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Research article

Cost effectiveness of nutrient retention in constructed wetlands at a landscape level

F. Djodjic [*], P. Geranmayeh, D. Collentine, H. Markensten, M. Futter

The Department of Aquatic Sciences and Assessment, SLU, P.O. Box 7050, SE-75007, Uppsala, Sweden

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ABSTRACT

Since 1990, over 13 000 ha of constructed wetlands (CWs) have been implemented to increase biodiversity and reduce nitrogen (N) and phosphorus (P) loads to Swedish waters. Despite the considerable number of CWs and ambitious investments planned for the coming three years, there is limited follow up of cost-efficiency of catchment- and landscape-scale nutrient retention by existing CWs. Such follow up evaluation could provide clear guidance regarding optimal size and location of future CWs. We present a three-step modelling approach to assess cost-efficiency of 233 CWs in two Swedish regions (East, 4321 km^2, and West, 916 km^2). Modelled nutrient retention in CWs was predominantly low, especially in the East, due to their suboptimal location in catchments, e.g., with inadequate upstream areas (low hydraulic loads) and/or low share of arable land (low nutrient loads). Suboptimal location of CWs generates both higher than necessary costs and low area-specific nutrient retention, leading to low cost-efficiency. Some high cost-efficiency CWs were identified, especially for N retention in the West. To increase their cost-efficiency, continued investments in CWs require clear guidance and instructions. To achieve optimal placement, both CW site and size in relation to incoming hydraulic and nutrient loads must be considered.

1. Introduction

Nitrogen (N) and phosphorus (P) cycles are important earth system processes. Eutrophication, caused by increased N and P loading to receiving waters, is the leading anthropogenic cause of impairment of many freshwater and coastal ecosystems world-wide (Chislock et al., 2013). Following successful reductions in point source nutrient loads (e.g., wastewater treatment plants and direct industrial discharges), agriculture is now the main non-point nutrient source contributing to eutrophication in much of the world (Carpenter et al., 1998; Sharpley et al., 2015). In Sweden, agriculture is the largest anthropogenic source of both N (23 300 tons) and P (460 tons) to the surrounding seas (Ejhed et al., 2016). To reduce nutrient losses from agricultural areas, Sweden has provided payments to landowners and farmers for implementation of mitigation measures primarily through the EU Rural Development Program (RDP), but also through other local and national initiatives. Evaluations of the two RDP program periods (2000–2006 and 2007–2013) concluded that construction or restoration of wetlands are cost-effective compared to other nutrient retention measures supported within the RDP (Andersson et al., 2009; Smith et al., 2016). In a modelling study evaluating potential measures to reduce P losses from agriculture, constructed wetlands (CWs) with optimized size and location based on hydraulic and P load were found to be the most cost-effective measure overall, even when all construction costs were assigned solely to P mitigation (Mårtensson et al., 2020).

In addition to the 6389 ha (ha) of wetlands created up to 2009 (Smith et al., 2016), 6924 ha were created between 2010 and 2021 with Swedish government support (SEPA, 2022), and 775 million SEK in the coming three year period (2021–2023) has been earmarked for establishment of new CWs. While CWs provide many ecosystem services, e.g., groundwater recharge, drought prevention/mitigation, flood risk reduction and mitigation of climate change effects, nutrient retention and support for biodiversity are their primary purposes (SEPA, 2019a, 2019b). Design and placement in the landscape of CWs varies depending on primary purpose. Nutrient retention in CWs, the focus of this study, varies depending on wetland design, position in the catchment, annual variation in water flow, and nutrient loading (Saunders and Kalff, 2001; Braskerud et al., 2005; Tonderski et al., 2005; Kynkäänniemi et al., 2013; Land et al., 2016). Despite the considerable number of existing CWs and ambitious plans for future investments, there is no clear

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[*] Corresponding author.
E-mail address: Faruk.Djodjic@slu.se (F. Djodjic).

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guidance regarding appropriate wetland size and location to increase cost-efficiency. Furthermore, there is limited follow-up of catchment- and landscape-scale cost-efficiency of nutrient retention in existing Swedish CWs (Graversgaard et al., 2021).

Recently, Djodjic et al. (2020) presented a three-step model to identify the optimal position and size of CWs based on hydrological and P loads. This model was used to compare cost-efficiency of theoretically optimized CWs compared with other proposed mitigation measures, including riparian buffer strips, structural liming and delayed soil tillage in five catchments (Mårtensson et al., 2020). The comparison showed that optimized CWs would be considerably more cost-effective overall than all other simulated measures, even over a wide range of construction costs (Mårtensson et al., 2020).

Here, we apply the technique developed by Djodjic et al. (2020) to evaluate cost-efficiency of nutrient (N and P) retention in 233 existing CWs. The CWs included in the study, distributed over two regions in Sweden, represent two different climatic and design conditions. We first estimate nutrient and hydrological loads to calculate nutrient retention in individual CWs in these regions. We then derive a range of cost estimates, which varied according to regional land values and design-specific construction costs. Using this data, we model the potential nutrient retention and construction costs to assess individual cost-efficiency of each wetland.

2. Material and methods

2.1. Catchments

Sweden is divided into 119 main catchment areas with a minimum size of at least 200 km^2 (SMHI, 2002). We worked with three neighboring main catchment areas in eastern Sweden (Nyköpingsån, 3629 km^2; Svärtaån 372 km^2; and a coastal catchment "63/64" 320 km^2) and an additional three main catchment areas in southwestern Sweden (Råån 193 km^2; Vegeå 488 km^2; and coastal catchment "94/95" 235 km^2), hereafter named East (4321 km^2) and West (916 km^2, Fig. 1). These two regions were selected to cover a wide range of important factors determining CW function, e.g., differences in land use and soil properties as well as differences in temperature, precipitation and discharge patterns (Table 1). Generally, the West has a higher proportion of arable land, and is warmer with higher precipitation and discharge, but with soils that have a lower clay content than those in the East (Table 1).

2.2. Identification and characterization of CWs

Information from three different sources was compiled in order to reliably identify and characterize as many individual CWs as possible in the study areas.

(i) Wetland areas were determined by intersecting point coordinates of individual CWs from the wetland database, version 2020 (SMHI, 2020). This database as an Excel file with point coordinates of individual CWs was intersected with the Geografiska Sverigedata (GSD) Property Map water layer. The GSD Property map is the most detailed map available for the scale range 1:5000–1:20 000. When CW point coordinates did not correspond with GSD water surfaces, points were imported into Google Earth in an attempt to identify CW water surface from available satellite images. Thereafter, the water surface was digitized with "Add polygon" tool in Google Earth.

(ii) Information on CWs was also taken from the Swedish Board of Agriculture Land Parcel Identification System (LPIS) database (European court of auditors, 2016). This database contains field polygons, which are usually larger than the water surface of the CW. To account for this discrepancy, block polygons were intersected and matched with the water surface layer obtained in (i). When there was no match, water surfaces were manually delineated using Google Earth.

(iii) information from the City of Helsingborg was used to identify additional CWs in the West Region (Helsingborg city building administration, 2015).

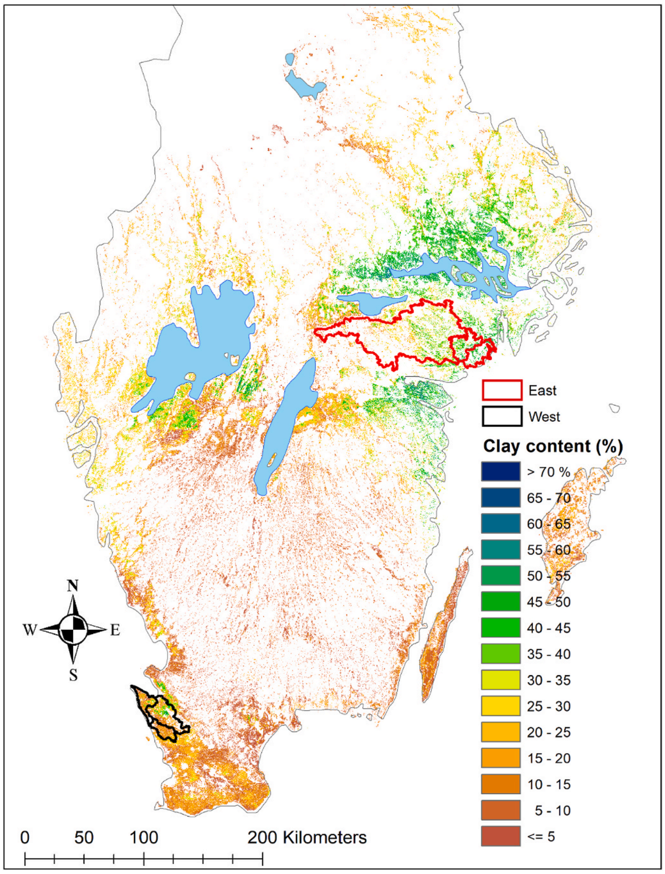

Fig. 1. Map of southern Sweden showing East (red polygons) and West (black polygons) regions, each consisting of three catchments and soil clay content on arable land (Piikki and Söderström, 2019). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Catchment, meteorological and hydrological characteristics in the two studied regions.

Region	Arable land[a] (%)	Clay content[b] (%)	Precipitation[c] (mm)	Temperature[d] (°C)	Discharge[e] (mm)
West	60	19.0 (±9.8)	677 (±48)	8.9 (±0.2)	278 (±54)
East	15	31.5 (±10.5)	602 (±32)	6.9 (±0.2)	196 (±23)

[a] Based on national land cover data (SEPA, 2019a,b).

[b] Based on the map of textural classes of Swedish agricultural soils (Söderström and Piikki, 2016; Piikki and Söderström, 2019).

[c] Average annual precipitation (1991–2020) for 13 meteorological stations in the West and 19 in the East (SMHI, 2022).

[d] Average annual temperature (1991–2020) period for five meteorological stations in the West and six in the East (SMHI, 2022).

[e] Modelled average annual discharge (Hansson et al., 2019).

2.3. Modelling nutrient loss reduction

Nutrient retention in the study wetlands was estimated using a combination of national, regional and site-specific data as well as a set of retention equations derived from measurements by Weisner et al. (2016). Regional N and P export coefficients were derived from the SOILN and ICECREAM models (Larsson et al., 2007; Johnsson et al., 2019). Outputs from these two models have long been used as the basis for estimating N and P losses from arable land in Sweden (Johnsson et al. 2008, 2016, 2019) and are also used for Pollutant Load Compilation calculation of nutrient loads to the Swedish marine environment (Ejhed et al., 2016; Hansson et al., 2019).

These export coefficients were used in a distributed (grid-based) model (Djodjic et al., 2020) to produce input nutrient loads for each CW. In the model, each grid cell is assigned a representative nutrient export coefficient based on land use category, with the exception of arable land. Land use distributions were calculated using a 10-m grid from national land cover data (SEPA, 2019a,b). For grid cells containing arable land, the representative export coefficient was assigned based on the map of textural classes of Swedish agricultural soils (Söderström and Piikki, 2016; Piikki and Söderström, 2019).

A hydrologically corrected Digital Elevation Model (DEM, 10-m grid) was obtained from a 2-m grid based on LiDAR data (Lantmäteriet, 2014). Water course lines from GSD Property maps were lowered by 100 m and burned into the DEM to ensure proper flow direction and accumulation, and used to delineate catchment areas for each individual CW. Average annual discharge was available for approximately 37 000 Swedish sub-catchments in Sweden from the S-HYPE model (Lindström et al., 2010). We used average annual discharge from 291 sub-catchments in the East and 35 in the West. Based on modelled mean annual specific runoff for each sub-catchment (Hansson et al., 2019) and flow accumulation lines, annual volumetric water loads ($m^3\ yr^{-1}$) were calculated individually for each CW. Annual volumetric water loads and CW water surface (m^2) were used to estimate hydraulic load (HL, m^3/m^2, i.e. m) for each CW.

Specific runoff (mm yr^{-1}) for each grid cell from sub-catchments in the two regions was then combined with modelled N and P export coefficients (mg l^{-1}) to calculate nutrient loads in that cell. Calculated loads for each grid cell were accumulated along flow accumulation lines for each individual CW to derive total (kg yr^{-1}) and area-normalized (kg ha^{-1} of CW yr^{-1}) loads of both N and P for that particular CW. Flow direction and flow accumulation calculations were performed using PCRaster (Schmitz et al., 2009).

We calculated potential nutrient retention in each CW using the estimated nutrient load data and retention functions developed by Weisner et al. (2016), who used measured data from 15 wetlands to estimate annual N and P retention based on areal nutrient loads. We have adapted the original Weisner et al. (2016) equations by inserting modelled area-normalized loads (N_L* and P_L*) described above to calculate potential CW nutrient retention:

$$N_R = 229.41 * \ln(N_L) - 1405.3 \tag{1}$$

where N_R is N retention and N_L is incoming N load, both in kg ha^{-1} yr^{-1}

$$P_R = -0.0003 * \ (P_L)^2 + 0.4584 * \ P_L \tag{2}$$

where P_R is P retention and P_L is incoming P load, both in kg ha^{-1} yr^{-1}

2.4. Modelling wetland cost efficiency

Finally, potential nutrient retention values were joined with estimated costs for CWs (based on Mårtensson et al. (2020)) to evaluate cost-efficiency. In general, CW cost efficiency is difficult to assess. The three primary objectives motivating public financial support for wetland construction (N retention, P retention, promoting biodiversity) are not exclusive. Estimating cost efficiency requires that costs be assigned to each objective. While all CWs, regardless of location, will have some positive effect on biodiversity, effect magnitude will vary depending on site. On the other hand, if the proportion of agricultural land in a catchment area is low, there will be low anthropogenic N or P loads and consequently a CW will have low nutrient retention. A comprehensive study including estimates of CW cost efficiency in Sweden suggested that half of total costs should be assigned to biodiversity and half to nutrient retention with this latter purpose equally divided between reduction of N and P (Weisner et al., 2015). An extensive review of RDP funding for 1788 wetlands constructed in Sweden between 2007 and 2020 found that 44% “were created with the purpose of helping with nutrient loss and water quality”, 39% for biodiversity and 17% for both purposes combined (Speks, 2021).

The total cost for a given CW is the sum of construction, land and maintenance costs. Construction usually account for the largest part of total costs and were here estimated as 350 000 SEK ha^{-1} CW distributed over 20 years, i.e. 17 500 SEK yr^{-1} (see Mårtensson et al., 2020). Construction costs are not expected to vary between regions as labor and capital costs are similar throughout Sweden. Land costs depend on land productivity, which varies by region. We used land costs of 7020 SEK ha^{-1} yr^{-1} in the West and 3300 SEK ha^{-1} yr^{-1} in the East, which are based on leasing cost data from an earlier Swedish study on cost efficiency of riparian buffer zones (Collentine et al., 2015).

One requirement for public support for CWs in Sweden has been that projects must also concurrently participate in a separate dedicated maintenance support program in the RDP. Since maintenance payments (currently 4000 SEK yr^{-1}) are intended to promote biodiversity all of these costs may be considered to be solely for this purpose. Therefore, the only relevant costs for estimating cost efficiency of nutrient load reduction are construction and land costs. Following Weisner et al. (2015a,b), we estimated cost-efficiency per kg N or P retained as 25% of total costs divided by total mass (kg) of N or P retained.

2.5. Statistics

Linear regressions were calculated for the proportion of agricultural land in the upstream catchments of the CWs and catchment-specific loads of both N and P. For all CWs where information was available, linear regressions were calculated between construction year and hydraulic load as well as N and P loads to quantify possible temporal trends. For each regression, R^2-values of the linear fit and corresponding p-values were calculated to quantify the percentage of variation explained. Analysis of variance (ANOVA) was performed to test for statistically significant differences between properties of CWs categorized according to main purpose (biological diversity, nutrient retention or flow regulation). The Tukey-Kramer Honestly Significant Difference (HSD) test was used to perform multiple comparisons of group means.

3. Results

3.1. CWs, catchments and hydraulic load

In total, we identified 144 CWs in the East with a total construction area of 821 ha and total water surface area of 576 ha. In the west, 89 CWs were identified with a total construction area of 204 ha and a total surface water area of 78 ha. Considering the much larger total catchment area of the East (~4X larger), CWs are a more common landscape feature in the West. Skåne County, in the West, contained 35% of the total CW area and 29% of the number of CWs funded under the RDP between 2007 and 2020, whereas the corresponding values for Södermanland, in the East, were only 6% of CW area and 3% of the number of CWs (Geranmayeh et al., unpublished data). In both regions, large variations between CWs were documented in both construction area (including shores, embankments and altered land) and water surface area (Table 2). Water surface areas had to be digitized based on Google Earth satellite images for 48 CWs in the East and 17 in the West. Water surface area is smaller than construction area, and there is a strong positive linear relationship between the two ($R^2 = 0.86$, $p < 0.0001$). The variation in both variables was larger for the CWs in the East (Table 2). Both

Table 2

Minimum, 25th, 50th (median), 75th percentile and maximum and mean values for total area, water surface area and catchment area as well as ratio between water surface area and catchment area. Total area is water surface area plus surrounding area excluded from the agricultural production, including shores, embankments and altered land. Relative size of the CW is the ratio between water surface and catchment area.

Catchment	Variable	Unit	MIN	Q1	Ave	Median	Q3	MAX
East	Construction area	ha	0.05	1.3	5.7	3.1	7.4	53.8
East	Water surface	ha	0.02	0.8	4.0	1.9	4.7	38.1
East	Catchment area	ha	1.3	28	186	71	191	2044
East	Relative size	%	0.02	1.4	5.4	3.6	6.6	38.8
West	Construction area	ha	0.05	0.6	2.3	1.3	3.0	11.4
West	Water surface	ha	0.03	0.2	0.9	0.5	1.1	7.7
West	Catchment area	ha	0.10	10.4	166	30	180	1463
West	Relative size	%	0.01	0.25	4.7	1.5	5.3	57.2

the median construction area (3.1 ha) and median water surface area (1.9 ha) in the East were larger than corresponding values for the West (1.3 and 0.5, respectively). Furthermore, CWs in the East were more than twice as large in the relative size of their catchment areas (median 3.6%) compared with the West (1.5%). Surprisingly, large wetlands were constructed in both regions, the largest CW in the West covers more than half the size of its catchment (57%).

Median HL was considerably lower in the East (5 m yr^{-1}) than the West (19 m, Fig. 2). This is also illustrated by the higher percentage of water surface area in relation to the CW catchment area in the East (median 3.6%) compared to the West (median 1.5%, Table 2).

3.2. Nutrient load and retention

The proportion of agricultural land upstream of a CW was strongly and positively correlated to catchment specific loads (kg ha^{-1} yr^{-1}) of both N and P. In the West, this relationship was stronger for N (R^2 = 0.53, $p < 0.0001$), whereas a very weak correlation was found for P (R^2 = 0.16, $p < 0.0001$). In the East, the relationship was somewhat stronger for P (R^2 = 0.86, $p < 0.0001$) than for N (R^2 = 0.67, $p < 0.0001$).

Very large variations of both N and P loads entering CWs were recorded. Generally, P loads per unit CW water surface area were rather low, with median values of 4 and 14 kg ha^{-1} yr^{-1} for East and West, respectively (Fig. 3). The higher loads in the West are a consequence of both a smaller CW size (Table 2) and a higher proportion of agricultural land in the catchments. As for N, modelled median values of incoming loads were much lower in the East (76 kg N ha^{-1} yr^{-1}) than the West (1466 kg N ha^{-1} yr^{-1}). This is a result of both a higher proportion of agricultural land in the West as well as a lower clay content. In Sweden, sandy soils with a lower clay content are more prone to N losses (Kyllmar et al., 2014).

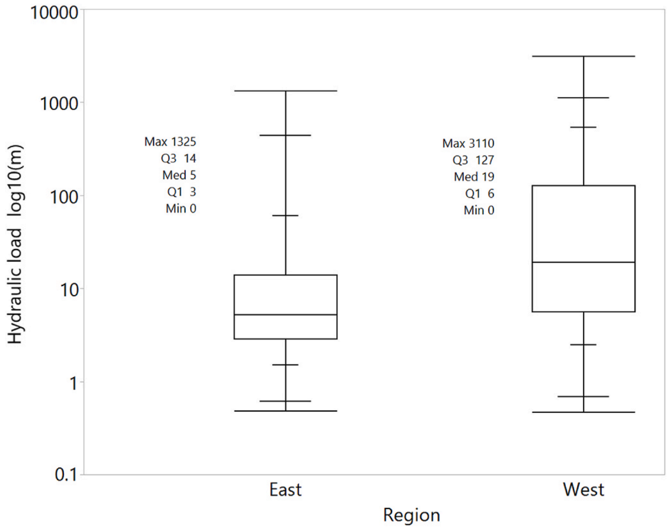

Fig. 2. Distribution of hydraulic load (HL) for CWs in two regions. Note the logarithmic y-scale. Quantile box shows minimum, 2.5%, 10%, 25%, 50% (median), 75%, 90%, 97.5% quantiles and maximum.

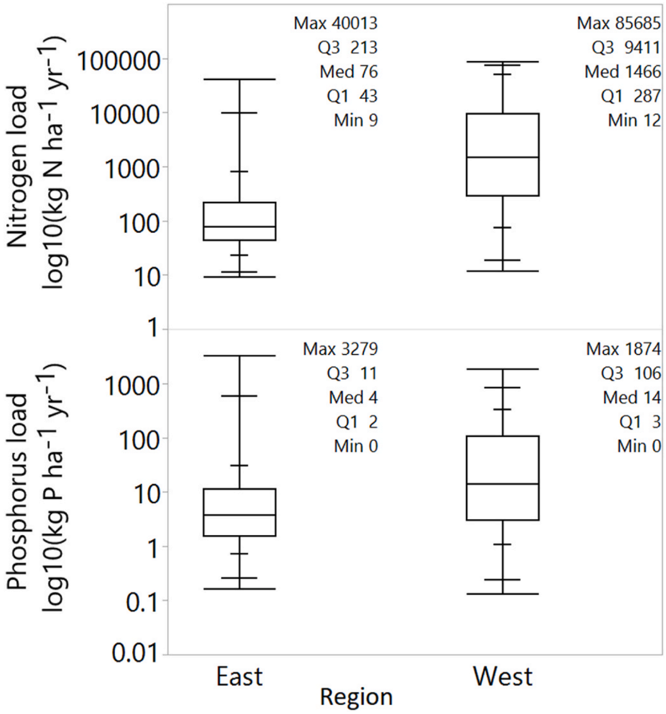

Fig. 3. Modelled nutrient loads (kg ha^{-1} yr^{-1} N or P) based on CW water surface area. Quantile box shows minimum, 2.5%, 10%, 25%, 50% (median), 75%, 90%, 97.5% quantiles and maximum. Note logarithmic y-axes.

Low nutrient loads also lead to low nutrient retention (Equations (1) and (2)). Additionally, all modelled N loads to CW water surfaces under approximately 458 kg N ha^{-1} yr^{-1} will result in negative retention (equation (1)). Indeed, 151 out of a total 233 CWs (65%) had negative retention values due to low N loads (Figs. 3 and 4). Most of these CWs (123) were situated in the East while 28 were located in the West. For estimating cost-efficiency, zero N reduction was assigned to CWs with negative retention, but calculated values were kept in Fig. 4. If all negative values are excluded, this results in a median N retention of 236 kg ha^{-1} in the East and 518 kg ha^{-1} in the West.

The same was true for estimated P retention (Equation (2)). As the range of P loads used to derive Equation (2) had maximum values below 1000 kg P ha^{-1} yr^{-1} (Weisner et al., 2016), estimated P retention is negative for P loads higher than 1528 kg P ha^{-1} yr^{-1} due to the polynomial functional form of the equation. However, only two CWs had incoming P loads exceeding this value. In estimating cost efficiency a zero P reduction was also assigned to these two CWs. Median P retention was very low, barely 2 kg ha^{-1} in the East and 6 kg ha^{-1} in the West.

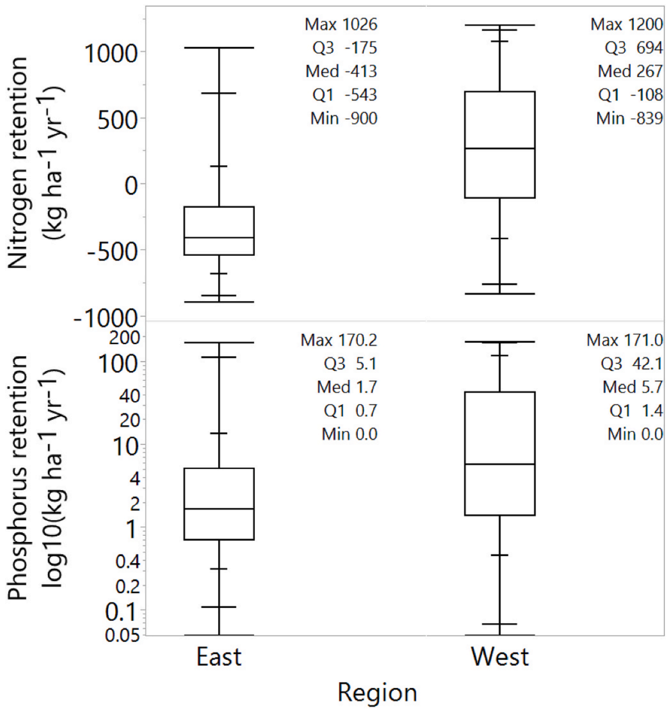

Fig. 4. Modelled retention (kg ha^{-1} yr^{-1}) of nutrients, N and P based on CW water surface area and year. Quantile box shows Minimum, 2.5%, 10%, 25%, 50% (median), 75%, 90%, 97.5% quantiles and Maximum. Note logarithmic y-axis for Phosphorus.

3.3. *Cost-efficiency estimation*

To assess the cost-efficiency of nutrient retention in the studied CWs, all CWs were grouped into cost-classes. The cost-classes are arbitrarily defined, but are related to RDP estimated average costs for N and P retention from 2007 to 2013 for other nutrient reduction measures; catch crops, spring plowing, and buffer zones (Smith et al., 2016). A high number of CWs were assigned to the lowest cost-efficiency classes (Tables 3 and 4, Fig. 5). For P, 44% (n = 144) CWs in the East and 42% (n = 89) CWs in the West were classified in the lowest cost-efficiency class (>5000 SEK kg^{-1} P; Table 3, Fig. 5). In the case of N, many more CWs (88%) in the East than the West (35%) were classified in the lowest cost-efficiency class (>500 SEK kg^{-1} N, Table 4, Fig. 5).

However, some very cost-effective CWs were identified, especially in the West and particularly for N. For instance, in 46 CWs in the West (52% of the total number of CWs), N retention costs were calculated to be below 100 SEK/kg N removed (Fig. 5). These cost-effective CWs stand for removal of 16.7 t N (94% of the modelled total N removal, Table 4). Similarly, the 15 most cost-effective CWs (10%) in the East removed 4.2 t N, which is 86% of total modelled removal (Table 4). On average, the most cost-efficient CWs retained 505 kg N ha^{-1} in the East and 700 kg N ha^{-1} in the West. For P, the pattern is the same in the West, where 31 (35%) of the most cost-effective CWs (<1000 SEK kg^{-1} P) account for 88% of the total modelled P retention, whereas P retention in the East is more equally distributed, and 19 (13%) of the most cost-effective CWs accounted for 37% of the total modelled P retention (Table 3). On average, the most cost-efficient CWs retained 75 kg P ha^{-1} in the East and 98 kg P ha^{-1} in the West.

There were 71 CWs with information on construction year, 36 in the East (from 2007 to 2019) and 35 in the West (from 2001 to 2017). A somewhat higher number of wetlands was constructed in the beginning of the period (2001–2006) in the West, whereas the opposite is true for the East where a higher number of wetlands was constructed towards the end of the period (2012–2017, Fig. S1). However, there was no statistically significant relationship between year of construction and hydraulic load (p = 0.73), N (p = 0.66) or P load (p = 0.26).

4. Discussion

The main finding from this study is that with appropriate sizing and location in the catchment, CWs can be a cost effective measure to mitigate nutrient loads from agricultural areas. Costs per kg N retained were estimated to be below 100 SEK for around half of the CWs in the West, which is similar to that for other N reduction measures, e.g., catch crops in the West (85 SEK kg^{-1} N) and spring plowing in the East (182 SEK kg^{-1} N) (Smith et al., 2016). CWs were in the lowest cost-class for P (<500 SEK kg^{-1}P) in the West (25%) and in the East (8%). This is more cost-effective than average costs for P retention with buffer zones, which varied between 725 SEK kg^{-1} P in the West and 45 392 SEK kg^{-1} P in the East (Smith et al., 2016). However, modelled nutrient retention in existing CWs was highly variable but predominantly low. Generally, cost-efficiency is low when CW area is large and incoming nutrient loads are low as this generates both a high cost and a low nutrient retention. Elsewhere, Iovanna et al. (2008) estimated the cost of removing one kg of nitrate N with CWs in the USA to approximately 30 SEK, and possibly even lower if the tile-drained areas with highest N losses are targeted. This is very much in line with the most cost-effective wetlands in this

Table 3
Number of constructed wetlands (CW), sum of CW area, sum of modelled P retention, sum of water surface area, average N retention, average cost per kg retained P and average modelled hydraulic load (HL) for different cost-efficiency classes where ¼ of the total costs was assigned to P retention.

Region	Cost-class	Number CW	Σ CW area	Σ P retention	Σ Water surface	Ave P retention	Ave cost	Ave HL
	SEK kg^{-1} P		ha	kg	ha	kg ha^{-1}	SEK kg^{-1} P	m
East	<500	11	15	346	9	75	247	366
East	500–1000	8	36	233	27	14	840	53
East	1000–2000	19	108	405	66	7	1415	23
East	2000–3000	15	50	108	35	3	2522	10
East	3000–4000	16	115	164	88	2	3567	9
East	4000–5000	12	102	121	80	9	4553	25
East	>5000	63	395	180	271	1	18 501	4
East	Total	144	821	1558	576	9	9385	40
West	<500	22	28	943	13	98	241	414
West	500–1000	9	28	225	11	27	773	96
West	1000–2000	8	14	53	5	22	1569	42
West	2000–3000	5	12	30	2	33	2537	53
West	3000–4000	5	10	17	3	4	3503	14
West	4000–5000	3	5	7	1	7	4589	17
West	>5000	37	107	50	43	1	29 714	90
West	Total	89	204	1324	78	32	13 126	158

Table 4
Number of constructed wetlands (CW), sum of CW area, sum of modelled N retention, sum of water surface area, average N retention, average cost per kg retained N and average modelled hydraulic load (HL) for different cost-efficiency classes where ¼ of the total costs was assigned to N removal.

Region	Cost-class	Number CW	Σ CW area	Σ N retention	Σ Water surface	Ave N retention	Ave cost	Ave HL
	SEK kg^{-1} N		ha	kg	ha	kg ha^{-1}	SEK kg^{-1} N	m
East	<50	10	15	2564	9	505	29	400
East	50–100	5	23	1593	11	180	84	93
East	100–200	3	15	604	**5**	117	127	48
East	200–300	0	–	–	–	–	–	–
East	300–400	0	–	–	–	–	–	–
East	400–500	0	–	–	–	–	–	–
East	>500	126	768	83	551	4	30 953	9
East	Total	144	821	4844	576	47	27 091	40
West	<50	34	52	13 356	25	700	26	241
West	50–100	12	42	3352	15	472	72	183
West	100–200	3	4	212	1	186	113	13
West	200–300	5	24	577	3	440	248	654
West	300–400	2	0.3	4	0.1	23	307	6
West	400–500	2	9	118	1	385	445	74
West	>500	31	73	124	33	7	11 727	5
West	Total	89	204	17 743	78	373	4139	158

study. Kavehei et al. (2021) estimated that N removed in CWs in tropical and subtropical Australia was somewhat more expensive, but still less than 370 SEK kg^{-1} dissolved inorganic N, which is still in the range with less cost-effective wetlands in this study (Table 4). In Canadian prairie wetlands, Yang et al. (2016) found that reduction of 1 kg P would cost less than 600 SEK, which is similar to the wetlands in region West in our Swedish study. All these studies emphasize the importance of targeting areas with high nutrient losses/concentrations as the best way to increase cost-efficiency.

Estimated nutrient retention of CWs showed a large variation in cost efficiency for both N and P (Tables 3 and 4) both between individual wetlands within a region and between regions. This is due only in small part to variation in costs. With the exception of land compensation costs, we assigned the same construction costs per ha for all CWs regardless of region or purpose (i.e., nutrient retention or biodiversity). In reality, excavation costs are usually higher when nutrient retention is the primary purpose (Geranmayeh et al. in preparation), as large biodiversity wetlands can be created at lower cost by. However, no such information was available for the wetlands included in this study. While land compensation costs were higher in the West because of higher agricultural productivity in this region, the effect on cost efficiency was low due to the size of these costs relative to construction costs, which is around 21% of the difference between total costs in the two regions.

There are several possible explanations for differences in efficiency. Many CWs, especially in the East, have biodiversity as a primary purpose so other criteria, e.g., large size and flat shores might have been more important design factors. First, there are regional differences: 61% of CWs in Skåne (West) were intended for nutrient retention CWs, 31% for biodiversity and 8% had a combined purpose (Geranmayeh et al. in prep). Corresponding values for CWs in Södermanland (where region East is included) are 29% for nutrient retention, 53% for biodiversity and 18% with combined purpose (Geranmayeh et al. in prep). Second, farmers' willingness to give up productive land is limited (Hansson et al., 2012), while unproductive land is more common to set aside. Therefore, as the national goal for wetland construction only has been to reach a certain area of implemented wetlands and there is no assigned money to achieve specific purposes, the criteria for approving plans for CWs by county level administrators may have not placed any great emphasis on nutrient retention, as this could have led to fewer applications being approved. Third, although there is some guidance regarding CW size and proportion of agricultural land in the catchment (SJV 2004), there are still no clear instructions or minimum limits on wetland area to catchment area ratios, HL or nutrient load. Although the evidence is limited, there are no clear trends in recent CWs towards higher incoming nutrient loads or retention, as there was no significant relationship between construction year and either nutrient loads or nutrient retention. To increase the capacity of future wetlands to capture more nutrients, it is crucial that they be sized and located appropriately.

In a systematic review of published studies on constructed and restored wetlands, Land et al. (2016) reported variation in median retention between 6.3 and 29 kg P ha^{-1}. Corresponding values for N varied between 14 and 140 kg N ha^{-1}. These values are comparable with our modelled values (Fig. 4). Weisner et al. (2015a,b) suggested that nutrient reduction levels as high as 50 kg P and 500 kg N/ha wetland water surface could be achieved through appropriate site design and placement. However, to achieve these levels would require loads of around 5000 kg N and 120 kg P/ha CW (Weisner et al., 2015). Such loads are much higher than most values calculated in this study, where we found only a few CWs with those levels of nutrient loads (Fig. 3). In the West, only 24 CWs had higher loads then this for N while 21 had higher loads for P (13 and 7 in the East respectively). The greater number of CWs in the West with higher nutrient loads was due to a larger share of agricultural land in those catchments. As expected, this generated higher N loads in the sandy West. Surprisingly, it also generated higher P loads than the East which has a higher proportion of clay soils.

Wetland size in relation to the inflowing water is also an important factor for nutrient retention. High HL, or a low wetland size in relative to its catchment, increases nutrient retention, but with undefined threshold values (Braskerud et al., 2005; Land et al., 2016; Geranmayeh et al., 2018). For example, Kynkäänniemi (2014) showed a strong positive correlation between P retention and HL under 250 m, but suggested also that there might be an upper limit for HL if a wetland is to retain P transported from clay-rich agricultural soils, such as those found in the East. 19 of the 233 study CWs (8%) were too small relative to their catchment area and incoming HL (>250 m) might be too high for effective nutrient retention. As Equation (2) (Weisner et al., 2016) does not take into account possible negative effects from high HL, the nutrient removal and cost-effectiveness of such CWs might be overestimated. Indeed, the most cost-effective CWs in both East and West (<500 SEK kg^{-1} P) had average HL values of 366 m and 414 m, respectively (Table 3). These CWs could be made larger, to increase water residence time and enhance sedimentation if the share of arable land and incoming loads are high. The same is true for N where the most cost-effective CWs in both East and West (<50 SEK kg-1 N) had average HL of 400 m and 241 m, respectively (Table 4). However, most CWs in the study (79%) had HL under 50 m and were thus too large relative to their catchment area and incoming nutrient loads to achieve high area-specific retention. The largest CWs in East and West comprised 39% and 57% of their catchments and were most probably constructed to increase

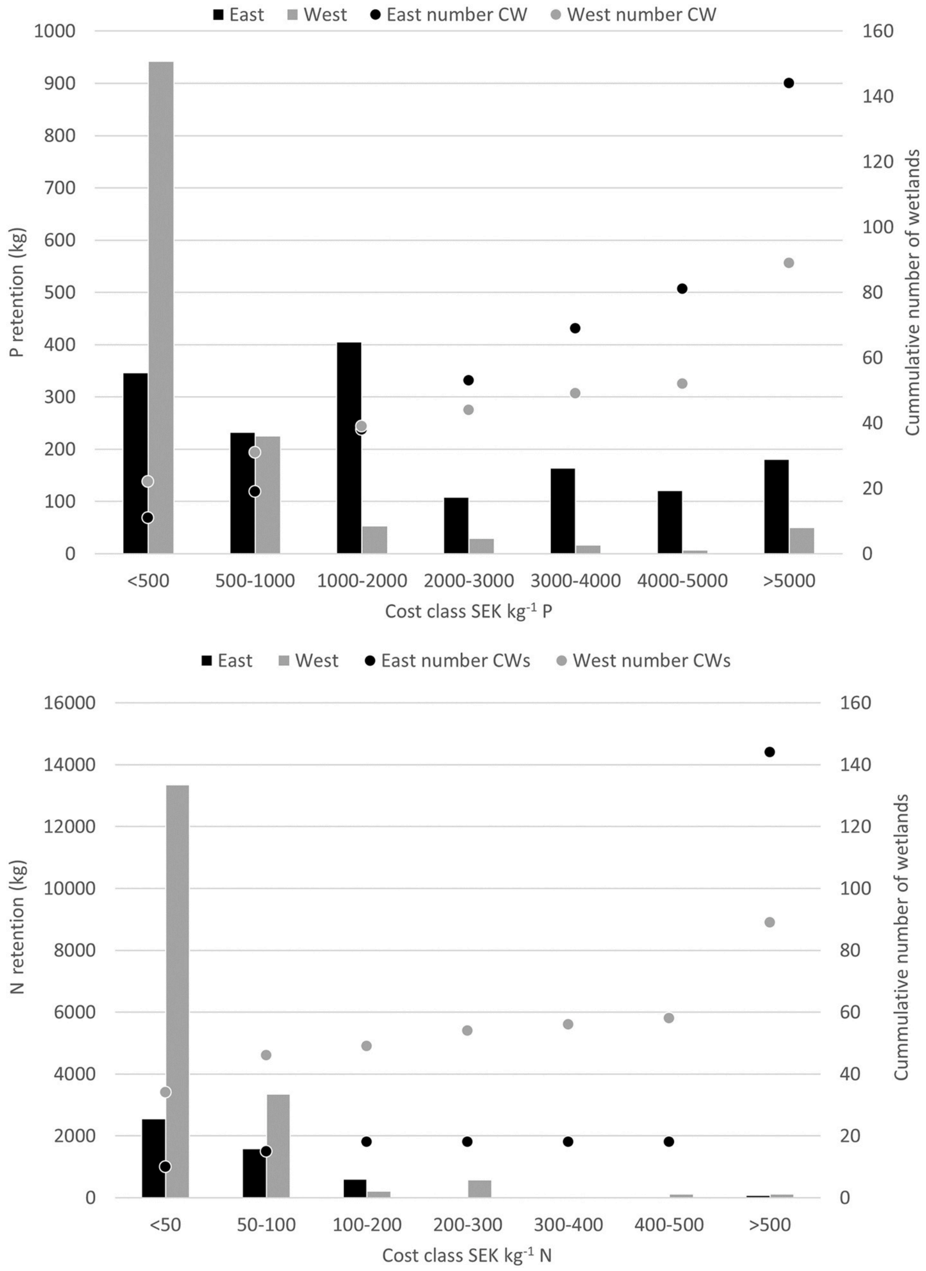

Fig. 5. Nutrient (N and P) retention and cumulative number of wetlands in different cost-efficiency classes (SEK per kg P/N ha^{-1} yr^{-1}) in two studied regions.

biodiversity.

Rather than reducing the size of existing wetlands to increase their efficiency, it may be better to differentiate economic incentives for CW establishment and maintenance based on their placement and purpose. When nutrient retention is the primary purpose of a CW, it might be better to design economic incentives that favor wetlands having sizes that correspond to an optimal HL and nutrient loading. Possibilities to separate levels of economic incentives for nutrient retention and increased biodiversity should be further investigated to evaluate benefits and shortcomings of this approach. If CWs are placed in areas with a large share of arable land, a large load reduction to the recipient could be a goal. However, if CWs are placed in areas with a low share of arable land, maintenance costs could be reduced and they could be left as important habitats for increased biodiversity.

Despite the large investments in CWs in Sweden, available information regarding purpose, characteristics and properties of individual CWs is still scarce and often inadequate. This hinders any attempts to follow-up CW functionality as there is a rather high threshold to gather relevant information. The Constructed Wetlands database (SMHI, 2020) is probably the most comprehensive source of information available in Sweden. However, its format (Excel-file), which may be transformed to point shape file, is rather inconvenient for further analyses. Although the database generally contains information on both wetland and catchment areas, a geodatabase with polygons of both CWs, water surface area and their catchment area would be more useful. We compiled data from several sources to get a representative picture of existing CWs in two catchments in Southern Sweden. The LPIS block/field database offers some additional information. The polygon format is an advantage, but the major drawback of this data source is that the information is only relevant for block units, which are the basis for subsides and, in general, larger than CW water surface areas. As the water surface area of the wetland is used to estimate nutrient retention efficiency (Kynkäänniemi, 2014; Weisner et al., 2015), this discrepancy may limit evaluation and follow-up studies, or lead to erroneous conclusions if block area is used.

Currently, agro-environmental payments for countermeasures against nutrient losses, which go beyond good agricultural practices, are based on per hectare payments, usually compensating farmers for lost income and not for possible improvement of the environment (Hansson et al., 2012; Graversgaard et al., 2021). In the case of CWs, farmers receive payments based on the area taken out of production (construction area), and not on the water surface area. For result- or value-based agro--environmental payment schemes, information on water surface area is essential for both estimating retention efficiency and cost-efficiency.

5. Conclusions

To ensure cost-effective use of future societal investments to reduce eutrophication, the focus of future CWs should be to optimize size and location in high load areas. Based on modelling of hydraulic and nutrient loading and retention, as well as estimation of cost-efficiency of 233 existing wetlands in two large and diverse regions in Sweden, the following main conclusions are drawn:

- CWs are competitive and cost-effective tools for reduction of nutrient losses even in the future and compared to other alternatives (Tables 3 and 4).
- Existing Swedish databases on CWs need to be updated and upgraded to geodatabases, including information on main purpose(s), year of construction, water surface area and catchment area polygons.
- Modelled nutrient (N and P) retention by existing CWs is extremely variable due to their placement in the landscape. In most cases, retention potential is low either due to low influent nutrient loads (too small a share of arable land in the catchment) or low HL (too large CW area relative to the catchment area)
- The effect of high HL, especially for N removal, needs to be further clarified. High HL often also indicates high nutrient loading and thereby high modelled nutrient retention. This might be erroneous due to negative correlations between HL and nutrient (N and P) retention with high HL.
- Rational continued investment in CWs to reduce eutrophication needs to be supported with clear guidance and instructions on the optimal position and size of the wetlands relative to incoming nutrient loads.

Credit author statement

Djodjic F.: Conceptualization, Methodology, Software, Validation, Formal analysis, Writing – original draft, review & editing, Visualization, Funding acquisition, **Geranmayeh, P**: Conceptualization, Validation, Writing – review & editing, **Collentine, D.**: Conceptualization, Validation, Writing – review & editing, **Markensten, H.**: Conceptualization, Software, Writing – review & editing, **Futter, M.**: Conceptualization, Validation, Writing – review & editing, Project administration, Funding acquisition.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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