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Research article

Estimating landscape-level water storage potential as a tool to mitigate floods and nutrient losses

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A B S T R A C T

Extreme weather events, which are becoming more frequent due to climate change, result in intensified nutrient losses and may override effects of agricultural mitigation measures. Using a landscape connectivity approach, we study the potential of water flow attenuation in upstream forest areas to prevent or mitigate waterlogging and flooding of downstream arable land, thereby contributing to reduced phosphorus (P) losses. We use soil distribution maps, high-resolution elevation data, land use maps and distributed modelling to quantify water storage potential and possible P reductions. In three out of four study catchments (119–915 km^2), calculated storage potential of detention basins located in upstream wetland and forest areas was sufficient to retain water volumes (0.7–3.6 million m^3) corresponding to discharge volumes produced during an episode with a 50 -year return period. Furthermore, it was estimated that 9–57 % of targeted annual P load reductions from arable land could be reached if stored water volumes bypass arable land without causing waterlogging/flooding leading to P mobilization and transport. As water storage potential is site-specific, prioritization and selection criteria need to be developed in collaboration with relevant stakeholders to achieve cost-efficient implementation of these measures. The methodology and results of this study have significant potential for application in landscapes with a mixture of forests and arable agriculture to aid land owners and managers to secure food production and improve water quality.

1. Introduction

Eutrophication is still a high priority environmental issue as excess nutrient export deteriorates recipient water quality (Smith et al., 1999; Sharpley et al., 2015; Bol et al., 2018). In much of northern Europe, diffuse losses from arable fields are the largest anthropogenic source of phosphorus (P) to downstream water recipients including the surrounding seas(Hansson et al., 2019). Both waterlogging of arable fields (Manik et al., 2019) occurring regularly during springs and flooding (Talbot et al., 2018) caused by extreme weather events negatively impact water quality. Extreme events contribute disproportionally to annual transport of both suspended solids (SS) and P (Djodjic and Markensten, 2019; Chang et al., 2023) as well as overriding positive effects of mitigation measures (Bieroza et al., 2019). Furthermore, climate change is predicted to cause increases in total monthly precipitation, rainfall intensity and runoff (Grusson et al., 2021a). Therefore, mitigating negative effects of extreme weather events including waterlogging and floods might benefit food production, food security and downstream water quality. The European Union (EU) Floods Directive 2007/60/EC requires all member states to identify areas at risk of flooding, to map the flood extent aswell as assets and humans in these areas, and finally to take adequate measures to reduce flood risk (Kundzewicz et al., 2018). The concept of retaining water in upstream areas to mitigate downstream flooding is well established (Collentine and Futter, 2018), but upstream water retention for downstream nutrient control is less so. Wilkinson et al. (2019) showed that flood runoff could be attenuated in small catchments (<10 km^2) by accumulating dispersed small-scale storage, but also concluded that there is a lack of evidence for measure effectiveness in larger catchments. Therefore, the need for large-scale studies of the effect of entire wetlandscapes is highlighted (Ekström et al., 2025) and references within). Landscape connectivity is the degree to which the landscape facilitates or impedes movement among resource patches (Taylor et al., 1993) and it depends on the quantity and spatial arrangement of the landscape (Tarabon et al., 2020). A common pattern of landscape connectivity in most rural areas in Sweden and elsewhere is headwater forests upstream of agricultural land. Thus instead of traditional sectoral approaches, using a landscape connectivity approach can simultaneously target several challenges

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including food security and impacts of extreme water hazards driven by climate change (Eriksson et al., 2018). With a landscape approach, managing societal challenges through nature-based solutions (NBS) might be a cost-effective path forward (Swedish Environment Protection Agency, 2022). However, the scientific evidence base of the hydrological impacts of NBS is still weak (Lalonde et al., 2024) and their effectiveness may not be guaranteed if simultaneously additional measures do not take place at a large scale, i.e., within the entire catchment/basin (Kuriqi and Hysa, 2022). From a landscape perspective, the availability of upstream forestland represents an untapped potential to create water storage that can mitigate floods and drought in downstream agricultural areas. In this study, we quantify potential for water retention including both surface and subsurface storage (including groundwater recharge). Subsurface storage is dependent on soil porosity and groundwater depth, whereas surface storage is constrained by topography and our ability to increase that potential with cost-effective embankments. Additionaly, specific focus is on the enhanced water retention in upstream forest/wetland areas to avoid flodding of downstream arable land and consequent reductions of difuse nutrient losses from terrestra to aquatic ecosystems.

The main objectives of this study are to (i) quantify the potential for water storage at the landscape level (100–1000 km^2), primarily in upstream forest areas, as well as to (ii) estimate possible reductions in P losses as a consequence of preventing or mitigating waterlogging and flooding of downstream arable land.

2. Material and methods

2.1. Study sites

The study focuses on four catchments in east-central Sweden (Fig. 1), where we have ongoing collaboration with municipal and county-level stakeholders. All four study catchments experience occasional floodings of the downstream areas, including both arable fields and urban areas. At the same time, nutrient losses from arable fields detoriate water quality in streams and additional measures are needed to improve water quality. Flood protection and nutrient loss mitigation from diffuse sources were identified by municipal and county-level stakholders as important challenges. The results presented here were delivered to relevant stakeholders with a goal to estimate possibilities for practical implementation of the results in study catchments. Two catchments, Hågaån and Enköpingsån, are smaller (119 and 164 km^2, respectively, Table 1), and the other two, Fyrisån and Svartån, are larger (915 and 761 km^2, respectively). Enköpingsåns catchment has a higher share of arable land, 42 %, compared to around 20 % in the other catchments. Small floods and waterlogging of arable fields are frequent; larger floods occurred recently in both Svartån (September 2023) and Enköpingsåns (February 2024) catchments. The cities of Uppsala, Enköping and Västerås are located at the outlet of Fyrisån, Enköpingsån and Svartån, respectively, whereas Hågaån is a mostly rural catchment. This part of Sweden is characterized by clay soils in the valleys and till soils mixed with organic soils and bare bedrock in upstream forested areas. Eskers, low ridges of glaciofluvial sand and gravel material with high.

permeability can also be found in the area. According to the Köppen-Geiger climate classification (Kottek et al., 2006), Fyrisån, Hågaån and Enköpingsån and southern parts of Svartån are situated in the Cfa zone (warm temperate, fully humid, hot summer) whereas the northern part of Svartån is in the Dfa zone (boreal, snow, fully humid, hot summer). Average annual temperature for the period 1991–2020 is around 6 °C and average annual precipitation varies between 400 and 600 mm. Hydrographs in this part of Sweden are characterized by streamflow above the yearly average during winter and lower during summer (Uvo et al., 2021).

Water quality in the four rivers does not meet Water Framework Directive Good Ecological Status criteria and agriculture is the main

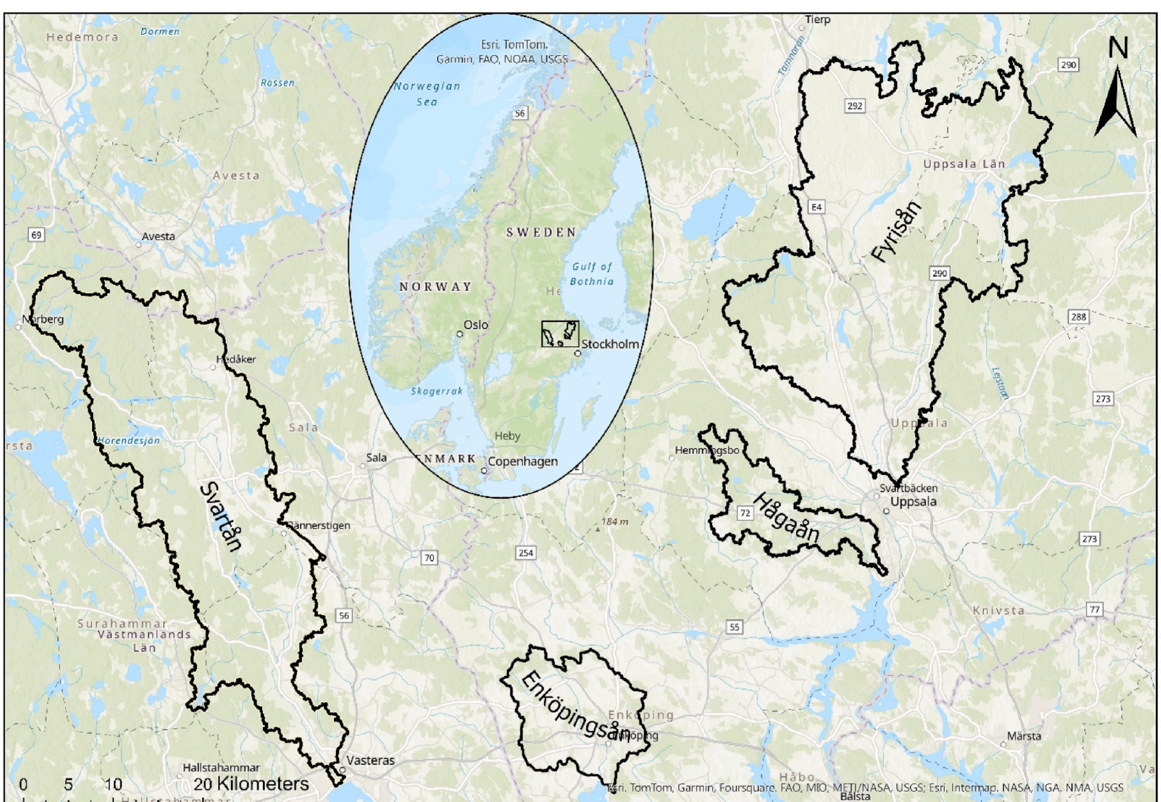

Fig. 1. Study catchments and their location in Sweden.

Table 1
Study catchments, area, land use distribution and flow statistics[a] where MHQ is mean annual high discharge, and HQ50 is discharge with return period of 50 years.

Catchment	Area	Wetland	Arable	Open land	Water	Forest	Pasture	MHQ[a]	HQ50[a]	HQ50
	km^2				%			m^3sec^{-1}		mm
Enköpingsån	164	1	42	16	0	38	3	6.0	10.7	5.6
Hågaån	119	7	21	12	1	58	2	5.3	10.3	5.8
Fyrisån	915	9	21	9	2	57	2	21.6	43.7	3.9
Svartån	761	9	19	7	4	59	2	26.1	42.6	4.5

[a] (Bergstrand et al., 2013).

source of nutrients (WISS, 2023).

2.2. Calculation of potential water storage

Water storage potential was quantified using soil distribution maps, a high-resolution digital elevation model (DEM) and GIS-based distributed modelling. The soil distribution map used combines the Geological Survey of Sweden soil map for non-agricultural areas and the Digital Arable Soil Map of Sweden, DSMS (Söderström and Piikki, 2016). DSMS is a 50 m × 50 m raster, whereas the Geological Survey of Sweden map is a combination of the best available data with a spatial resolution ranging from 1:50 000 to 1:250 000. Values of soil-specific groundwater depth and effective porosity (Table S1) were extracted from Hjerne et al. (2021). Subsurface water storage potential was calculated by multiplying soil-specific groundwater depth and effective porosity.

The basis for modelling surface water storage potential was a raster format DEM. A 2-m grid based on LiDAR data was used, with a density of 0.5–1 point m^{-2} and accuracy usually better than 0.1 m (Lantmäteriet, 2014).

The procedure for calculating water storage potential is as follows. First, all pits with a core area (flood-sensitive) larger than 1 ha were identified (Fig. 2) using PCRaster software for environmental modelling (Schmitz et al., 2009). Next, sub-catchment areas for all identified pits were delineated. The point with lowest elevation at the sub-catchment border (hereafter overflow point) was determined. Thereafter all cells with elevation higher than the elevation in pit point, but lower than the elevation in the overflow point, were identified as a pit core area in each sub-catchment. Potential water storage in each pit sub-catchment was calculated by multiplying this elevation difference with the area of each cell (4 m^2), followed by summarizing the calculated volumes within each sub-catchment. This value represents the current water volumes that can be stored in existing depressions.

A scenario with a maximum embankment height of 1 m at the sub-catchment border was calculated to further explore possibilities to store water. This was done by imposing 1 m high embankments at the overflow point at the border of each sub-catchment. Thereafter, all cells on the sub-catchment border with elevations lower than the overflow point + 1m were identified. By doing this, the required length of necessary embankment was also determined. Theoretically, the embankment length is shorter in topographically more suitable catchments for detention basin creation than in topographically less suitable catchments. The new potential storage volume was calculated in the same way as above, but this time using the difference between elevation at overflow point + 1 m and the elevation at pit point. Water volumes calculated in this way are limited only by the area and depth of created detention basin, and represent capacity potential. In reality, the storage volume can also be supply limited, i.e. by sub-catchment area and the potential amount of precipitation and flow entering the created detention basin. Therefore, supply potential was also calculated for an extreme 50-mm flow episode, where water from the upstream catchment was accumulated and compared to the calculated capacity potential (sub-surface and above soil surface). When calculated supply

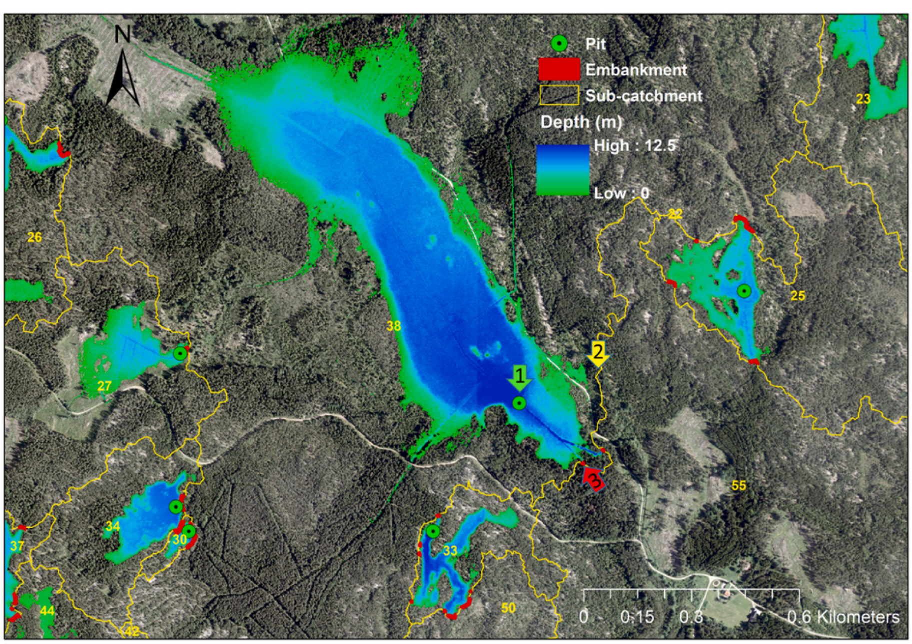

Fig. 2. Methodology for calculating water storage potential. First, all pits with core areas larger than 1 ha were identified (green arrow no. 1). Thereafter, sub-catchments were delineated for all pits (yellow arrow no. 2). The lowest elevation point at sub-catchment border (overflow point) was identified (red arrow no. 3). Thereafter a scenario with a 1 m high embankment at overflow point was created, where all raster cells at the sub-catchment border with elevation lower than elevation at overflow point + 1m were identified (red lines at sub-catchment borders).

potential from the surrounding catchment entering the detention basin was lower than the calculated capacity potential, the detention basin storage volume was assumed to be supply limited, and the supply potential was identified as the final water storage volume. On the other hand, if the supply potential entering the detention basin was greater than the capacity potential below and above soil surface, then the detention basin cannot retain all the water produced in its sub-catchment, the potential water storage is capacity limited, and is determined by calculated storage volume. The statistical test for effect size (Cohen's d) was calculated to estimate the difference in potential storage volumes between catchments.

The methodology described here identified pits all over the studied catchments. As this study focused on upstream forest/wetland areas, the national soil cover data layer (Swedish Environmental Protection Agency, 2023) was used to determine the distribution of land use categories flooded by imposing the 1m embankments. The National soil cover data layer is used here because it is a recent data set (2023) in high-resolution format (10 m raster). Thus, based on this data for each core area, it was possible to select and prioritize areas dominated by specific land cover, for instance wetland and/or forest.

2.3. Calculation of potential phosphorus reductions

Area-specific nutrient losses from forest soil in Sweden are low and considered a part of the natural background. In southern Sweden, the default forest export coefficient is 13 μg P l^{-1} (Hansson et al., 2019). Nutrient losses from arable land are considerably higher. Regional arable land P export coefficients were derived from the ICECREAM model (Larsson et al., 2007; Johnsson et al., 2019). Outputs from this model are used as the basis for estimating 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). In short, ICECREAM calculates P losses based on a set of parameters characterizing the production system, including geographical region, and representing climate, agricultural management and yields, crop distribution, soil textural distribution, soil P content and field slope. This study used the average export value for arable crops for each soil texture class of arable land present in a given catchment. All export coefficients used in this study are representative of central Sweden (leaching region 6 (Johnsson et al., 2019),), where all study areas are located. The DSMS (Söderström and Piikki, 2016) was used to determine the distribution of arable land soil texture classes in each catchment. Thereafter, export coefficient for each textural class were area-weighted to calculate export coefficients for arable land in each catchment (Table S2). Potential P loads were subsequently calculated using stored water volumes and both forest export coefficients and area-weighted export coefficients for arable land. The difference between the load calculated with the area-weighted export coefficient for arable land and the load calculated with the forest export coefficient represents the potential P reduction, assuming that the stored water in forest detention basins will not flood downstream arable land and mobilize P from arable soils. Once again, the statistical test for effect size (Cohen's d) was calculated to estimate the difference in potential P load reductions between catchments.

Finally, water authorities in Sweden have calculated total and sectoral P reductions to reach WFD Good Ecological Status for each water body (Erlandsson Lampa et al., 2021). Here, the estimated potential P load reductions were compared to the calculated targeted load from agriculture needed to meet WFD goals, summarized for all water bodies (lakes and streams) located in the study catchments.

2.4. Data analyses

The results were summarized in three ways, starting with total values per catchment. Second, as the focus of the study is on upstream, non-agricultural parts of the catchments, a subset of the detention basins covering at least 90 % of a combination of wetland and forest soil, and at the same time having a potential water storage higher than 10 000 m^3 was also selected. Finally, another selection from this subset was made to estimate the number of detention basins needed to store water volumes produced during a discharge episode with return period of 50 years (Table 1, HQ50).

3. Results and discussion

The total number of identified pits, 209–2313 (Table 2, Fig. 3), varied between catchments and was related to the catchment size. In spite of these large differences, the Cohen's d calculated for the potential storage volumes in different catchments was low and varied between 0.06 and 0.27, indicating small effect size. In other words, the actual difference in mean potential storage volumes between catchments is low. Most of the water storage potential was surface storage, with median subsurface storage varying between 3.4 % in Enköpingsån and 11.7 % in Fyrisån (Table 2 and Fig. 4). Enköpingsån has double the proportion of arable land (42 %, Table 1) consisting mostly of clay and silty clay soils with very low subsurface storage potential. Geomorphology of the catchment has a direct impact on the runoff amount and speed from the upland to the main channel (Kuriqi and Hysa, 2022). In three of four catchments (Enköpingsån, Fyrisån and Svartån), deep permeable glaciofluvial deposits in the form of eskers (Fig. 5) are present, with potentially large storage volumes. However, the storage potential in these areas is often supply limited, as restricted water flows from surrounding areas reach these eskers. Other than that, the subsurface storage potential is usually capacity limited, especially for clay soils in the valleys and upstream bare bedrock areas. Using best available information on soil effective porosity from available literature is however rather coarse method and needs to be further investigated and tested with for instance dynamic hydrological modelling. Water storage potential varies greatly both within and between catchments as well as between individual detention basins (Fig. 4), emphasizing the need for individual basin-level estimation of potential effects and with due consideration taken to local preconditions for detention basin establishment. Attenuation of large water volumes which is needed to reduce negative effects of flooding will require a considerable number of suitable detention basins in each catchment. Further, our results show that the potential effect need to be carefully estimated for each individual

Table 2
Some characteristics of potential detention basins per studied catchment. Conditions for detention basin selection are that detention basin area covers at least 90 % of a combination of drained wetland and forest soil, and having a storage potential larger than 10 000 m^3.

Catchment	Enköpingsån	Hågaån	Fyrisån	Svartån
Total no. of detention basins	377	209	2313	902
Subsurface storage (%)	3.4	8.1	11.7	8.4
No. of selected detention basins	14	27	504	165
Detention basin area, A (ha)	139	337	5297	1247
A (% of total catchment)	0.85	2.82	5.79	1.64
Embankment length (m)	4374	2340	319 565	63 016
Total potential storage (m^3)	435 544	1230 771	19 910 052	6089933
No. to reach HQ50	na	4	20	38
Detention basin area, A (ha)	na	163	601	546
A (% of total catchment)	na	1.40	0.66	0.72
Embankment length (m)	na	323	36 010	26 022

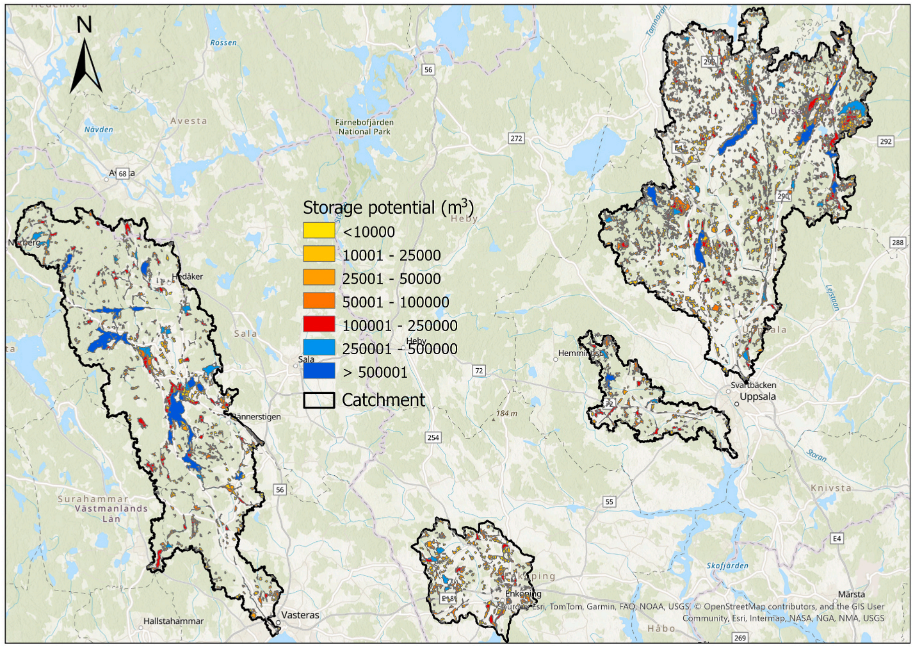

Fig. 3. Water storage potential for individual detention basins in four study catchments.

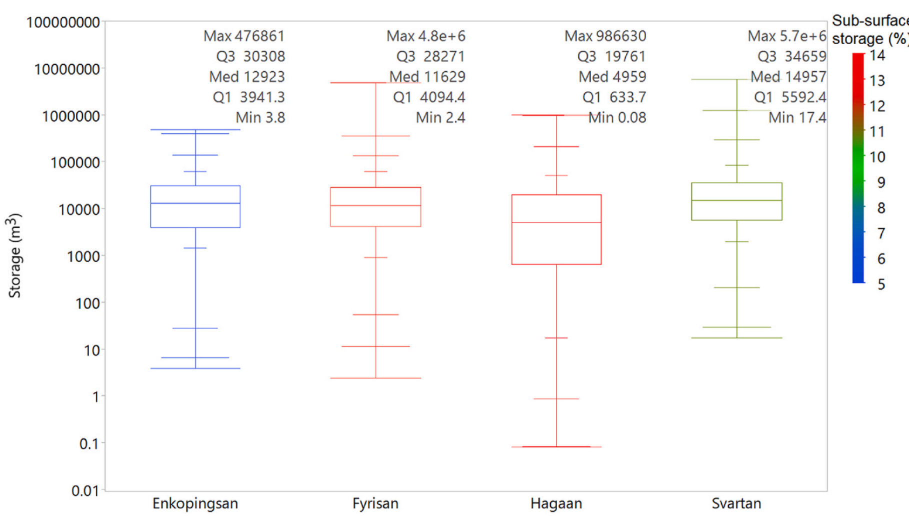

Fig. 4. Box-plots showing the distribution of the total potential water storage capacity in detention basins for each catchment. Quantile box shows minimum, 2.5 %, 10 %, 25 %, 50 % (median), 75 %, 90 %, 97.5 % quantiles and maximum. Note logarithmic y-axe. The color shows the potential to store water under the soil surface, as a percentage of total storage potential.

detention basin, based on local conditions, but due attention needs to be paid when assessing the incremental effect of a group of detention basins at catchment level.

For instance, imposing the two previously mentioned criteria (storage potential > 10,000 m^3 and >90 % wetland/forest) resulted in a considerably lower number of selected detention basins in studied catchments (Table 2). Peskett et al. (2025) estimated the effects of six flood storage ponds in a 69 km^2 catchment in Scotland, UK and showed that ponds can help to reduce flow peaks, but generally in small catchments and for small events. However, the potential detention basins in our study have considerably higher storage potential (Fig. 3) compared to Scotland study (maximum 6649 m^3). The lowest number of detention basins fulfilling the criteria (14 detention basins) was found in Enköpingsåns catchment, a catchment with lowest share of wetland/-forest soil (Table 1). Here, the total volume stored in 14 selected detention basins comprised slightly less than half (47 %) of the potential discharge volume produced during an episode with 50 years return period (HQ50, Table 2).

On the other hand, in the Hågaån catchment, construction of only 4 large detention basins covering 1.4 % of the total catchment area would be enough to store volumes corresponding to HQ50 (Table 2). This could be done by creating 323 m of 1m-high embankments. Suitable topography coinciding with a large share of wetland/forest soil in this catchment resulted in the possibility to reach large storage volumes with relatively small investments. However, other criteria need also to be included in the decision-making process to find most cost-effective solutions. For instance, catchment officers emphasized the importance of the detection of the potential restauration sites which were previously drained with open ditches. The largest detention basin in Fig. 2 is an example of such site, where plugging a ditch (dark blue line in the south-east, indicating higher water depth) with minor interventions can lead to establishment of rather large detention basin. Additionally, such

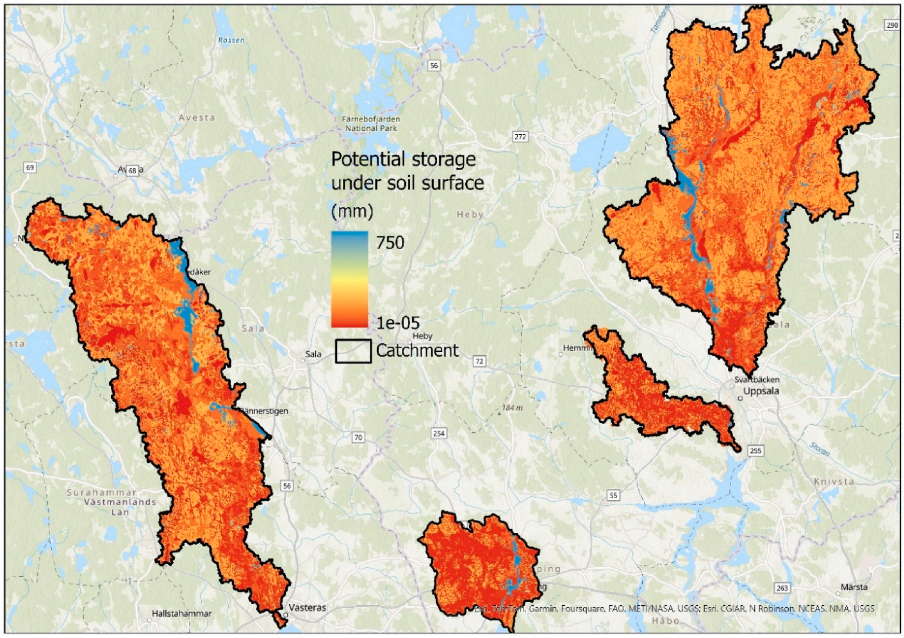

Fig. 5. Potential water storage (mm) under the soil surface for four catchments. Higher potential storage values (blue) are connected with deep permeable glaciofluvial deposits (eskers).

restauration efforts are much more juridically feasible compared to the establishment of new detention basins.

In the two larger catchments, Fyrisån and Svartån, considerably longer total embankment lengths are needed to create the detention basins to delay water volumes corresponding to HQ50 (Table 2). However, the detention basins relative areas (<1 % of catchment area) required to store water volumes corresponding to HQ50 were considerably lower. Both pit core area (1 ha), used here to identify pits in the catchments, and the proposed embankment height (1 m) are arbitrary. The number of identified pits could be reduced by increasing the core area, which might be especially relevant for the larger catchments, to refine the selection of larger detention basins. Another possible interesting development would be to develop optimization routine for embankment height. As many of the identified detention basins are suplly limited, i.e. limited by the water volumes generetad in their catchment, the necessary embankment height could be adjusted (i.e. lowered) to match a predefined magnitude of flow episode one would like to attenuate.

The calculated area-weighted export coefficient for arable land was lowest in Fyrisån (Table 3). There is a higher percentage of lighter loam soils in the Fyrisån catchment, whereas the other three catchments are heavily dominated by silty clay loam (Svartån) and silty clay soils (Enköpingsån and Hågaån). In Sweden, P losses are usually positively correlated to clay content in arable soil (Kyllmar et al., 2014), as clay soils are more susceptible to mobilization and transport of SS and attached P (Djodjic and Markensten, 2019; Sandström et al., 2020). As expected, the calculated P load reduction was lowest in Enköpingsån in absolute and relative terms (Table 3). Water storage potential in this catchment did not reach the volumes corresponding to HQ50 (Table 2), and the targeted load reduction was also higher due to a larger share of arable land (Table 1) and high P export coefficient (Table 3). Only 9 % of the targeted agricultural load reduction from this catchment could be offset with the 14 potential detention basins (Table 2) located on forest/wetland soils. The Cohen's d calculated for the potential P load reductions comparing Enköpingsån with other three catchments was high reaching 1.3, 1.6 and 3.7 (for comparisons with Hågaån, Svartån and Fyrisån, respectively) indicating large effect size. Few available sites for potential detention basins in Enköpingsån due to lower share of forest/wetland resulted in considerably lower average potential P load reduction. The reduction percentage was much higher for the other three catchments (32–57 %, Table 3). The findings presented here illustrate an unrealized potential to reduce nutrient losses from arable land by preventing water flow from upstream forest areas reaching downstream arable land, where nutrient-poor forest water can mobilize and transport nutrients from nutrient-enriched arable soils.

There are a number of uncertainties connected to these estimates of nutrient loss reduction. The assumption that all water stored in upstream detention basins will reach arable land and mobilize nutrients might not be met, leading to an overestimation of the P load reductions. On the other hand, calculated export coefficients are based on annual averages, and might underestimate P losses during extreme flow episodes with flooding, waterlogged soils, erosion and surface runoff (Heathwaite and Dils, 2000; Tang et al., 2016). Additionally, P release was found to depend on the ratio between the concentration of iron-bound P and amorphous iron (Loeb et al., 2008) or the soils' degree of P saturation (Djodjic and Mattsson, 2013) but we could not take into account this due to the lack of data. While estimates presented here are based on one large flood event (HQ50), smaller flood events can also negatively impact water quality (Talbot et al., 2018). However, while modelling of a storage capacity in detention basins indicate variable but in general large potential, these results need to be followed up by the dynamic hydrological modelling to test the performance of detention basins

Table 3
Potential phosphorus load reduction per study catchment calculated as the difference between area-weighted export coefficient for arable land and export coefficient for forest.

Catchment	Enköpingsån	Hågaån	Fyrisån	Svartån
Potential water storage (m^3)	435 544	708 480	3611520	3490560
Area-weighted export coefficient (mg P l^{-1})	0.44	0.45	0.37	0.43
P load (kg)	192	319	1336	1501
P load difference (kg)	186	310	1289	1456
Targeted load from arable land (kg yr^{-1})[a]	2181	954	3086	2565
Reduction (%)	9	32	42	57

[a] Data from Water Information System in Sweden (Erlandsson Lampa et al., 2021).

under different conditions, including for instance short intensive rains, prolonged wet periods with low intensity rains and snowmelt periods. Storage capacity prior to an event is the dominant factor controlling the performance of detention basins but also the rates at wich the basins fill and drain (Peskett et al., 2025). For instance, Ekström et al. (2025) showed in a modelling study that the flow-regulating capability of the constructed wetlands was related to the outflow mechanism, antecedent water level and the magnitude of the flow entering the wetlands. Such modelling should also allow for a sensitivity and uncertainty analysis of the model parameters as well as estimation of the effects both locally (i.e. downstream detention basins) and further downstream (catchment outlet). Detention basins designed to attenuate larger storm events will also help mitigate smaller episodes which may mean that actual nutrient retention potential is higher than reported here. On-going climate change will also lead to increased irrigation needs in Sweden due to a higher probability of dry spring weather (Grusson et al., 2021b). In such circumstances, water stored in upstream forest detention basins might become a valuable resource for irrigating downstream arable land. However, this requires discharge regulation in the detention basin and finding a balance between the detention basins function to prevent floods and their role as irrigation reservoirs, as water filled detention basins have limited buffering capacity for any extreme episodes. We suggest these detention basins should have an outlet that could be regulated to lower the water surface before high episodes.

In general, our results show that a large potential to store water in upstream forest/wetland areas exists in most cases, and that such water storage may have positive effects on the reduction of nutrient, particularly P, losses during extreme weather events. Having said that, not all upstream areas are particularly suitable for the creation of water storage detention basins and there is a need to develop selection criteria to identify the most promising sites. Birkinshaw and Krivtsov (2022) showed that risk, the location of a retention pond within a river catchment is important, and it can make the flooding worse at the outlet if it is located in the wrong location. The selection criteria include, but are not limited to, some parameters that can be easily calculated according to the methodology presented here. For instance, criteria such as calculated storage volume, detention basin area (area that will be flooded), and the required length of the embankments (as an indicator of required investment) are important factors to include when selecting suitable sites. Similarly, precise location of detention basins, expansion and composition of the area that will be affected by water and the current land use as well as landowner priorities are additional important criteria. Our study highlights further the need for large-scale of entire catchments/wetlandscapes (Thorslund et al., 2017; Quin and Destouni, 2018). Hambäck et al. (2023) argue that there is a need for a change in scale from a focus on single wetlands to wetlandscapes (multiple neighboring wetlands including their catchments and surrounding landscape features), and our results support that idea. Additional selection criteria need to be developed depending on the main purpose of upstream detention basins (i.e. flood prevention, nutrient reduction etc.). In some parts of Sweden, including the Fyrisån catchment, eskers are used for artificial groundwater recharge where raw river water is pumped into eskers to increase their capacity to deliver drinking water. Existing eskers in study catchments were indicated as having high subsurface storage potential but are often supply limited. A combination of detention basins to intercept water before pumping it up to eskers might be an alternative to not only store water and recharge groundwater but also to reduce floods. As the local preconditions governing suitability for water storage are highly variable within catchments, a systematic approach is needed to select suitable and cost-effective solutions (Djodjic et al., 2022). At present, upstream detention basins and wetlands are not included among selected countermeasures to reduce nutrients. We present here the first estimates of the potential to reduce nutrient losses from arable land at catchment level, by intercepting and slowing upstream water flows and avoiding flooding and waterlogging of arable land. Such estimates can be made for individual detention basins to further increase the knowledge base for land managers and facilitate informed decision-making at landscape level. This broader knowledge base needs to be followed by adequate policy and legislation development to motivate landowners to implement upstream detention basins. The multiple benefits of upstream detention basins such as flood mitigation on arable and urban areas, nutrient loss reduction and possible irrigation during drought periods to increase crop yields must be balanced by possible trade-offs associated with the loss of productive forest land or unintended increases in mosquito populations or possible negative effects on greenhouse gas emissions and/or risks for elevated methylmercury formation (Laudon et al., 2023). However, the additional costs for landowners for detention basin construction and maintenance must be recognized and supported by broader society and stakeholders, especially sensitive downstream sectors which may be the main beneficiaries.

Sweden continues to invest in wetland construction/restoration (Djodjic et al., 2020) to increase biodiversity, to increase nutrient retention, and to reduce greenhouse gas emissions. As focus of this study was on the potential detention basins located on old wetland soil, they mostly coincide with the last objective, where rewetting of the wetlands aims at reductions of CO_2 emissions (Zou et al., 2022).

4. Conclusions and future perspectives

Extreme precipitation events are expected to become more frequent, increasing risks for both floods and nutrient losses. Our results show there might exist significant potential at the landscape scale (100–1000 km^2) to attenuate water flows in upstream, forested parts of catchments to reduce flooding of arable land and urban areas. However, the potential water storage capacity is extremely varying and site-specific, and local preconditions in terms of topography and underlying soil properties dictate both the storage capacity magnitude and the required investments to secure large storage potential. Therefore, prioritization needs to be assessed on an individual detention basin basis, considering a number of criteria, including the potential for water storage and nutrient loss prevention, the value of areas that will be flooded, the value of areas to protect downstream, as well as the level of efforts needed to secure efficient damming (the length of embankments). The methodology and results presented here cover a majority of these criteria and can be a valuable input for discussions regarding the suitability and the potential of detention basins in upstream forest areas to protect downstream arable land and settlements. However, in spite of the demonstrated large storage potential at landscape level, the main limitation of this study is that the results represent a snapshot in time and do not take into consideration the dynamic nature of catchment hydrology. Therefore, the

next research step needs to involve dynamic hydrologic modelling to estimate the buffering efficiency of detention basins during a serie of precipitation and discharge events, with consideration taken to adjacent moisture conditions and the ability of detention basins to both accumulate water and slowly release it under controlled conditions.

The next step in the current research project is collaboration with the stakeholders at the municipal level, water strategists and catchment officers to discuss received results and scenarios as well as possibilities and obstacles in order to prioritize detention basin selection on the road to practical implementation. The received results and maps have been presented and delivered to project partners and are a discussion base in the negotiations with local landowners to find most cost-effective solutions. Another future challenge is integration with other NBS in agricultural landscape (e.g. constructed wetlands) and definition of proper policies and instruments to facilitate higher implementation of detention basins.

CRediT authorship contribution statement

Faruk Djodjic: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Pia Geranmayeh:** Writing – review & editing, Project administration, Conceptualization. **Emma E. Lannergård:** Writing – review & editing, Project administration, Conceptualization. **Martyn Futter:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization.

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.

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Appendix A. Supplementary data

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Data availability

Data will be made available on request.

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