* and greater scaup *A. marila* profited from establishing populations of the non-native freshwater mussels zebra mussel *Dreissena polymorpha* and quagga mussel *D. rostriformis*. Piscivorous waterbirds like the great

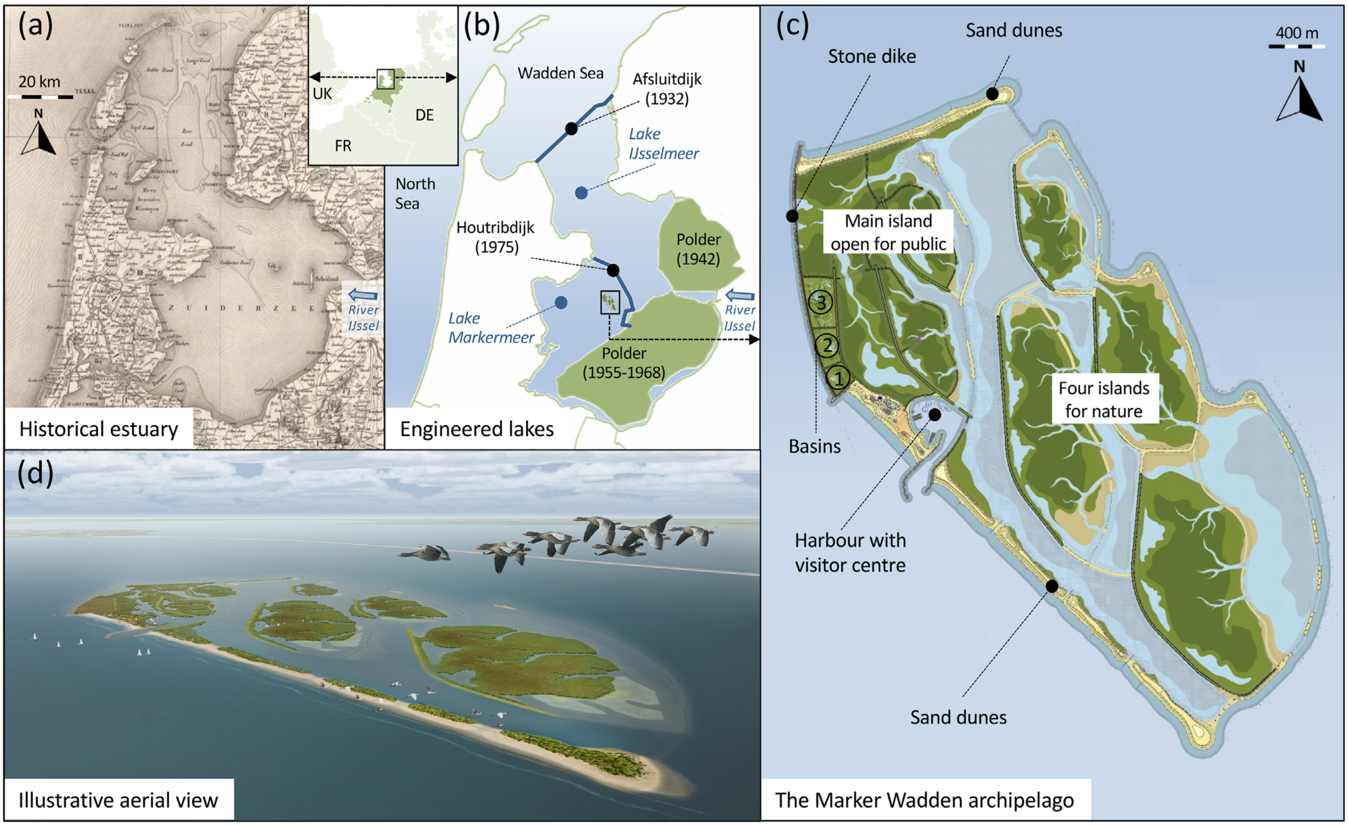

FIGURE 1 Overview of the location and structure of the Marker Wadden project. (a) The central marine estuary in the Netherlands in 1850 with its main inflow from the river IJssel. (b) After a series of catastrophic floods in the late nineteenth and early twentieth centuries, several dikes were built to prevent flooding. The estuary was closed by a 32-km long dike (Afsluitdijk) in 1932, followed by several phases of land reclamation (polders), and finally the construction of a 27-km dike (Houtribdijk) in 1975. This created the 70,000-ha freshwater lake Markermeer in the southwest with limited riverine input and the 113,000-ha lake IJsselmeer in the northeast still fed by the river IJssel. (c) To enhance the ecological integrity of lake Markermeer without the loss of existing ecosystem services, from 2016 to 2020 the soft-sediment islands of the 'Marker Wadden' were built close to the Houtribdijk. Five islands were constructed – on the leeward side of stone dikes and sand dunes – by creating ring dikes from local deep Pleistocene sands (extracted from between 8 and 35 m deep in the lake's sediment) that were subsequently mostly filled with fine clays and silts from the top 5–8 m of the lake's sediment. In 2017, a harbour was constructed with stone dikes, and in 2018 a long-stretching sand dike was built in a southwest direction. This allowed the creation of more islands in the sheltered areas in subsequent years via sand dikes filled with fine clays and silts. Subsidence of the clays and silts to just below the water-level resulted in marshlands with water levels <1 m, which were reconnected to the lake water in late 2020. Only the main island is accessible to visitors via a small harbour with a visitor centre. (d) The Marker Wadden is illustrated as an aerial view. Image credits: (a) Kadaster, Apeldoorn, the Netherlands; (c) Boskalis, Capelle aan de IJssel, the Netherlands; (d) Bureau Vista, Amsterdam, the Netherlands

crested grebe *Podiceps cristatus*, smew *Mergellus albellus* and common merganser *Mergus merganser* started thriving on a rich stock of fish such as smelt *Osmerus eperlanus* as food source (Noordhuis, 2014). However, over the last decades, the ecological integrity of particularly lake Markermeer has been strongly declining (Lammens et al., 2008; Noordhuis, 2014). Compared to the 1980s, numbers of many benthivorous and piscivorous bird species have halved, coinciding with a decrease of the smelt population to one-tenth of its biomass (de Graaf & Keller, 2010; Noordhuis, 2014). These decreases in the higher trophic levels of the food web were likely caused by multiple coinciding factors, including an increase in turbidity and a decrease in primary productivity (Noordhuis, 2014; van der Velde et al., 2010; van Riel et al., 2019). This declining ecological integrity resulted in a long-standing societal wish for a nature-based solution to this problem, that is, a solution addressing the societal challenge by working with and enhancing nature (Seddon et al., 2020). The goal was to improve the lake's ecological integrity by adding the structure and dynamics that are more typical for a natural freshwater lake at low altitudes (Heino et al., 2021), but without compromising the many ecosystem services it currently provides (Lammens et al., 2008).

Classical restoration of lake Markermeer is ecologically impossible, because the historical reference of the lake is marine, and after damming, the freshwater lake developed into a different ecosystem that has no true historical reference condition. Furthermore, classical restoration by, for example, removing the dikes is socio-economically undesired due to the current economic and societal functions (flood protection, freshwater storage, water recreation, freshwater fisheries) (Gulati & van Donk, 2002). Therefore, the Dutch Society for Nature Conservation ('Natuurmonumenten'), in cooperation with provincial and national authorities, proposed an innovative large-scale nature-based solution. It follows a rewilding approach by restoring natural processes as much as possible, whereas it uses engineering to achieve this. This approach encompasses the building of a 700-ha archipelago consisting of five islands in the lake – named 'Marker Wadden' – between 2016 and 2020. Here we present the concept and first results of the Marker Wadden project, an ambitious, large-scale project in the Netherlands aimed at improving the ecological integrity of lake Markermeer while maintaining the lake's current ecosystem functions and services.

2 | THE MARKER WADDEN PROJECT

To reverse the decline of lake Markermeer's ecological integrity, the Marker Wadden project aims to enhance the food web bottom-up via nature-based solutions. The project, therefore, targets three factors that are currently missing in comparison to more natural lakes and are thought to limit primary production (Figure 2). First, historically the marine estuary was a highly productive, nutrient-rich coastal system due to marine and riverine inputs (Figure 2a). Nutrient levels that sustain primary production are currently low in the water column of the freshwater lake, due to closing off most marine and riverine inputs and retention of available nutrients in the iron-rich sediment. Second, the sediment of lake Markermeer consists of Pleistocene sands covered with a 5–8-m layer of Holocene clays, silts and fine sands (Troelstra et al., 2018), in turn covered with a layer of floating mud (Figure 2b). This 0.1–0.2 m upper layer of floating mud consists of a fine fraction with a maximum settling velocity < 0.01 mm s^{-1} and a slightly coarser fraction with a settling velocity between 0.5 and 4.0 mm s^{-1}, that is easily resuspended at wind speeds over 4 m s^{-1} (Vijverberg *et al.*, 2011). While the floating mud was historically able to sink towards deeper areas of the larger estuary, the enclosed shallow water in lake Markermeer with a >25-km wind fetch length now suffers from continuous resuspension of this fine material (Figure 2b). Lake Markermeer essentially became similar to a land-locked shallow lake with a long fetch length (Figures 1a and 1b), leading to suspended sediment concentrations of easily 50 mg L^{-1} near the surface – increasing to well over 100 mg L^{-1} in case of very strong winds (van Kessel et al., 2008; Vijverberg et al., 2011). Fine sediment resuspension reduces light availability for primary production in the water column and may hamper zooplankton feeding, thereby limiting the trophic transfer efficiency of phytoplankton to higher trophic levels (e.g. de Lucas Pardo et al., 2015; G.-Tóth et al., 2011; Penning et al., 2013). Third, basalt and asphalt dikes form homogeneous steep, hard shorelines – and the water level is stable, managed, and reversed (maximum variation 0.5–1.0 m, high in summer and low in winter). This offers limited space for ecological processes relying on land–water transitions and the littoral zone – such as reproduction by fish, nutrient cycling and the influx of carbon from terrestrial sources (Benson & Magnuson, 1992; McGoff et al., 2013).

The Marker Wadden project aims to mitigate the negative effects of these aforementioned factors by constructing an archipelago of islands that add land–water connections, shelter, shallow and deeper waters to the lake (Figures 1 and 2c). These constructions aim to add previously missing habitat types and dynamics more typical of lowland natural freshwater lakes (Heino et al., 2021; Schindler & Scheuerell, 2002) to this human-created lake. The construction of the archipelago started in 2016 by building stone dikes and sand dunes on the windward side (west) to provide shelter for subsequent constructions. On the leeward side of these strong structures, islands were constructed from the sediment of lake Markermeer itself. These islands were constructed as ring dikes made of deeper Pleistocene sands, extracted from the lake bottom at depths ranging between 8 and over 35 m deep. The areas within these ring dikes were subsequently predominantly filled – to levels above lake water level – with the fine clays and silts from the top 5–8 m of the lake bottom (Troelstra et al., 2018). Subsidence of the clays and silts to below the lake's water level (Temmink et al., 2021) resulted in marshlands with shallow water levels (<1 m), which were partly reconnected to the lake water at the end of 2020. The constructed islands add natural shorelines with gradual land–water transitions and waters between ~0.5 and 2 m deep to the lake, plus multiple sand excavations areas of over 35 m deep with their possible distinct own value (Figure 2c). The construction procedure itself removed fine sediments from the lake, and the sheltered waters between the islands were expected to further stimulate the settling of suspended sediments.

The construction of the islands also created a series of land–water connections, which would be typical for more natural freshwater lakes but were previously lacking in lake Markermeer. These land–water connections were hypothesized to stimulate primary production by increasing runoff of nutrients from land to water. The shallow waters that develop between the islands would be more productive due to higher nutrient availability, quick warming in spring, and shelter from the wind, which reduces resuspension of the fine clays and silts. Hence, primary production was thought to increase, as this is no longer hampered by nutrients and light limitation (Schallenberg et al., 2013). The establishment of submerged macrophyte- and shoreline-vegetation could further help in trapping suspended solids (Barko & James, 1998). These processes combined were hypothesized to positively affect the lake's food web via stimulation of primary production, providing habitat structure and increasing the efficiency of energy transfer to higher trophic levels – leading to higher functional diversity at all levels of the food web. The vision behind Marker Wadden is that it could induce highly productive conditions providing foraging and spawning and breeding habitat for higher trophic levels such as fish and waterbirds.

The Marker Wadden project also aimed to enhance the recreational function of the lake. The largest of the five newly constructed islands was therefore made accessible to the general public, whereas the other islands remain closed for the public (Natuurmonumenten, 2013). On the largest island, the Dutch Society for Nature Conservation constructed a small settlement (Figure 1c). This has been built off-grid using exclusively sustainable materials and includes a small harbour, five holiday houses and a visitor centre. Moreover, they constructed a group accommodation and a field station for educational and research purposes, run a ferry to enable recreationists to visit the island, offer guided tours, and educate about nature. This is combined with dedicated regular communication about the project and the involvement of volunteers during all aspects of the project to ensure societal acceptance. The project therefore deliberately integrates

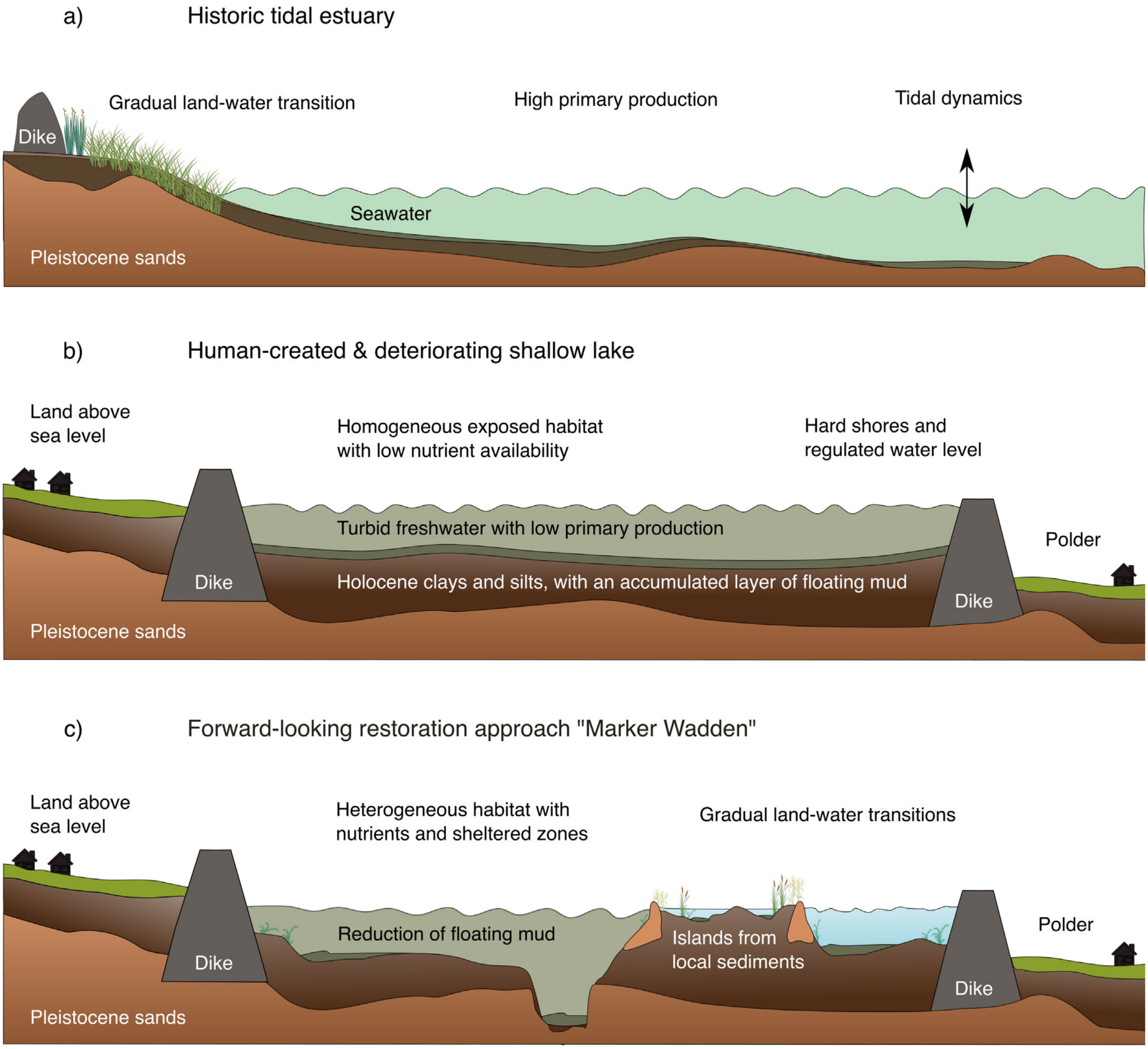

FIGURE 2 Schematic overview of the changes in the study area over the last century. (a) Before the 1930s, a highly productive tidal estuary was present with gradual land–water transitions. (b) In the twentieth century, basalt dike constructions created the homogeneous shallow freshwater lake Markermeer with stabilized water levels, which trapped high amounts of fine sediments (called 'floating mud') and lead to high turbidity. A littoral zone was absent, and primary production decreased. (c) Between 2016 and 2020, the Marker Wadden archipelago was constructed to add more heterogeneous habitat to the freshwater lake. The islands include soft shores with gradual land–water transitions that provide nutrients for primary production and create sheltered areas where turbidity decreases due to a reduction of resuspension and accumulation of easily resuspended sediments in deeper areas

recreation, nature education, innovation and research (Natuurmonumenten, 2013).

3 | FIRST OBSERVATIONS ON ECOLOGICAL INTEGRITY

Our first observations on ecological implications of the Marker Wadden project – even though it is still under development – suggest that nature is able to quickly profit from the newly created habitats (for a timeline, see Figure 3). The expected effects of the islands on primary production via reduction of suspended sediment concentrations followed by an increase in light levels in the water column have proven difficult to assess at this early phase of the project, in part because the building activities initially created sediment resuspension themselves. However, the construction of the archipelago included the creation of three basins of each 3–4 ha at an early building phase (late 2016; Figure 1c). Each basin was a part of the lake that became surrounded by

dikes – sheltering the water and separating it from the rest of the lake – but otherwise leaving it identical to the open lake water.

As a proof of concept of how shelter can affect the aquatic food web, we surveyed the development of these basins three years after their construction (on the 24 May 2019) by comparing the sheltered basins to three locations in the open water close to the basins just off Marker Wadden. At three locations in the open water and in each of the basins, we examined the aquatic food web by assessing (1) total chlorophyll-a concentrations in fresh water samples using a PHYTO-PAM phytoplankton analyser (Heinz Walz 91090 GmbH, Effeltrich, Germany), with the sum of the blue, green and brown channels as an indication of total phytoplankton concentrations (μg L^{-1}); (2) zooplankton densities by concentrating 30 L of water through a 80-μm zooplankton net into a 50-mL tube and fixating it with lugol's iodine, followed by counting zooplankton under a LEICA M125C stereo microscope; (3) macrophyte presence by dragging a 30-cm wide rake four times across 1 m of sediment, washing and drying the collected material at 60°C for 48 h, and weighing the dried material to the nearest 0.1 g; (4) sampling benthic macrofauna by grabbing a 15 × 15 cm sediment sample from the top 10-cm of the lake bottom, and estimating their dry weight based on identifications to species level and their known length-biomass relationships.

The sheltered conditions affected the food webs in the three basins within 3 years. Basin 1 moved towards a more phytoplankton-dominated state, with a zooplankton community consisting mostly of Copepoda and high densities of Annelida in the sediment (Figure 4). Basins 2 and 3 moved towards much clearer conditions (Figure 4b), with lower phytoplankton concentrations but large Cladocera visible by the naked eye (Figure 4d). In these two basins, three macrophyte species developed (Figure 4f), and macrofauna became dominated by Arthropoda and Mollusca instead of Annelida – including Chironomid larvae, freshwater snails and locally high densities of opossum shrimps *Neomysis* sp. (Figure 4h). Although each basin developed differently, these early observations suggest that merely creating shelter in lake Markermeer has the potential to affect multiple trophic levels and their relations in the food web within 3 years. The observation that macrophytes can colonize the sheltered areas among the islands was confirmed in a larger-scale macrophyte survey on the Marker Wadden in 2020. Underwater vegetation was mapped in the shallow waters

FIGURE 3 Timeline of the construction of the islands showing their rapid development in aerial and corresponding ground pictures from selected representative locations for the different years since 2015. The first sand ring dikes appeared above the water level in the spring of 2016, followed by filling with clays and silts and quickly expanding in surface area in 2017. In 2018, pioneering vegetation such as marsh fleawort*Tephroseris palustris* appeared, which expanded in 2019 to a surface cover of the islands of >25% by species such as willows, marsh fleawort and broadleaf cattail *T. latifolia* (Van der Winden, 2019). In 2020, ring dikes were opened, the meanwhile vegetated marshlands were reconnected to the open water and helophytes further developed on the land–water transitions. Aerial views were obtained from Satellietdataportaal (2021); ground pictures by the authors

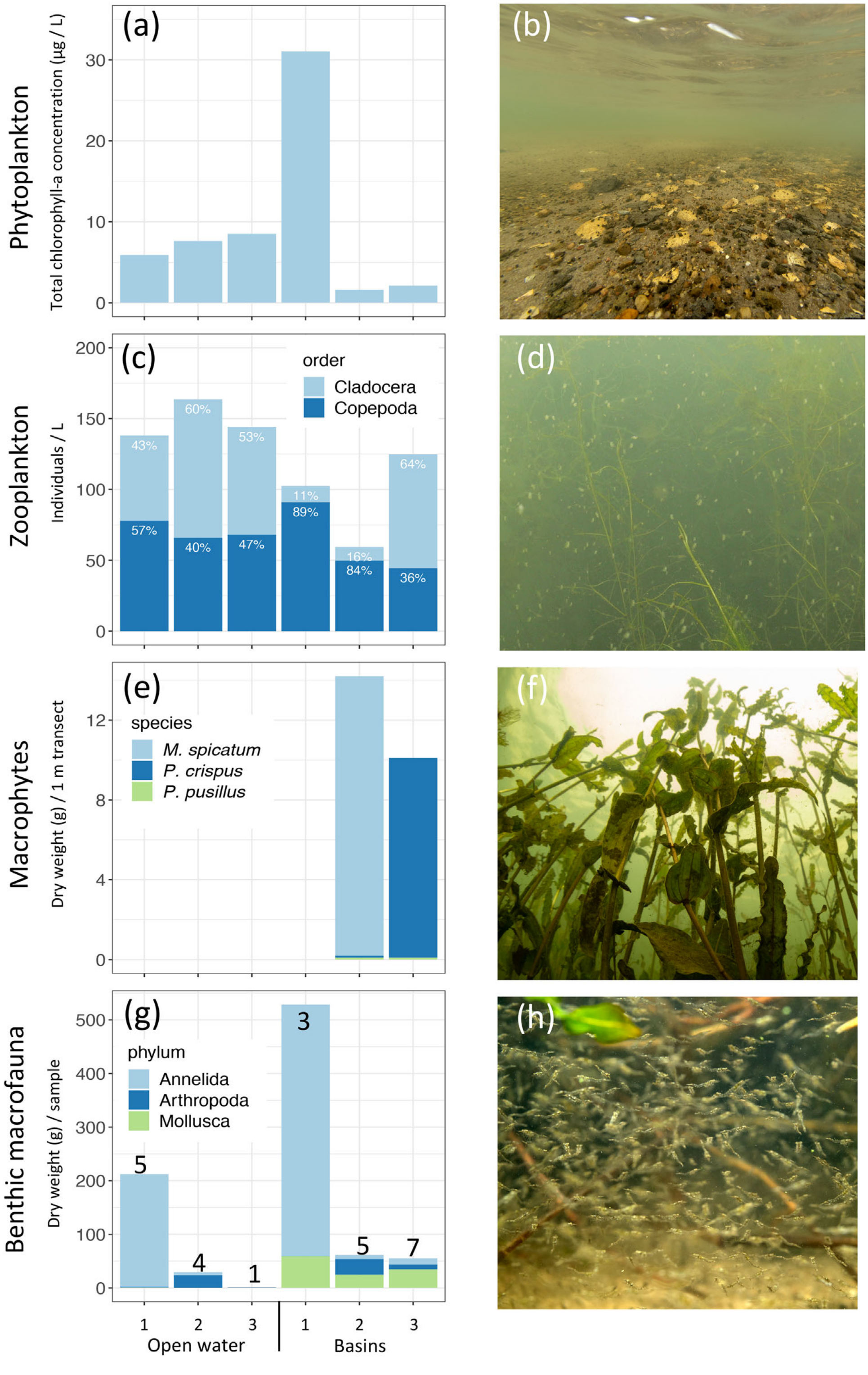

FIGURE 4 Observed status of different trophic levels in the open water and their developments in the three sheltered basins after three years. (a, b) Phytoplankton (indicated by total chlorophyll-a concentrations) increased strongly in basin 1 but decreased in basins 2 and 3 where the water became clearer. (c, d) Zooplankton communities in the open water consisted of similar numbers of Copepoda and Cladocera, but relative densities of both orders started to shift in the basins – leading to high densities of large zooplankton in basins 2 and 3. (e, f) Macrophytes developed under the clear conditions of basins 2 and 3, including *Myriophyllum spicatum, Potamogeton crispus and Potamogeton pusillus*. (g) Macrofauna became more diverse in basins 2 and 3 with a shift towards more Arthropoda (including Chironomid larvae, opossum shrimps *Neomysis* sp.) and Mollusca (including the New Zealand mud snail *Potamopyrgus antipodarum* and European stream valvata *Valvata piscinalis*) and fewer Annelida (dominated by Tubificidae). The numbers above the columns in panel g indicate total species numbers. (h) Macrofauna in the basins included locally high densities of opossum shrimps. Photo credits: Arthur de Bruin

between the islands, which revealed the presence of low densities of eight submerged macrophytes and four Charophyte species. Dominant species were sago pondweed *Potamogeton pectinatus*, horned pondweed *Zannichellia palustris*, common stonewort *Chara vulgaris* and starry stonewort *Nitellopsis obtuse* (Scirpus Ecologisch Advies, 2020). Before the project started, these species rarely occurred in the eastern part of the lake (Vonk et al., 2019), likely because the fine clay soil type combined with strong winds made this part of the lake less suitable for macrophyte establishment (Van Zuidam & Peeters, 2015).

In the marshlands, vegetation developed on the land–water transition zones within one growing season. In the first year, marsh fleawort *Tephroseris palustris* was the most dominant species, probably because it is a wind-dispersed, early pioneering plant that can easily establish in shallow water. Willows *Salix* sp. colonized and dominated the drier marshland zones. The aim of the project was to develop helophyte marshes rather than wet forests. Therefore, willows were actively removed and their germination prevented by water management until 2020, and rhizomes of common reed *Phragmites australis* and broadleaf cattail *Typha latifolia* were actively sown and protected against herbivores – as grazing pressure in aquatic systems can be high (Bakker et al., 2016). Protection against avian herbivores (notably greylag geese *Anser anser*) at the establishment phase of the vegetation resulted in the rapid development of helophyte vegetation at the land–water transition zones (de Rijk & Dulfer, 2020).

Surveys of higher trophic levels included assessments on what the new habitat could offer to fishes and birds. Fish were surveyed in 2018 and 2019, finding 19 different species – and including high larval densities in several of the new shallow habitat types. Dominant native species are common roach *Rutilus rutilus*, European perch *Perca fluviatilis* and Eurasian ruffe *Gymnocephalus cernua*, but also four typically pioneering non-native Gobidae can be found (Emmerik, 2018, 2019). Numerous bird species use the islands, which are extensively monitored. Over 20,000 sand martins *Riparia riparia*, 3000 northern shovelers *Spatula clypeata*, 1000 pied avocets *Recurvirostra avosetta*, 1000 black terns *Chlidonias niger* and hundreds of little gulls *Hydrocoloeus minutus* colonized the islands within 3 years. For northern shovelers, black terns and common terns *Sterna hirundo* the islands harboured, respectively, > 6%, 2% and 2% of the flyway population at a given moment in 2019 (Van der Winden, 2019). For common ringed plover *Charadrius hiaticula* and common terns, more than 10% of the national population was attracted to the new habitat. Many of the observed bird species had been present in much lower numbers and/or did not breed in such numbers for decades in the Netherlands. Rarer species such as greater flamingos *Phoenicopterus roseus* and Eurasian spoonbills *Platalea leucorodia* were also encountered, and nests were found of gull-billed terns *Gelochelidon nilotica* and long-tailed ducks *Clangula hyemalis* – two bird species that had not been breeding in the Netherlands for decades.

Overall, functional diversity seems to locally increase in many trophic layers and a shift may be on its way from a simplistic food web to a structurally more complex food web. This allows more coexistence of different trophic levels in the food web under the wider range of abiotic conditions. Natural processes are quickly taking advantage of the increased heterogeneity, land–water transitions and gradual shorelines typical of more natural temperate freshwater lakes. Even though the former estuarine conditions in this ecosystem did not return, the ecosystem seems to be developing towards higher ecological integrity that might increase resilience to future perturbations (Carpenter & Cottingham, 1997; Scheffer et al., 2001). Whether or not the Marker Wadden project is sufficient to change the downward trend in the lake, completely remains to be determined.

4 | THE FUTURE OF NATURE DEVELOPMENT

The twenty-first century requires nature-based solutions and thus new views on nature, sustainability, resilience, ecological restoration, rewilding and other forms of nature development. Initiatives for improving the ecological integrity of many human-impacted areas are often slowed down or stopped by societal resistance to give up existing benefits derived from ecosystems, or by a lack of vision on how a system should be developed. Here, we present a new perspective on nature development and rewilding ecosystems, in a situation where a return to a former ecosystem state was impossible due to the lack of historic reference, and strong societal adherence to existing (novel) benefits.

In the first 4 years since the start of the Marker Wadden project, the trends are positive. There are no signs that important functions of the lake such as flood protection, freshwater storage or fisheries are negatively affected. With respect to recreation, the largest of the islands was opened for the general public in September 2018 – and welcomed over 20 000 visitors, 180 recreational charter vessels and 2 000 recreational ships for an overnight stay in the harbour in the year 2019 (Natuurmonumenten, 2019). In 2019, the islands featured over 150 times in the regional and national news, which increased to over 250 times in 2020. It is too early to assess how the project likely affects the many ecosystem services that the lake currently provides, but the first observations and responses from society are very positive.

The concept of a forward-looking approach to enhancing ecological integrity that we outline here can hopefully inspire other scientists and practitioners to design and initiate innovative solutions that do not collide with ecosystem multifunctionality. The Marker Wadden is designed with a dual function, aiming to facilitate human activities as well as increase ecological integrity and natural values of a degrading ecosystem. Although illustrated with an aquatic case study, this new way of thinking may pave ways to enhance natural values in many types of human-made systems and counteract the loss of vital ecosystems globally. If given a chance, nature has great capacity to maintain ecological integrity while providing ecosystem functions to human societies.

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CONFLICT OF INTEREST

The co-authors RP and AB work for the non-profit nature conservation organization that has been responsible for building the Marker Wadden (Natuurmonumenten). We declare no conflicts of interest.

AUTHORS' CONTRIBUTIONS

LB, HO and CL initiated the writing and HJ and AB contributed the data. After discussions with all authors about the concept design and interpretation, CL and RT wrote the first draft of the manuscript. All authors subsequently contributed to writing the final paper.

DATA AVAILABILITY STATEMENT

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