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RESEARCH ARTICLE

Mass development of aquatic plants: Effects of contrasting management scenarios on a suite of ecosystem services

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Abstract

1. Dense beds of aquatic plants are often perceived as nuisance and therefore mechanically removed, often at substantial cost. Such removal, however, may affect a range of ecosystem functions and consequently also the ecosystem services that benefit society.
2. We studied five cases: River Otra (Norway), River Spree (Germany), Lake Kemnade (Germany), Lake Grand-Lieu (France) and Hartbeespoort Dam (South Africa). In all, nuisance aquatic plant growth is managed, but dominant species, geographic setting and major societal uses are different. We quantified 12 final ecosystem services as flows per area and year in biophysical and monetary terms. Quantified services were food and fodder production, commercial fisheries, hunting and gathering wild products, hydropower production, drinking and irrigation water production, flood prevention, carbon sequestration, active and passive recreation and biodiversity conservation (nonuse).
3. These services were related to aquatic plant cover via a range of ecosystem functions, and the effects were estimated of three plant removal regimes on the relative importance of the quantified ecosystem services and on the total sum of the monetary estimates (total economic value, TEV). The three removal regimes were 'maximum removal', 'current practice' and 'do nothing'.
4. In all five cases, TEV was dominated by different forms of recreation. TEV was highest for Lake Kemnade, where visitor densities were highest. TEV was most sensitive to the different management regimes in Lake Kemnade, because a threshold in aesthetic appreciation was passed in the 'do-nothing' regime, and in

Hartbeespoort Dam, because of the effect on boating and angling. In the other cases, the different removal regimes had little effect on the estimated TEV.

5. *Synthesis and applications*. Since recreation dominated the estimated societal benefits in the studied ecosystems, also where provision of hydropower, drinking water or irrigation water were relevant, effects on recreation should be a core consideration in the management of nuisance aquatic plants. Furthermore, aquatic plant management strategies will benefit from taking into account the differences in perceived nuisance among different categories of recreative users before engaging in costly removal.

KEYWORDS

aquatic macrophytes, ecosystem functions, integrated weed management, introduced invasive plants, keystone species, mass development

1 | INTRODUCTION

Native as well as introduced aquatic plants can develop very dense stands that are perceived as nuisance and obstruct different uses of water bodies in their landscapes. This may range from recreative swimming, angling and boating (Verhofstad & Bakker, 2019), having access to schools or markets (Honla, Segbefia, Appiah, & Mensah, 2019; Honla, Segbefia, Appiah, Mensah, & Atakora, 2019) to flooding of adjacent land (Boerema et al., 2014; Vereecken et al., 2006), clogging of a hydropower plant intake (Dugdale et al., 2013) and irrigation channels (Armellina et al., 1996) or hindering commercial transport (Güereña et al., 2015). Experienced nuisance has led to a range of control and removal measures, including the use of herbicides, the release of herbivorous grass-carp (*Ctenopharyngodon idella*) or host-specific herbivorous insects, sediment coverage with plastic and mechanical harvesting, which is currently the main approach worldwide (Hill & Coetzee, 2017; Hussner et al., 2017; Pieterse & Murphy, 1990; Thiemer et al., 2021). However, aquatic vegetation contributes important ecological functions (Carpenter & Lodge, 1986; Kuiper et al., 2017), and these can be linked directly or indirectly to a range of ecosystem services that are beneficial to society (Boerema et al., 2014; Janssen et al., 2021). Thus, radical removal of aquatic vegetation may have unforeseen negative consequences when such services are reduced or no longer provided. However, the strength of the functional relations between vegetation and ecosystem services is not necessarily generalizable across ecosystems (Carpenter & Lodge, 1986; Hilt et al., 2017; Rasmussen et al., 2021). For example, some species are more efficient in nutrient uptake than others (Denny, 1972) and some species are more readily eaten by herbivores than others (Bakker et al., 2016). Existing literature suggests different optimal plant cover for different ecosystem functions. Grimm (1990) suggested 25%–60% for a well-developed shallow lake fish community with pike. Verschoren et al. (2017) reported that 50%–60% optimizes the balance between drainage capacity (high with low vegetation) and groundwater infiltration, nutrient and particle retention in lowland streams (low with low vegetation, see also Kleeberg et al., 2010). Shoreline protection from wave erosion is highest behind dense stands (Vermaat et al., 2000), and phytoplankton abundance can be reduced by variably extensive plant stands depending on the prevailing mechanism (3%–100% cover, Hilt & Gross, 2008).

People's perception of aquatic plant nuisance likely is context-specific, depending among others on the predominant use of a water body (Verhofstad & Bakker, 2019), and on cultural aspects. Here, we use the definition 'experienced nuisance' to cover the subjective nature of this nuisance (e.g. Gifford et al., 2011). The importance of context for both the ecosystem and the perception of nuisance among residents and visitors justifies a comparative approach of specific case studies that share perceived nuisance but differ in other ways. Verhofstad and Bakker (2019) reviewed the literature on perceived nuisance by submerged vegetation in shallow lakes and concluded that no simple threshold can be derived but both water depth above the plant canopy and cover should be included. Verhofstad and Bakker (2019) also suggest that a cover between 25% and 75% would be optimal for a diverse fish community and for clear water, which they interpret as ecosystem services.

In this study, we linked the most important ecological functions of aquatic vegetation to *final* ecosystem services that are of benefit to humans. We use the concept of 'final services' from Boyd and Banzhaf (2007) as it is helpfully consistent and prevents double counting (e.g. Fu et al., 2011). We did so in five different case studies where mass development of aquatic plants is considered a nuisance and is managed. We systematically used the Mononen cascade framework (Immerzeel et al., 2021; Mononen et al., 2016; Vermaat et al., 2020, 2021), which allows for a standardized comparison among cases and management measures using monetary value estimates. While our comparisons use monetary value estimates, we do not intend to imply that these can be directly transferable into market values. Instead, we see this valuation step as comparable to a simplified weighing as in multicriteria analysis (cf. Wittmer et al., 2006), which can be used in communication with policymakers and the public at large (Bouma & Van Beukering, 2015; Hauck et al., 2013; Hermelingmeier & Nicholas, 2017).

Our objective was to assess whether different plant removal regimes would affect the relative importance of different ecosystem services and their summed total economic value estimate (TEV). We hypothesize that moderate plant removal would lead to intermediate cover and would maximize the sum and diversity of all quantified ecosystem services.

2 | MATERIALS AND METHODS

2.1 | Study sites

The five study sites were selected based on reported major aquatic plant nuisance problems (Table 1; Misteli et al., 2023; Thiemer et al., 2023). We included rivers and lakes that contrast in plant growth form and have different predominant types of use and geographic setting. One of the sites is a nature reserve (Lake Grand-Lieu) with restricted access in the core area, whereas access is free in all other sites (Table 1; see also Thiemer et al., 2023). The difference in prevailing plant growth form (submerged, emergent and free-floating, Table 1) among the different study sites, can have an impact on the final ecosystem services provided. For example, submerged plants do not transpire and as such do not contribute to water loss from evapotranspiration, whereas floating and emergent plants do (Table 1; Figure 1).

At each site, the vegetation reached the water surface, at least during the main growing season. Therefore, there was no need to take the depth of free water above the plant canopy into account, and we could use cover instead of the percentage plant volume inhabited (PVI; Engloner, 2015) as argued by Verhofstad and Bakker (2019). Current removal practices at the study sites clear submerged and emergent vegetation to a substantial depth below the surface.

2.2 | Modelled common management regimes

For comparability, we used three common management regimes in our assessments. In recognition of the local situation, we attempted to cover a wide span while remaining not too far from economic and realistic feasibility, based on information from local water management. We therefore chose the following three management regimes: 'do nothing', 'current' and 'maximum feasible removal'. Current cover was obtained from the fieldwork done within the framework of the MadMacs project (Table 2, see also Harpenslager et al., 2022; Misteli et al., 2023; Thiemer et al., 2023). Vegetation cover for the 'do-nothing' and 'maximum feasible removal' regime was deduced after discussions with local water managers, specifically for each case study site (Table 2).

TABLE 1 Description of the study sites (adopted from Thiemer, 2022).

Site (country), coordinates (lat/long)[a]	Area, annual mean discharge	Important current forms of use	Nutrient status	Nuisance species	Mean plant biomass (g DW m^{-2})
River Otra at Rysstad (Norway) 59.088/−7.550	69 $m^3 s^{-1}$ upstream of the study reach 11 km length and 210 ha	Hydropower, recreation	Oligotrophic	Submerged, native *Juncus bulbosus* (bulbous rush) canopy often reaching the water surface	148 ± 35
River Spree from Grosse Tränke to Lake Dämeritz (Germany) 52.430/−13.678	14 $m^3 s^{-1}$ for a reach of 34 km length and an area, including floodplain of 2050 ha	Recreation, agriculture in the floodplain	Eutrophic	Submerged and emergent, native *Sagittaria sagittifolia* (arrowhead)	335 ± 61
Lake Kemnade (Germany) 51.416/−7.260	125 ha, created in the valley of the river Ruhr	Recreation, hydropower, drinking water, flood regulation	Eutrophic	Submerged, introduced *Elodea nuttallii* (*Nuttall's waterweed*) canopy reaching the water surface	421 ± 180
Lake Grand-Lieu (France) 47.133/−1.674	Seasonal variation with summer drawdown, 3500–6300 ha; summer level open water 2700 ha and wet pastures 2400 ha	Strict nature reserve, professional fishermen; recreation and agriculture along its banks	Eutrophic	Emergent and amphibious, introduced *Ludwigia grandiflora* and *L. peploides* (water primrose)	183 ± 85
Lake Hartbeespoort Dam (Republic of South Africa) −25.749/−27.833	Reservoir, 1850 ha	Irrigation, drinking water, recreation	Hypertrophic	Free-floating, introduced *Pontederia crassipes* (water hyacinth)	972 ± 137

[a]Negative latitudes are S of the equator, negative longitudes are E of Greenwich.

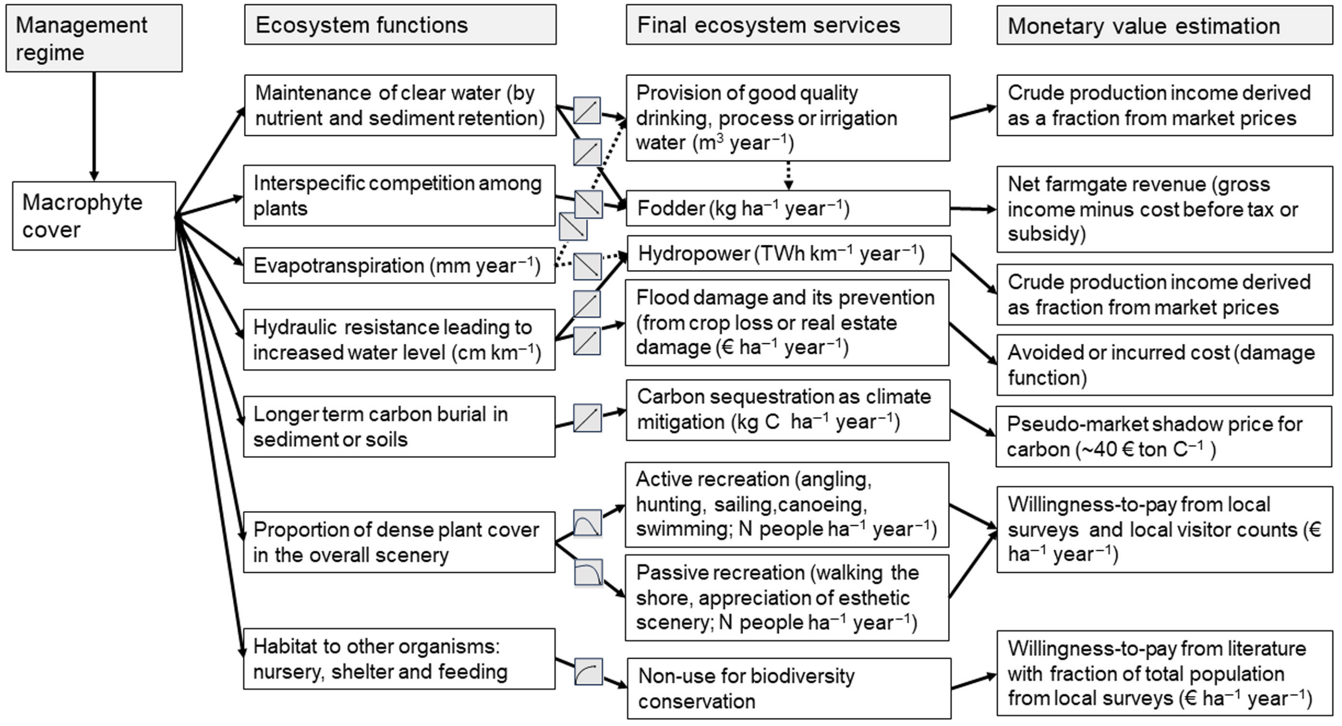

FIGURE 1 Flow scheme relating plant management regimes via macrophyte cover and ecosystem functions to final ecosystem services in biophysical terms and monetary values. For clarity, only those functions and services are depicted that are common to several cases. For each case, we started from a larger number of functions and services in an extensive spreadsheet table (see Table S1). Broken arrows indicate that the relation is potentially important in some of the cases (see also Table 3). Icons at the links between function and service qualitatively indicate the form of the relationship.

TABLE 2 Estimated percentage mean vegetation cover at (or near) the water surface for the three management regimes and five case study sites.

Site	Do nothing	Current	Maximum removal	Source of information
River Otra	65	64	35	MadMacs fieldwork[a]
River Spree	60	40	10	MadMacs fieldwork
Lake Kemnade	90	44	0	Podraza et al. (2008), MadMacs fieldwork
Lake Grand-Lieu (In water + on shore)[b]	4 + 6	3 + 5	0 + 0	SNPN (2017), Baldo (2020), MadMacs fieldwork
Lake Hartbeespoort Dam	50	40	10	Mitchell and Crawford (2016), MadMacs fieldwork

[a]S. Schneider compiled fieldwork cover data and estimated cover values for the three regimes and a conversion of the five-point cover scale in the surveys to per cent cover in an unpublished report.

[b]In Grand-Lieu, the *Ludwigia* species expanded along the shoreline and covered parts of both nearshore water as well as wet pastures.

2.3 | Ecosystem services framework

We deployed the Mononen cascade (Immerzeel et al., 2021; Mononen et al., 2016; Vermaat et al., 2020, 2021) to relate plant cover to a range of final services via the effect on ecosystem functions (i.e. intermediate services; Boyd & Banzhaf, 2007). We first compiled a matrix of potential functions and final services and deduced the relations between these based on literature (Table S1). For each case, we selected the functions and final services from this matrix that would be relevant and then compiled peer-reviewed and grey literature as well as locally available information from websites and communication with local authorities, angling and boating entrepreneurs and clubs, in order to quantify both functions and services (see Figure 1; Table 3). Table 3 stipulates our approach to estimating each service and gives the sources of information used.

Our workflow from plant cover via function to services can be explained best with an example for which we take hydraulic resistance and flooding in the river Spree: We derived from literature the effect of the area with dense water plant cover in the river Spree on increased water level upstream and on raised groundwater level in the adjacent floodplain wetlands and pastures (Lewandowski et al., 2009; Köhler, unpublished). We then assessed the negative effect on the productivity of the meadows and the positive effect on red-listed plant species in the wetland reserves. We base the former on median productivity statistics from the federal state of Brandenburg (LELF, 2020: a net farmgate revenue

TABLE 3 Final ecosystem services quantified in the five case studies, including their links to ecosystem functions. The Common International Classification of Ecosystem Services (CICES) code is conformed by Haines-Young and Potschin (2017), a benchmark classification of ecosystem services. The second column indicates for which site the service is first potentially relevant and then following ':' whether it also has an actual value and a monetary estimate (G, Grand-Lieu; H, Hartbeespoort Dam; K, Kemnade; O, Otra; S, Spree). Columns 3 to 5 indicate the workflow with the relation to an ecosystem function, the biophysical units of the final ecosystem service and the valuation approach.

Final service (CICES code)	Potentially relevant: monetary valued[a]	Relation to ecosystem function	Quantification of the final service in biophysical terms	Monetary valuation approach	Source of information
Fodder (1.1.1.1)	S, G: S, G	G: Flooding of floodplain, competition by invasive weeds; S: raised groundwater table reducing agricultural productivity	Reduction in yield or area accessible for cattle grazing	Net farmgate revenue	Farm yield statistics: Landesamt etc. (2020, S) and Agreste (2019, G). Flooded area G: SNPN (2017); floodplains S from thematic map with 'gesicherte ueberschwemmungsgebiete' on the geodata service of the federal state Brandenburg (https://apw.brandenburg.de), with area estimated using Google Earth (S)
Compost (~1.1.1.1)	H, S: H	Harvested plant material	Biomass is collected and processed into compost for gardening; at S the material is included in the municipal composting system and becomes negligible in mass so cannot be valued; at H a company generates a product	Comparable to crude net farmgate revenue as 10% of reported consumer price	H: About 2% of the standing stock of water hyacinth reportedly has been harvested as part of the Metsi a Me project (Mitchell & Crawford, 2016), see also the compost company website: www.hyamatlaorganics.co.za
Professional fisheries (~1.1.3.1)	G: not measurable	Increased plant growth may impede boating and gear	Change in quantity of fish landed	Crude revenue estimate as 50% of consumer price	Baldo (2020): no measurable effect on fish yield in Lake Grand-Lieu
Drinking water (4.2.1.1)	O, S, K, H: H	Maintenance of clear water (CICES 2.2.5.1) by nutrient or suspended sediment retention	Effect on drinking water production	Crude estimate of production costs as 50% of consumer price	Local drinking water companies; no effect of more or less nuisance plants estimated for O (extraction from river occurs but negligible), S (bank infiltration is only 9% of annual river flow), K (flow too high for the plants to have any effect); H: water hyacinth cover prevents toxic cyanobacterial blooms hence this service is valued as 'less toxic algae' from the prevented cost of extra treatment using a conservative half the price from Dore et al. (2013)

(Continues)

TABLE 3 (Continued)

Final service (CICES code)	Potentially relevant: monetary valued[a]	Relation to ecosystem function	Quantification of the final service in biophysical terms	Monetary valuation approach	Source of information
Irrigation water for crops (4.2.1.2)	H: H	Maintenance of clear water (CICES 2.2.5.1) by nutrient or suspended sediment retention; possibly evapotranspiration losses	Effect on total volume of irrigation water available of sufficient quality: more or less water hyacinth compared with current will lead to less or more transpiration, corrected for differences in evaporation from the free water surface	Estimate of irrigation water price to farmer: 0.26 rand or 0.02 €m^{-3}; reduction to 50% of consumer price not implemented	Fraser et al. (2016)
Hydropower (4.2.1.3)	O, H: none	Sufficient (geomorphological) gradient	O: Dislodged and decaying plant material clogs the downstream water intake at Hekni, this material is regularly removed	O: the removal occurs at negligible cost, the detritus is deposed of on-site	H: no longer used for hydropower (Ashton et al., 1985) O: personal observation
Flood prevention (2.2.1.3)	S: S	Hydraulic resistance of dense beds increases water level upstream	Increased water level affects groundwater level in the floodplains; dense nuisance plants may increase ponding and flood risk; affects crop yield or domestic infrastructure	S: Damage effects on net farmgate revenue; domestic infrastructure via a damage function	S: As in Vermaat et al. (2021), based on De Moel and Aerts (2011); estimation of raised groundwater from Lewandowski et al. (2009) and Köhler (unpublished)
Erosion prevention (2.2.1.1)	S: none	Dense plant beds may protect the physical shore from potentially eroding wave exposure	Length of shoreline retreating, possibly leading to land loss	Investment in bank protection, vale of lost land	Has been suggested for the Spree but has not been quantified, Köhler (pers. comm.)
Carbon sequestration for greenhouse gas mitigation (2.2.6.1)	All: all	Part of the plant biomass produced is buried in the sediment and will be subject to slow decay and longer-term storage	Decaying biomass stored in the sediment	From the shadow market, a carbon price of 40 € ton C^{-1} is taken	This conservative estimate is the lower quartile of the range observed in the European Emission Trading System (20–100) from 2020 to 2022, and it is in range with the estimates of the global social cost of carbon for 5 SSP scenarios in Tol (2019)
Active Recreation (boating, angling, swimming; 3.1.1)	All (no swimming in K)	Dense plant beds physically impede activities	Preference curves of perceived impediment versus plant cover	Appreciation combined with travel cost and a proportion of the population—case-specific	Derived from survey data (Figure 4, Thiemer et al., 2023); mean travel distance for nonresidents (Table 4) multiplied by a conservative low-end travel cost from Juutinen et al. (2022) of 0.05–0.22 €km^{-1} depending on local fuel price; for residents using a low-end short trip cost from Juutinen et al. (2022) of 5 € and a case-specific variable number of trips

TABLE 3 (Continued)

Final service (CICES code)	Potentially relevant: monetary valued[a]	Relation to ecosystem function	Quantification of the final service in biophysical terms	Monetary valuation approach	Source of information
Active recreation (continued)	O, S: O, S	Maintenance of clear water (CICES 2.2.5.1) by nutrient or suspended sediment retention	Effect on recreative appreciation from preference curves	Water requires sufficient clarity for bathing; incorporated into recreative appreciation	Derived from survey data, as the previous
Passive (beach) recreation, appreciation of scenery (3.1.2)	All		Preference curve of perceived impediment versus plant cover	Appreciation combined with conservative travel cost estimate and a proportion of the population engaged—case-specific	Derived from survey data, as the previous.
Biodiversity nonuse (3.2)	All		Preference curve	Appreciation combined with willingness to pay for nonuse and a proportion of the population—case-specific	Fraction of population derived from survey data in Thiemer et al. (2023); willingness to pay for biodiversity nonuse from Garcia et al. (2011) for France, Boesch et al. (2018) for Germany and Norway, and Turpie et al. (2017) for South Africa

[a]G, Lake Grand-Lieu; H, Hartbeespoort Dam; K, Lake Kemnade; O, River Otra; S, River Spree.

for fodder of 380 ha^{-1} year^{-1}) and assume that a current average growing season groundwater level at 40 cm is suboptimal (70%), whereas 'maximum removal' will lead to a decline in groundwater level to 70 cm and improve productivity to 100% and 'do nothing' would raise groundwater to 20 cm and reduce productivity to 50%. These numbers were multiplied with the area of agricultural land and then normalized to the total study area. Conversely, based on Runhaar et al. (1997), sensitive wetland angiosperms can be assumed to require spring groundwater levels near 25 cm; hence, the current 40 cm can be assumed to allow survival but may lead to some decline, whereas 70 cm would likely lead to extinction and 20 cm would allow expansion of these wetland species. The effect of groundwater level on red-listed wetland species is linked to the cultural service 'biodiversity nonuse' which we take to reflect the value attached to nature conservation with a multiplier based on the above argumentation: 90% for current, 100% for 'do nothing' and 10% for 'maximum removal'. Similar causality arguments have been constructed for all services included.

After compilation, the values used were quality-checked by all co-authors, including those that had case-study-specific experience. An overview flow diagram was created for each site that allows plant cover to be varied resulting in biophysical and monetary value estimates of each final service, including the summed TEV (Figure S1 gives the overview flow diagram from the spreadsheet for the river Spree as an example).

We used data from extensive questionnaires carried out for the MadMacs project (for detailed description of the questionnaires and their collection see Thiemer et al., 2023) at each site to estimate the values of cultural services (cf. Immerzeel et al., 2021, 2022). The on-site collection of the printed surveys was done in accordance with the COVID-19 restrictions prevalent at the given time for each site. Our surveys were anonymous and complied with the data protection and privacy rules in the given country. Respondents were approached face-to-face in the field or did actively fill out the online survey, so they were well-informed and consented in their participation. We refer to Thiemer et al. (2023) for further information and a complete survey text as Supporting Information. For the current study, we used the questions where respondents were asked: (i) to indicate at what level out of five they perceive the plants to be a nuisance, (ii) whether they consider themselves resident or nonresident, (iii) to distribute 100 points over several services to indicate their priorities (swimming, boating, angling, awareness and appreciation of biodiversity conservation, aesthetic appreciation of the scenic landscape) and (iv) the distance travelled for visiting the study area (one-way from residence to study site, km). The number of respondents varied between sites and so did their travel distance (Table 4); note that not all respondents filled out all questions completely, so different questions may have different numbers of respondents. Before inclusion in the final data sets, individual survey responses were screened for inconsistencies, outliers or apparent protest answers in, for example reported days spent, age and types of activity and only included those that also filled out the questions on willingness to pay for removal—survey data that are not used in the current study. Differences in distribution patterns of perceived nuisance

TABLE 4 Number of resident and nonresident respondents that completed the survey for the questions analysed here. We also include an estimate of travel distance (km, one-way, mean ± standard error).

Site	N residents	N visitors	N total	Travel distance residents	Travel distance visitors
River Otra	62	83	145	6.9 ± 3.5	176.0 ± 19.3
River Spree	134	77	211	4.0 ± 1.8	44.1 ± 10.1
Lake Kemnade	149	174	323	8.4 ± 0.5	23.8 ± 2.1
Lake Grand-Lieu	177	129	306	5.5 ± 0.8	75.8 ± 7.6
Lake Hartbeespoort Dam	210	65	275	9.4 ± 1.2	72.0 ± 21.0

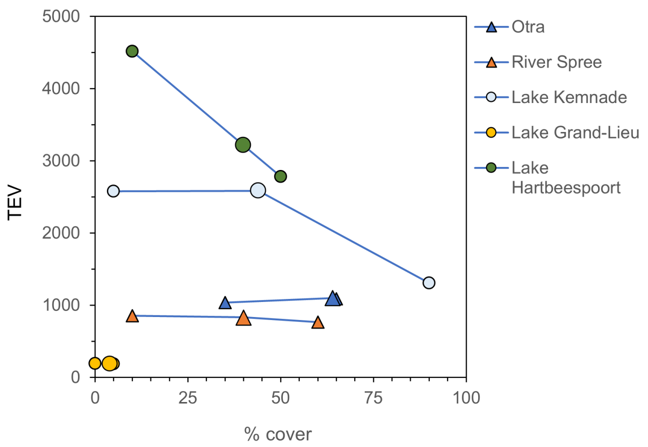

FIGURE 2 Effect of modelled plant management regime (left-to-right: maximum feasible removal, current and do nothing; the 'current' symbol is plotted larger) via percentage aquatic plant cover on the sum of ecosystem services provided (TEV, €ha^{-1}year^{-1}) in the five study sites. In Lake Grand-Lieu, the non-native *Ludwigia* spec. covers a limited area of the total lake. TEV, total economic value.

among visitors and residents were compared with χ^2 tests, and the frequency distributions were used to construct preference curves. Travel distance was used for a monetary estimate of active and passive recreation (Table 3). We interpret the former as any interactive activity in the area, for example including bird watching, and the latter as an appreciation of the location and just being there, based on the CICES (Common International Classification of Ecosystem Services) classification of Haines-Young and Potschin (2017).

3 | RESULTS

In three out of the five investigated case studies, we found that major changes in aquatic plant cover had little or no effect on the summed monetary value estimate of all quantified final ecosystem services (i.e. TEV, Figure 2). For both the Spree and the Otra, this involved a considerable span in cover (10%–60% in the Otra, Table 2; Figure 2), hence also in effort of plant removal. In Lake Kemnade, the major increase in plant cover in the 'do-nothing' regime had a negative effect on TEV. This was mainly in the aesthetic appreciation (Figure 3) of the place by people engaged in different forms of recreation on the banks of the lake, like walking and picknicking. In Hartbeespoort Dam, however, both the increase and the reduction in water hyacinth (*Pontederia crassipes*) cover affected TEV: More plants decreased and less plants increased the monetary value estimate, particularly for boating and angling (Figure 3). None of the five case studies showed a clear optimum in TEV at intermediate plant cover; hence, our tentative hypothesis is not supported.

Whereas different forms of recreation (i.e. cultural services) generally dominated TEV in all five case studies, their relative importance was different (Figure 3). Only in the Spree and Lake Grand-Lieu, the provisioning service 'fodder' to grazing cattle in the floodplain or wet meadows contributed substantially to the total (respectively, 19% and 24%) under the 'current' plant removal regime. The Spree and Hartbeespoort Dam had the highest diversity in services provided (both eight services, Figure 3): a.o. fodder, C-sequestration, boating, appreciation of aesthetic scenery and biodiversity nonuse. In Hartbeespoort Dam, reduced water hyacinth cover led to an increased incidence of cyanobacteria (Harpenslager et al., 2022). We estimated that this would increase the cost of drinking water production and hence can be interpreted as a disservice, but this decrease was far less than the increased benefit due to boating and angling. Our analysis captured very few trade-offs among different services. The only apparent one was a trade-off in the Spree between the provision of fodder (higher at low aquatic plant density and more rapid drainage with lower water levels) versus the biodiversity value due to increased survival probability of red-listed wetland plant species (higher with high plant density and raising river water levels with increased impoundment; Figure 3). The strict nature reserve of Lake Grand-Lieu had the lowest TEV. This is very likely due to the limited access, although the marginal zone attracts recreation, also from the nearby city Nantes. The nearby Atlantic coast likely offers attractive alternative recreation destinations.

From the survey, we could derive which plant cover was perceived as a threshold for being a nuisance, as the pattern was quite explicit in all cases except Lake Grand-Lieu (Figure 4). Often, but not always this threshold differed among categories of users and between residents and visitors (Figure 4). First, residents perceived

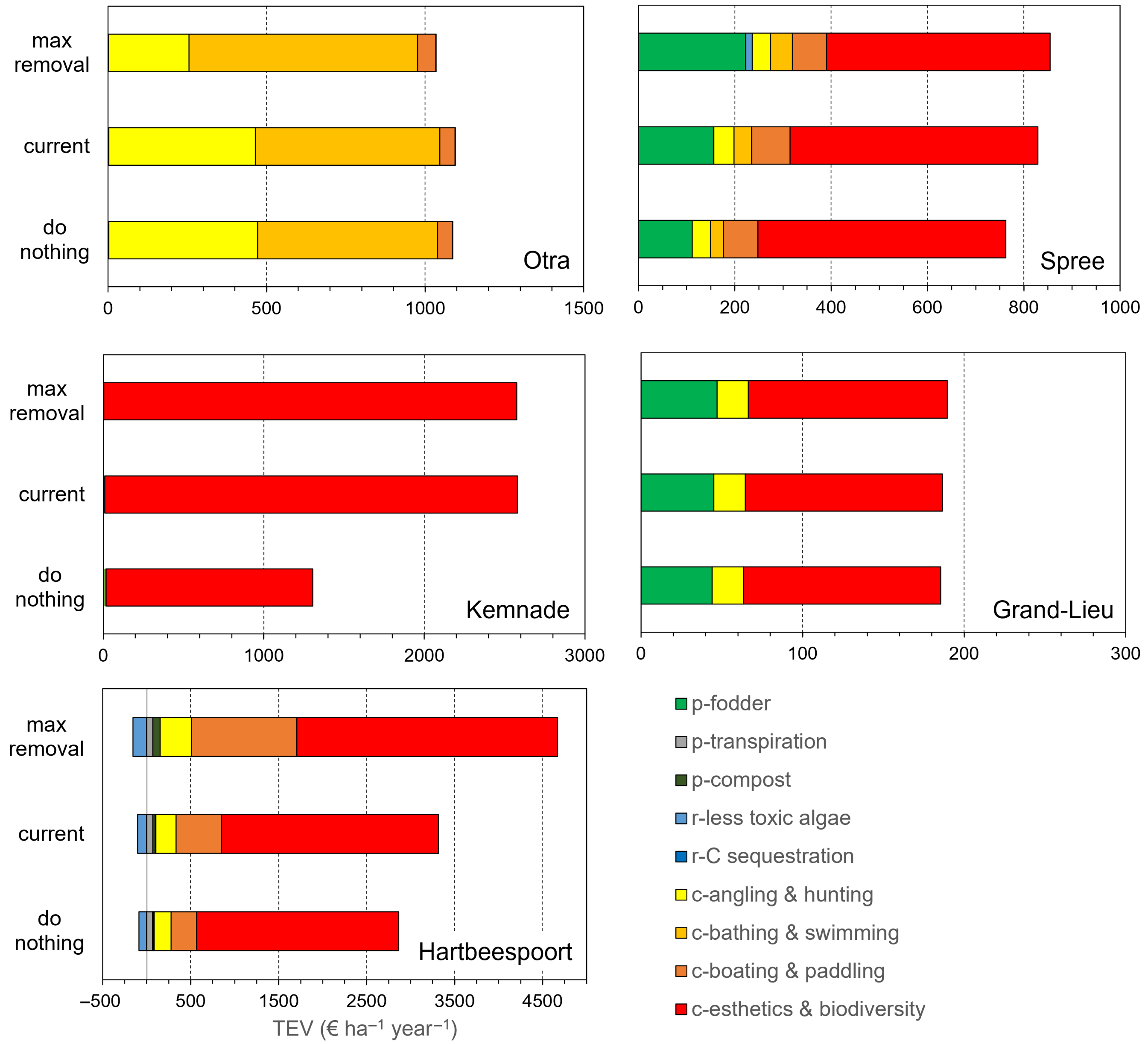

FIGURE 3 Effect of management regime (do-nothing, current and maximum removal) via aquatic plant cover on the monetary value estimate (€ ha^{-1} $year^{-1}$) of different services that add up to total economic value (TEV). Service sequence is the same in all sites, but some services are negligible or absent in some study sites (absent: fodder in O, K, H; less toxic algae in O, K, G; bathing in K; transpiration and compost only present in H). The suffix 'p-', 'r-'and 'c-'denote that this is a provisioning, regulating or cultural service, respectively. Distribution of values over the different services was significantly different ($p(\chi^2) < 0.001$) among the three management regimes in all cases but Grand-Lieu.

a nuisance at lower levels than current and at lower levels than visitors in the Otra, the Spree and likely Hartbeespoort Dam ($p < 0.10$ only). Second, only in the Otra a substantially higher proportion of the visitors found the plants no problem or concluded that 'they did not know'. At Lake Grand-Lieu, significantly more residents than visitors found that dense stands of invasive *Ludwigia* were no problem. Here, it was those that appreciate the scenery who also found 'the weeds no problem', whereas those interested in biodiversity were already concerned at a low plant cover, likely because the invasive character of *Ludwigia* is well known (Figure 4). Only in the Otra and Hartbeespoort Dam, few recreative users answered that weeds are no problem, whereas in the two German cases (River Spree, Lake Kemnade) a large proportion of those respondents that appreciated biodiversity also found the presence of aquatic plants no problem. We used the patterns in perceived nuisance to construct threshold knowledge rules that estimate the monetary value of the different forms of recreation, including biodiversity nonuse (cf. Table 3; Figure 3).

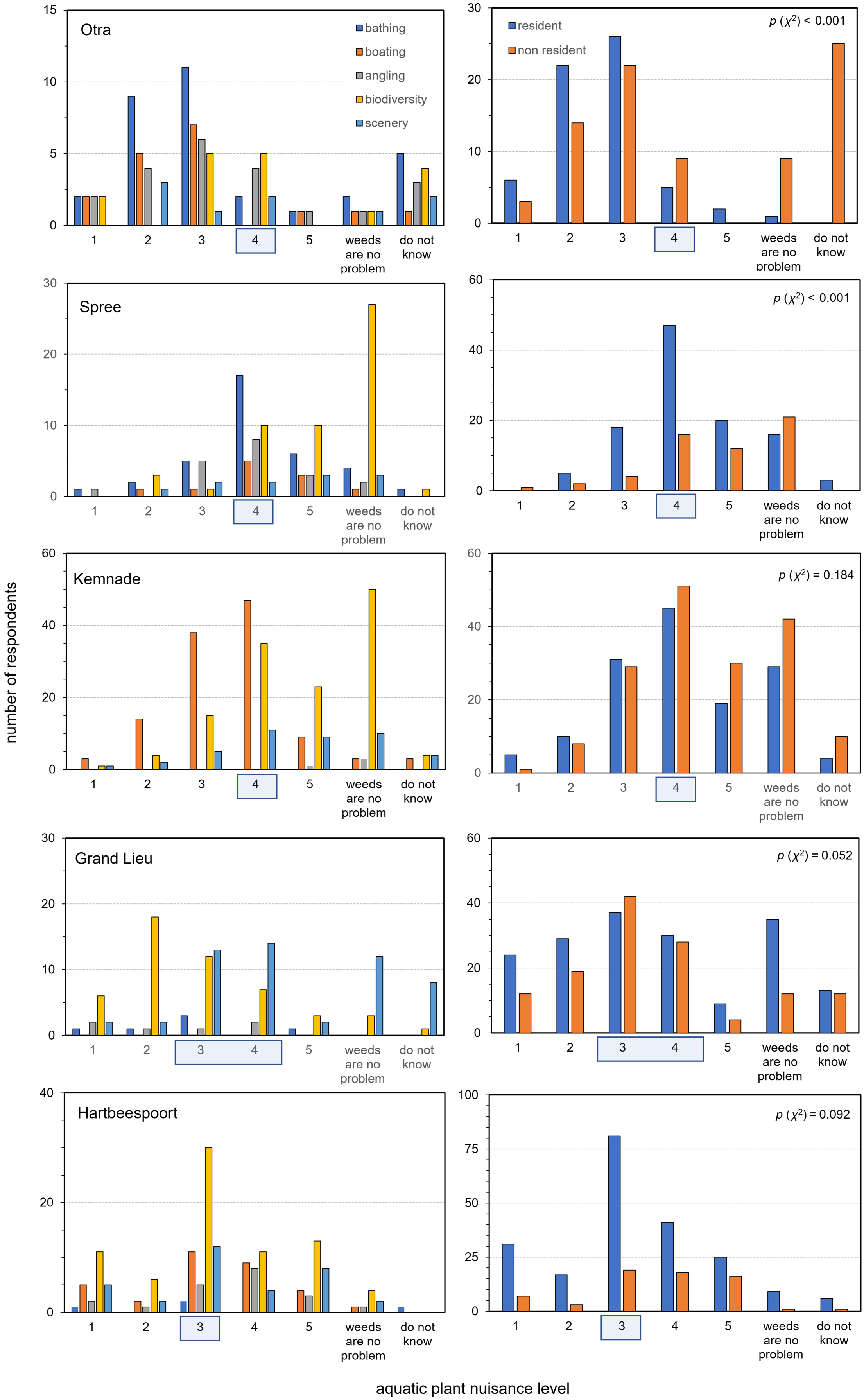
Otra
bathing
boating
angling
biodiversity
scenery
resident
non resident
p (χ2) < 0.001
Spree
p (χ2) < 0.001
Kemnade
p (χ2) = 0.184
Grand Lieu
p (χ2) = 0.052
Hartbeespoort
p (χ2) = 0.092
1
2
3
4
5
weeds are no problem
do not know
number of respondents
aquatic plant nuisance level

FIGURE 4 Left: Aquatic plant density at which different groups of survey respondents report they experience nuisance. Presented are absolute numbers of respondents, not percentages, so the length of the vertical axis differs among graphs. A respondent was selected to belong to a group when she/he allocated 50 or more of the available 100 points to this final service. Right: the same, but for the two categories resident and nonresident. Here, a χ^2 test was done to assess whether the distribution differed between residents and visitors, and the resulting level of significance is indicated in the top right corner. Respondents could select five different levels of plant cover, ranging from 0% to 100% of the water surface covered. Raw data were processed envisaging a respondent moving up from low to high cover and deciding on the threshold where nuisance is experienced. Current aquatic plant cover is indicated with the blue frame on the horizontal axis.

4 | DISCUSSION

We found no clear evidence for our hypothesis that moderate plant removal would maximize aesthetic perception and the sum and diversity of all quantified ecosystem services. On the contrary, in three out of the five case studies we found no effect of aquatic plant cover on our estimate of TEV. The two other case studies, Lake Kemnade and Hartbeespoort Dam, showed a positive effect of increased plant removal (Figure 2). In Hartbeespoort Dam, we also found a decline in estimated TEV with reduced removal. In other words, more or less aquatic plant cover often does not affect important uses of these lakes and rivers very much, even though some user groups experienced nuisance. This should serve as a cautionary message to water managers: particular user groups may be vocal in demanding more removal effort, but the effect on the total societal benefit may be questionable, and a careful consideration of the importance of different user categories is warranted.

Then, irrespective of management regime, we observed that recreation contributed most to TEV in all five cases, be it in/on the water and physically active or on the banks and less active. This importance of recreation relative to provisioning services, such as agricultural food production or silvicultural timber production, or regulating services such as nutrient retention, was also found by Immerzeel et al. (2021). Boerema et al. (2014) valued ecosystem services provided by a Belgian lowland stream network that is subject to regular aquatic plant removal. These authors, however, did not include recreation in their assessment. They found that the annual cost of aquatic plant removal was only narrowly compensated by the benefits and this is mainly due to flood prevention of agricultural land. Excluding the different forms of recreation from our estimates for the current situation and limiting ourselves to only provisioning and regulating services would reduce TEV to 24% at most (Lake Grand-Lieu). For Hartbeespoort Dam, such a value estimate without recreation would be marginally negative due to the negative effect of cyanobacterial blooms on irrigation water quality versus positive effects of water hyacinth's reduction of evaporative water loss and compost production. Boerema et al. (2014) concluded that if only a few ecosystem services would be included in the cost–benefit assessment before deciding on aquatic plant removal, the benefits of removal would already be negative. We did not carry out a cost–benefit assessment, but obtained estimates of annual management costs from local managers. These range from 4 to 224 € ha^{-1} $year^{-1}$ (expressed per total system area, median 58 across these five case studies; unpublished information collected by S. Schneider), but show no relation with the benefit achieved by such removal if we compare the current with the do-nothing regime (Figure 2).

The predominance of recreation in our monetary value estimates makes our approach necessarily sensitive to errors in the number of people that engage in the different forms of recreation and to the way we estimate an individual willingness to pay. The former was indeed particularly uncertain for Hartbeespoort Dam, where in the absence of reported data we assumed the number of visitors to be a simple multiple of 10 times the number of residents. Given the considerable availability of facilities around the Dam, this is likely a rather conservative factor. Changing this factor 10 substantially up- or downward would not have altered the overall pattern for this site, however. For the other case studies, public statistics were available or visitor numbers could be estimated from parking lot counts (Lake Kemnade). For the individual willingness to pay, we used a low-end travel cost assuming private car or public transport. The latter was used for visitors of Lake Müggelsee, a popular bathing lake in Berlin immediately downstream of our study section in the Spree that is affected by changes in aquatic plants in the river (Table 3). Another point of methodological concern may be the spatial extent and delineation of the study area. Since we were interested in the perception among different categories of users, we had to use a part of the landscape around the water body with nuisance plant growth that is intuitively experienced as a homogeneous unit by humans. This, for example, implies the inclusion of floodplains, and it leads to large differences in area among the studied systems whereas different types of use may only use parts of a system. Still, we normalized over the total area of each selected study area, since we see no other way to aggregate for among-site comparisons (cf. De Groot et al., 2012). Finally, the fact that all our sites had the plant canopy at the surface enabled us to use cover as a simple and tangible factor describing the extent of the nuisance vegetation. We did not have to factor in the depth of the water column above the canopy or use PVI (cf. Verhofstad & Bakker, 2019). At other sites, and notably for uses requiring deeper open water, such as commercial navigation or sailing, direct extrapolation of our findings may be unjustified. Here, the idea of stimulating low-canopy vegetation such as charophytes to replace taller elodeids is worthwhile considering, though as yet only in an experimental phase in a lake downstream of our Lake Kemnade (Podraza, pers. Comm.). High nutrient availability in many aquatic systems experiencing mass development is likely unfavourable for low canopy growth forms such as charophytes or isoetids (e.g. Melzer, 1999; Murphy et al., 2018). Also, it should be noted that mowing boats rarely remove vegetation effectively deeper than 1.5 m (Gettys et al., 2020; Podraza et al., 2008).

An important finding from our surveys is that different forms of recreation predominate in different case studies. In the Otra (angling and boating) and Hartbeespoort Dam (angling, boating), active recreation on the water contributed most to overall societal benefit. In the river Spree, Lake Kemnade and Lake Grand-Lieu, this applied to more passive forms of recreation on the banks (weekend trips, walks and picnics). Since visitors engaging in these different forms of recreation differ greatly in their perception of nuisance (Figure 4, left panels; also Thiemer et al., 2023), it is important for water managers to reflect upon the predominant types of use when developing a plant management strategy. This is relevant for water systems that currently witness mass development of aquatic plants and for those with a high risk of developing nuisance growth (i.e. shallow and nutrient-rich, Chambers et al., 1999; Coetzee et al., 2022), a point to be considered when new canals, lakes or ponds are planned. Aesthetic perception of a water surface in a landscape setting is less sensitive to the presence of dense aquatic plant beds than activities such as swimming or boating, and plants with conspicuous flowers (*Ludwigia* spec., water hyacinth) are perceived less of a nuisance than those without (Thiemer et al., 2023). Clearly, different forms of recreation will require different intensities of plant removal, in terms of both area and depth. For bathing, maintenance removal may be necessary only at designated beaches, whereas sailing boats require larger areas with deeper plant-free water column. Hence, cover and plant height in the water column are important to consider separately (Verhofstad & Bakker, 2019).

Janssen et al. (2021) state that 'knowledge is lacking about the full set of … ecosystem services and their relative importance'. Our study addressed this issue in the sense that we have applied a rigorous analytical framework quantifying all final services relative to plant cover, which thus allows for an assessment of their relative importance. Whereas we show that the summed value of final ecosystem services is less sensitive to aquatic plant removal than expected, their relative importance differs among the five studied cases. We therefore argue that the societal benefits of different forms of recreation should not be ignored when managing water bodies that are subject to mass development of aquatic plants.

AUTHOR CONTRIBUTIONS

Jan E. Vermaat, Kirstine Thiemer, Bart Immerzeel and Susanne C. Schneider developed the concept of the paper. Kirstine Thiemer, Bart Immerzeel, Jan E. Vermaat, Mathieu Baldo, Susanne C. Schneider, Keneilwe Sebola, Sarah F. Harpenslager and Sabine Hilt collected the data. Jan E. Vermaat compiled the case study spreadsheets that were then reviewed by all. Susanne C. Schneider collected the information from the institutional stakeholders. Jan E. Vermaat performed the analyses and wrote the first draft of the manuscript. Jan E. Vermaat, Kirstine Thiemer, Bart Immerzeel, Susanne C. Schneider, Keneilwe Sebola, Julie Coetzee, Antonella Petruzzella, Samuel N. Motitsoe, Mathieu Baldo, Benjamin Misteli, Gabrielle Thiébaut, Sabine Hilt, Jan Köhler and Sarah F. Harpenslager critically reviewed and accepted the final version of the manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors are not aware of any conflict of interest. Sarah F. Harpenslager is an associate editor of the Journal of Applied Ecology, but did not take part in the peer review or decision-making process for this paper.

DATA AVAILABILITY STATEMENT

Survey data are deposited in the permanent data archive DATAVERSE. NO https://doi.org/10.18710/FUWNJL (Vermaat, 2023), according to the contract with the Norwegian Research Council. Working spreadsheets for each case are available upon request from the corresponding author.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Figure S1. Flow scheme for the river Spree case study linking macrophyte cover via intermediate functions or services to final services and then summing up to a monetary estimate of total economic value (€ ha^{-1} $year^{-1}$).

Table S1. Full overview of all potential functions that were considered to potentially contribute to a final ecosystem service in one of the case study sites.

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