WetKit Hydro-ES : Wetland Toolkit for Hydrological Ecosystem Services

Purpose, goals and questions

The overall goal of this project is to provide practitioners, land owners, water managers and relevant authorities with a toolkit to evaluate and promote the implementation of wetlands in agricultural landscapes. This toolkit will support a holistic and multi-functional approach to climate adaptation in line with existing socio-economic and institutional contexts by optimizing the delivery of hydrologically-related ecosystem services (ES) with a view to maximizing co-benefits whilst minimizing negative consequences.

Specifically, the project will identify concrete actions for using wetlands as Nature-based Solutions (NBS) to enhance the vertical components of the hydrological cycle (e.g. storage, infiltration and atmospheric vapor recycling) while limiting lateral flows (e.g., reducing both the total amount of runoff and peak flows while maintaining base flows, Fig. 1). In Sweden, water management in production landscapes (i.e. farms and forests) has focused on drainage to optimize lateral water flows[1] and maximize production for food, feed and fiber. This has contributed to the situation today where climate change and land management are leading to increasingly frequent and severe floods and droughts. In relation to that, there is a strong need for a paradigm shift which changes the focus of water management from optimizing lateral flows for rapidly moving water out of the catchment to a more holistic perspective which incorporates both lateral and vertical water fluxes to build a more resilient landscape. The key ambition behind our project is to facilitate this shift, by increasing awareness of the benefits from wetlands, and providing practical evidence-based tools for relevant actors to support wetland creation, restoration and management.

We will focus on hydrological ES which increase resilience to extreme climate events (flood and drought mitigation, wetter soils, groundwater recharge, evaporative cooling), other benefits (nutrient retention, carbon sequestration, maintenance of biodiversity) and related trade-offs (loss of productive land, greenhouse gas (GHG) production). Our goal is to contribute to the development of context-sensitive, evidence-based policies and strategies using wetland management to improve landscape resilience to climate-change while maintaining food and fibre production and ES delivery

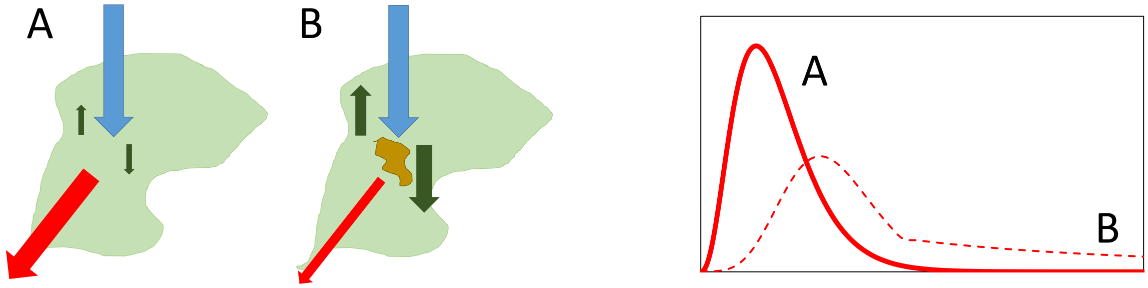

Figure 1: The overall project goal is to identify targeted wetland creation, restoration and management actions to increase vertical water flows (atmospheric vapour recycling and infiltration; green arrows) while moderating lateral flows (surface runoff). The goal is to move from a situation where most precipitation falling in the catchment (blue) moves laterally as surface runoff (red; Panel A) to a situation where wetlands reduce lateral flows while enhancing atmospheric vapour recycling and groundwater infiltration (Panel B). The net effect of these actions is to reduce the height of the flood peak hydrograph and contribute to maintenance of base flows.

The purpose of this project is to generate and communicate the knowledge needed to use wetlands as NBS for optimal delivery of hydrologic ES based on a shift from lateral to vertical water fluxes. We will identify, validate and communicate targeted principles, strategies and guidelines that support farmers, land managers and relevant authorities to successfully implement place-specific measures aimed at wetland protection, management and planning with an overall goal of increasing landscape resilience to extreme climate events and wetlands multifunctionality. Specifically, we will identify sustainable management actions to enhance, restore or create wetlands, thereby ensuring the ongoing delivery of hydrology-related ES that increase landscape resilience to extreme climate events in the face of climate change.

Research questions and hypotheses

What is the impact of constructed agricultural wetlands on hydrologic processes at a local and a catchment scale? Specifically: (i) what existing evidence is there for effects of wetlands on components of local and catchment-scale water balances, i.e., infiltration, water holding, flows of atmospheric water vapour and runoff; (ii) what new measurements are needed to better develop the evidence base for Swedish conditions (iii) how important are wetland type, size and location in the catchment as predictors of effectiveness in converting lateral water fluxes to vertical fluxes, (iv) to what degree can management activities influence these factors.

What is the best way to optimize wetland multifunctionality? Specifically, what wetland design or management actions will simultaneously maximize hydrological ES while retaining nutrients, sequestering carbon (C) and promoting biodiversity while avoiding excessive GHG emissions and loss of productive land?

Controlled and uncontrolled factors influencing wetland hydrologic functioning and multifunctionality? Specifically, (i) what is the potential impact of extreme climate events (droughts and floods) on lateral and vertical water fluxes from wetlands, (ii) what is the effect of these hydrological changes on nutrient retention and wetland C/GHG balances; (iii) how does wetland size and position in the catchment affect response to extreme climate events?

How are agricultural wetlands perceived by relevant stakeholders? Specifically, what are the perceptions of farmers, land owners, water managers, authorities, regulatory bodies, academics and non-governmental organizations (NGOs) on (i) the potential for agricultural wetlands to deliver multiple ES with specific focus on hydrologic ES which enhances landscape-scale resilience to extreme events, (ii) the existing barriers and enabling factors for agricultural wetland creation, restoration and management.

Expected result

The expected result of this project is practical guidance and tools for optimal "no regrets" wetland management strategies which will contribute to climate adaptation by maximizing the delivery of hydrologic and other ES while minimizing undesired trade-offs, e.g., GHG emissions and loss of productive land. The increased landscape resilience accruing from optimal wetland placement and management will help landowners, farmers and water managers to face extreme events and to protect against soil erosion and nutrient loss. By identifying management options which can maximize GHG sequestration, wetlands in agricultural landscapes will decrease the overall C-footprint of agriculture. The key outputs include a web-based handbook and decision support tools including high-resolution maps showing location of wetlands of different sizes, optimized from a multi-functional criteria as well as a popular science film highlighting the role of multifunctional nature of agricultural wetlands with a focus on hydrologic ES. We anticipate that the film will increase awareness amongst the general public, farmers and land owners about the importance of wetlands.

We expect the project to:

(i) Extend the evidence base needed to critically evaluate the role of wetlands in providing hydrological ES through a combination of targeted data collection and synthesis. Here, we will conduct targeted field measurement campaigns at a suite of agricultural wetlands so as to better constrain their role in flood and drought risk mitigation, as well as deriving better estimates of their potential to promote infiltration, groundwater recharge and contribute to evaporative cooling through atmospheric vapour recycling. The potential for delivery of these hydrological ES will be complemented with measurements of GHG emission, C sequestration and nutrient retention needed to assess multi-functionality. Furthermore, we will synthesize existing best practices about wetland placement, function and management from Sweden, Denmark and other relevant areas in Europe by extending earlier reviews[2,3,4,5,6] to provide clear guidance for optimal use of wetlands for delivery of hydrological ES in a Swedish context.

(ii) Provide credible estimates of the implications of a changing climate on wetland hydrological ES when the frequency and intensity of precipitation events changes. Using a recently developed protocol to evaluate the impact of extreme precipitation events on runoff[R07], with the PERSiST model[8]; a catchment hydrological model designed for flexible representation of evaporation (atmospheric vapour recycling), landscape water retention (surface, soil and groundwater stores), routing and runoff (lateral movement) (www.persistmodel.org) to explore and predict the hydrological ES effects of constructed wetlands in the agricultural landscape. PERSiST will be used together with a GIS-based model based on high resolution (2X2 m) lidar derived topography and land management layers[9,10] to evaluate potential wetland sites. Our evaluation toolkit will also include models for estimating site-level GHG emission[11] and nutrient retention[12]. All of these models will be further customized so as to maximize their usefulness in a Swedish context.

(iii) Identify social, economic and institutional factors influencing wetland creation, maintenance and restoration with a focus on hydrologic ES potential in Swedish agricultural landscapes and develop a support system to promote their implementation. Using protocols we developed[13], we will survey farmer and land owner perceptions of wetland ES, their awareness of the need for wetland creation, restoration and management, and their willingness to support wetlands. Additionally, we will conduct a series of targeted interviews with professional stakeholders working with wetlands (i.e., water managers, local authorities. Regulatory bodies, academics and NGOs) to reveal existing barriers and supporting factors of wetlands creation, restoration and management in the Swedish context. Interview and survey results will be used as a base for in-depth focus group discussions with stakeholders at a series of workshops. The role of stakeholder workshops will be to (i) develop a dialogue with relevant stakeholders early on in the project, (ii) provide a platform to debate the factors which influence stakeholder decision making, and institutional barriers and opportunities for using wetlands as NBS[14,15,16], as well as potential improvements that would lead to more frequent use of wetlands as NBS, and (iii) co-develop and test the toolkit described above and an existing evaluation methodology (AE-Footprint)[17] that will be expanded to provide decision support for ranking potential wetland sites in terms of.hydrological ES potential, multi-functionality an climate resilience.

(iv) Develop a unique film highlighting the current and future potential for wetlands as a multifunctional NBS delivering hydrologic and other ES in Sweden. The goal of the film is to raise awareness amongst the general public about the importance of constructed wetland in agricultural landscapes, their role in the hydrological cycle, and the other ecosystem services they provide. With award winning film maker Johan Heurgren (www.heurgren.se), we will produce a high quality Swedish language popular science program about the hydrologic ecosystem services delivered by wetlands. This film will synthesize work in the first three components in an easily understandable manner so as to raise public awareness about the vital role of wetlands in climate mitigation and adaptation. We will follow the same model as in our FORMAS-funded “Forest Water” project and produce a broadcast quality Swedish language TV program.

Benefit for the Swedish EPA and SwAM - relevance and practical use

The work of the project is expected to lead to a more frequent use of wetlands as NBS for increasing climate change resilience and delivery of multiple ES, which will directly support the Swedish Environmental Objective “Thriving Wetlands”. The project will also support the Environmental Objectives “Varied agricultural landscape”, “A rich diversity of plant and animal life” and contribute to “Reduced climate impact” As an integral outcome of the project, the results will be made available in forms (a guidance document summarizing best practices, web-based evaluation tool and a film) which can be used that can be used by the Swedish EPA and the SwAM to promote understanding among the general public and increase uptake by stakeholders after the project is concluded.

Target groups

Target groups include farmers, land owners, water managers, municipalities and other relevant authorities at multiple governance levels including national actors, i.e., the Swedish EPA and SwAM. Farmers and other rural land owners are the group with the largest potential to change their land management to give a higher priority to wetland creation, maintenance and restoration. Municipalities are implementers, influencers and beneficiaries. Within their territories, municipalities can implement measures to create, maintain or restore wetlands. As municipalities have responsibility for environmental issues, they can influence landowners and farmers through information campaigns and awareness raising. The role of wetlands as natural flood mitigation measures may also generate important downstream flood risk reductions[18] that if recognized by municipalities would support greater uptake.

The research task - Theory and methodology

The research task is to study wetlands as socio-ecological systems with a view to understanding the biophysical and social barriers to hydrological ES delivery form multifunctional wetlands in the Swedish agricultural landscape.

The biophysical factors influencing wetland hydrologic ES delivery can be conceptualized into the controlled and uncontrolled extrinsic and intrinsic dimensions (Fig. 2). All intrinsic factors are related to wetland location and management, while extrinsic factors include those amenable to management (e.g. crop type and land use) as well as those which are outside the scope of management control (e.g. catchment properties and climate). Of special interest is the manner in which extrinsic controlled factors (i.e. land management) can help to increase resilience to climate change and other extrinsic uncontrolled factors.

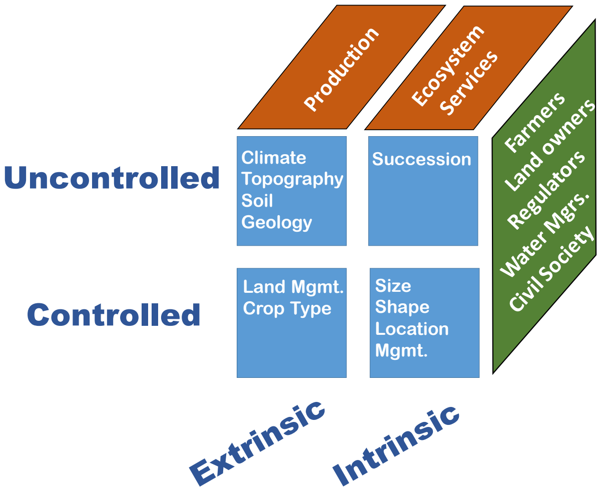

Figure 2: Environmental (blue), economic (brown) and social (green) dimensions influencing the potential for agricultural wetlands to deliver hydrologic ecosystem services (ES). Environmental factors are either controlled or uncontrolled, depending whether or not they are amenable to management and extrinsic *vs.* intrinsic depending on whether they are properties of the wetland or the surrounding catchment. Economic factors can be related to either actual costs associated with wetland creation and maintenance or the value of ES accruing from the wetland. Social factors are related to the different perceptions of wetland benefits held by different stakeholder groups.

When addressing social factors, we will focus on the perceptions of wetlands held by different stakeholder groups and on institutional barriers and enabling factors for wetland development and use as NBS for delivery of hydrologic ES. Whenever possible, economic factors related to wetland construction, operation and maintenance will be assessed and the value of ES delivered by wetlands will be quantified with a special consideration of multi-functionality[19].

State of knowledge

Wetlands are widely proposed as NBS for ES delivery[20,21,22] and for supporting the UN Sustainable Development Goals[51]. The benefits of wetlands for biodiversity[23], water purification and other hydrological services[2,24], and recreation and cultural services[3] are well-recognized.. Sweden has devoted a significant amount of resources to the creation of wetlands in the agricultural landscape. Approximately 4000 wetlands covering 9000 ha were created between 2006 and 2015[24], and constructed wetlands are an important part of Water Framework Directive Programmes of Measures for eutrophication control[14,44].

While the influence of wetlands on the hydrological cycle is generally positive, and removal or drainage of wetlands often has negative effects on total runoff and peak flows, there are notable Swedish exceptions; e.g. drainage of forest wetlands resulted in a counterintuitive decrease in peak flows[25]. It is therefore overly simplistic to assume that intact wetlands always deliver more hydrological benefits than other land uses and that restoration of degraded wetlands automatically results in net ecosystem service benefits. For instance, restoration of degraded wetlands may have unintended outcomes, e.g., nutrient leaching, GHG production and loss of productive land. Balancing and communicating the tradeoffs associated with the use of wetlands as NBS for hydrologic ES delivery requires a transdisciplinary approach combining social and natural sciences with strong involvement from actors outside the academic environment (e.g., farmers, land managers and communication specialists).

Programs currently supported in Sweden through the EU Rural Development Program and other public dedicated financing (LOVA) have primary goals of reducing nutrient losses (N and P) and/or positive impacts on biodiversity. The direct benefits to landowners from the establishment of wetlands in the current programs are financial and, to some degree, enhanced recreational opportunities. Quantifying the impact of wetlands on their capacity for water retention is expected to show that they reduce flood risk during extreme rain events and increase access to water during drought periods While both of these benefits are important for local landowners and farmers they also have significant downstream benefits with respect to reducing the risk for flooding. A dialogue that allows local stakeholders (landowners and farmers) and downstream stakeholders (public water managers) to explore water retention benefits is expected to lead to an increased understanding of both wetland placement and the shared benefits of this placement. This in turn will support wetland creation and restoration.

Wetlands alter lateral and vertical hydrological fluxes[2,6]. By slowing runoff, wetlands moderate peak flows and contribute to base flow maintenance (lateral flux). Although the flow reduction potential of wetlands is widely recognized, the spatial data and tools for predicting the hydrochemical consequences of land management were, until recently, lacking. High resolution lidar data offers new opportunities for managing NBS[18]. We have employed these data to identify critical source areas for P losses[10] and subsequently initiated stakeholder dialogue concerning the most cost-effective locations for nutrient abatement measures. Lidar data can also be used to generate landscape-scale quantification of water storage potential[26], making it possible to estimate the amount of water that could be retained in created or restored wetlands.Simultaneously, the water-slowing function of wetlands gives potential for increased rates of infiltration to groundwater and atmospheric vapor recycling (vertical flux). While enhanced infiltration is promoted as one hydrological ES delivered by wetlands[20,21,22], direct measurements of groundwater infiltration underneath wetlands are limited[27]. Recently a superior, combined approach based on modelling and empirical measurements for estimating groundwater infiltration beneath wetlands has been proposed[28].

These hydrologic effects in turn affect the delivery of other ES. For example, nutrient retention is largely dependent on hydraulic loading rate (HLR), i.e., the speed at which water moves through the landscape. Decreasing the HLR allows for the settling of particle-bound nutrients (C, N, P) and provide key conditions for denitrification to occur, i.e. low oxygen and a C- and N -rich environment. Denitrification is a microbial process that converts nitrate (NO_3^-) present in the water into gaseous forms of N (N_2O and N_2). This process is particularly desirable in agricultural areas where excess NO_3^- is present as it decreases eutrophication of aquatic ecosystems. Hence, wetland creation and restoration are considered effective mitigation methods for decreasing nitrogen (N) losses from agricultural land[23,34,35].

However, there are also potential uncertainties and risks in using wetlands. For rewetted former agricultural land there is a risk that P accumulated in soils will be released[36,37]. This can potentially be balanced by retention of particulate P by sedimentation and biological uptake that are expected to become significant processes in restored wetlands[38]. In addition, wetlands release GHGs and are the largest natural source of atmospheric methane (CH_4)[39]. Small wetlands may be disproportionately important for GHG emissions, but are inadequately studied[40]. Furthermore, bubble emissions of CH_4 (ebullition) are poorly quantified for small waterbodies despite being the dominant pathway of CH_4 emission[41] and ebullition is enhanced by eutrophication and climate warming[33]. Balanced against these GHG emissions is the C sequestration potential of these systems. This C sequestration arises due to organic C (OC) accumulation in wetland sediments. Wetlands in agricultural landscapes have particularly high OC accumulation rates because fertilizer increases primary production and because agricultural soils are often rich in OC and prone to rapid erosion[43]. If C sequestration exceeds C emissions (converting all GHG as CO_2 equivalent), the wetland is a net C sink. Considering that wetlands are being increasingly promoted in rural landscapes for hydrological ES delivery and to improve water quality, it is important to quantify their impact on GHG and C dynamics, considering all gases and pathways

To minimize negative consequences of wetland creation it is crucial to not only understand all the aforementioned processes but also to correctly locate created wetlands in the landscape. This placement determines the amount of water and nutrients reaching the wetland, both of which are important factors for wetland nutrient retention efficiency[29,30]. However, little attention so far have been paid to optimizing wetland placement in the landscape to increase water and nutrient retention. Our new high-resolution distributed models[9] and their implementation for large scales[10] creates a base for quantification of water and nutrient fluxes at the scale and precision (subcatchment-farm-field) relevant for end-user (farmers, advisory services and authorities). We have used these models to optimise placement and size of constructed wetlands in agricultural landscapes in order to maximize P retention[31]. With a similar approach[26,32] it will be possible to estimate wetland water storage capacity so as to reduce downstream flood risk and to mitigate against the effects of drought.

While evidence-based ecological knowledge is necessary for providing tools and strategies for wetland development and management that support multiple ES, it is not sufficient for efficient implementation. Tools and approaches must be adjusted to the needs of relevant stakeholders, and co-developed with them to create the sense of ownership, and thus stronger motivation, for their application. In addition, there is a need for increasing the awareness of wetland ES benefits among both the general public and the actors that create, restore and manage wetlands. In our project we will address all these aspects by socio-economic investigation into perceptions of wetlands, and strong collaboration with relevant stakeholders.

In this work we will build on the existing research concerning enabling factors and barriers in NBS implementation. There are numerous Swedish studies of the social factors influencing successful wetland projects[13,14,44,45], including one where we identified success factors for coastal wetland restoration[13]. While this study had a focus on coastal wetlands as fish nurseries, there are transferable recommendations that can be used in this project. Studies have also evaluated the factors that influence farmer willingness to participate in wetland management schemes[24,44,45]. Finally, studies have addressed water governance issues related to wetland management at the municipal and regional levels[14,15,16].

Organization and management

The project is organized around five work packages (WP). Work Package 0 focuses on project administration, coordination and reporting. The remaining four WPs are devoted to addressing the four concrete goals identified earlier. WP1 will focus on data collection and synthesis of local and landscape-scale biophysical factors influencing wetland hydrological functioning. WP1 is devoted to evaluating the implications of a changing climate on the delivery of hydrological ES from constructed wetlands in the agricultural landscape. WP2 will address the relationship between multi-functionality (climate impacts and nutrient retention) hydrological ES. WP3 will build the decision support toolkit while WP4 will identify the social and institutional factors which facilitate or hinder the uptake of wetlands as a climate adaptation measure while WP5 is production of a broadcast-quality film and supporting learning material highlighting the hydrological ES delivered by Swedish agricultural wetlands.

The consortium consists of PI Martyn Futter (MF) and co-applicants Joachim Audet (JA), Malgorzata Blicharska (MB), Dennis Collentine (DC), Faruk Djodjic (FD), Pia Geranmayeh (PG), Johan Heurgren (JH) and Mike Peacock (MP). All members of the consortium have successful on-going collaborations. The 8-member consortium includes men (6) and women (2) from academia (7) and the private sector (1). The academics include a mixture of senior (3), mid- (2) and early career (2) researchers. WP leads are indicated in **bold**. As SLU does not charge overhead on all items, the project overhead has been adjusted accordingly.

WP0: **Project Administration and Management (MF)**

This WP will be responsible for the day to day running of the project, project coordination, liaison with the reference group, financial administration, and ensuring that schedules are maintained.

WP1: **Role of agricultural wetlands in the hydrological cycle** (**FD**, JA, MF, PG, MP)
This WP will consist of five tasks to (i) identify candidate wetlands, (ii) measure components of wetland water balances in the field, (iii) perform laboratory analyses needed for partitioning of vertical water fluxes, (iv) calibrate wetland and catchment scale water balance models to estimate rates of infiltration, atmospheric vapor recycling (evapotranspiration) and runoff and (v) document and synthesize best practices for ensuring hydrological ES delivery from constructed wetlands. The primary goal of this WP is to produce multi-year estimates of lateral and vertical water fluxes at 40 agricultural wetlands in the Mälardalen region of Central Sweden.

Task 1: *Identification and characterization of wetland candidate sites*: Forty constructed agricultural wetlands overlaying clay and sandy soils will be monitored. The 20 wetlands on clay have already been identified and preliminary characterizations conducted as part of another project[49]. The protocols used for identifying wetlands on clay soils will be used to identify 20 additional agricultural wetlands on sandy soils. Wetlands will be selected to span a range of primary purpose (e.g., nutrient retention, biodiversity, hydrological ES), HLR, shape and age.

For each wetland, the drainage catchment will be mapped using a combination of lidar and site visits. Detailed maps of wetland bathymetry and shape will be prepared. Land use, soil types and other relevant catchment characteristics will be extracted using geographical information (GIS) tools and using available national and global databases[49]. At each site, terrestrial riparian vegetation around the wetlands and emergent and submerged aquatic vegetation will be characterized and quantified (e.g. species identification, abundance, percent cover). Two sediment cores will be collected from each wetland. These cores will be used for laboratory infiltration testing needed to assess groundwater recharge potential and for estimating C-sequestration and nutrient retention[48] in WP2.

Task 2: *Field Campaigns for water balance estimation:* So as to assess changes in water storage, each wetland will be instrumented with an automated water level logger (OnSet HOBO U20L or similar). Precipitation inputs will be derived from gridded data sets, which we have shown to be more effective than instrumental measurements for hydrological modelling[52]. Soil moisture adjacent to the wetland will be measured using an OnSet S-SMD-M005 (or similar). Water level and soil moisture data will be recorded using OnSet HOBO USB-MicroStation (or similar). Each site will be visited 4X/yr to download the loggers, to take water chemistry samples and to collect drone footage. The following water chemistry parameters will be analyzed: total P, particulate P, total N, DOC, nitrate (NO_3^-), ammonium (NH_4^+), phosphate (PO_4^{3-}), and chlorophyll a (Chl. a). Water clarity (Secchi depth), pH, conductivity and oxygen concentration will be measured in the field. Vegetation mapping by drones will be conducted to support WP2 task 4 and to provide additional material for the film and learning environment (WP5).

Task 3: *Laboratory Analysis of Potential Infiltration Rates:* As the proposed field measurements cannot effectively partition vertical water fluxes into upward (atmospheric vapor recycling) and downward (groundwater recharge components), we will estimate potential infiltration rates below the wetland using laboratory measurements of water movement in sediment cores collected in Task 1. These laboratory measurements will then be used to constrain the infiltration term of a wetland water balance model[R28].

Task 4: *Water balance modelling:* Wetland[28] and catchment[8] scale water balance modelling will be conducted based on data collected in tasks 2 and 3. The catchment-scale model will be calibrated using a novel "soft calibration" scheme based on soil moisture measurements which we have developed for locations where streamflow data are not available[51]. Models for the 40 wetlands calibrated to present day conditions will be used in WP3 to assess possible effects of changing precipitation regimes on wetland hydrological functions. These calibrated models will be used to support stakeholder workshops (WP4.2).

Task 5: *Synthesis of best practices*: We will produce a review of wetland hydrological ES delivery focusing on constructed agricultural wetlands in the Swedish landscape. The main purpose of this task is to use the results of this WP to extend existing reviews of wetland hydrological function[2,3,4,5,6] and ES delivery[20,21,22,R55] so as to produce a guidance document suitable for use by stakeholders and to provide content for the WP5.2 "story map". This task will link to WP3.4.

WP2: **Optimizing wetland multi-functionality** (**PG**, JA, FD, MP)
This WP will address the potential for C-sequestration (task 1), nutrient retention (task 2) and biodiversity-promoting ES (task 3) in constructed agricultural wetlands viewed through the lens of wetland hydrological function.

Task 1: *Wetlands in the carbon cycle* A survey of GHG emissions and C-sequestration will be performed at the 40 wetlands monitored in WP1. The goal of this survey is to relate C-sequestration to wetland hydrological functioning. Sites will be sampled 4X/yr (once per season) for two years. A few (10-20) wetlands will be monitored more intensively for 1 year to investigate temporal variation at a higher resolution needed to obtain reliable estimates of CH_4 ebullition and diurnal variations in CO_2, CH_4 and N_2O. The potential for C-sequestration under different wetland management scenarios will be explored and the impact on the total GHG emission from agriculture will be quantified. GHG emissions will be determined using multiple methods. Dissolved CO_2, CH_4, and N_2O concentrations will be measured using headspace technique and gas chromatography[46].These measurements will be complemented by high temporal resolution CO_2 and CH_4 flux measurements using floating chambers connected to a portable GHG analyser (Picarro Gas Scouter) so as to characterize CH_4 ebullition events and improve the characterisation of this critical but often neglected emission pathway. Floating chambers equipped with CO_2 sensors [47] will be used to record partial pressure of CO_2 at high temporal resolution (5 min) so as to quantify diurnal variation. Several chambers will be used at each wetlands to obtain estimates representative of the spatial variability of bubble emission. C-sequestration will be quantified using a combination of long-term estimates derived from sediment cores and short term rates estimated using sediment traps. Long-term OC accumulation rates at the 40 wetlands will be estimated by determining OC content in profiles in sediment cores collected from each wetland. Sediment traps will be installed and collected quarterly over two years to quantify sediment accumulation rates. Collected sediments will be weighted and their OC content determined so as to provide present-day OC accumulation rate estimates· Traps will be deigned to provide realistic estimates of sediment accumulation rates[50].

Task 2*: Nutrient retention and hydrological ES* Nitrogen and P retention will be quantified for the 40 candidate wetlands characterized in WP1. Long-term P retention since wetland construction will be quantified based on analyses of sediment cores collected in WP1. Seasonal and annual N retention will be quantified based on the water samples collected in Task 1 and modelled water flow (WP1.4). Wetland HLR will be estimated based on modelled water flow and wetland area. Both long-term average and extreme HLRs for the wetland life time will be estimated for each site using protocols we have developed earlier for extreme event analysis[7]. The maximum and optimal HLRs for N and P retention will be estimated and used for developing a tool for optimal placement and size of wetlands (WP3.2). Modelling of water, N and P retention using our methods as well as currently existing estimation methods[29,30] will be performed to facilitate upscaling.

Task 3: *Promoting Biodiversity* Results of the vegetation surveys (WP1.1, WP1.2) will be analyzed to identify the relationship between hydrological ES and site biodiversity and to explore whether or not vegetation metrics can be used as a proxy for hydrological functioning.

Task 4: *Wetland multi-functionality from a hydrological perspective:* The data generated from the large number of wetlands surveyed in this project are unique. By measuring hydrological function, C-sequestration, nutrient retention and plant communities at 40 wetlands on representative soils with varying HLRs, we will have a valuable data set for assessing wetland multi-functionality and quantifying four of the Swedish Environmental Objectives related to "Thriving Wetlands", "Reduced Climate Impact", a "Varied Agricultural Landscape" and "A rich diversity of plant and animal life". By using this data set and new spatial data and models we will provide guidance for optimized wetland design and placement in regard to HLR (in a changed climate), high nutrient retention, increased biodiversity and minimal GHG impact. Consideration of multi-functionality is especially important as there is evidence, e.g., that wetland N removal could be higher with better design and placement and that nutrient wetlands have high species richness as well.[23]

WP3: **Controlled and uncontrolled factors influencing wetland hydrologic functioning and multifunctionality** (**MF**, DC, FD, PG)2.2)

This WP will assess the potential impact of extreme climate events (droughts and floods) on lateral and vertical water fluxes from wetlands (task 1), the effect of these hydrological changes on nutrient retention and wetland C/GHG balances (task 2) and determine how wetland size and position in the catchment affects response to extreme climate events (task 3).

Task 1: *Climate change impacts on wetland hydrological functioning*: the calibrated model setups from WP1, we will explore the manner in which changes in the magnitude and frequency of extreme precipitation events[7] alters wetland hydrological function. We will consider the interactive effects of increased drought severity, more frequent extreme rainfall, and a warmer climate on vertical and later al water fluxes. The projected changes in wetland hydrology will then be quantified as changes in HLR so as to assess possible consequences for nutrient retention and GHG production.

Task 2: *Effects of extreme events hydrological events on wetland multifunctionality* So as to quantify the potential effects of extreme hydrologic events (floods and droughts) on wetland multifunctionality, we will combine modelled climate change impacts on wetland hydrology (task 1) with predictive models hydrologic controls on nutrient retention (WP2.1) and C-sequestration (WP2.2).

Task 3: *Optimal sizing and placement of wetlands for climate resilience and multi-functionality:* To maximize multi-functionality and climate resilience, it is crucial to correctly place created wetlands in the landscapes. The HLR is an important factor for nutrient retention, and thus for GHG budgets. This gives us an opportunity to optimize wetlands size and location to maximize either certain ecosystem service, or to achieve synergy effects and avoid goal conflicts. We will apply high-resolution distributed models[9] developed by our group to predict wetland function in candidate catchments based on empirical and modelling data generated in WP1&2. These new GIS based methods create a base for quantification of water, nutrient and C fluxes at the scale and precision (subcatchment-farm-field) relevant for end-user (farmers, land owners, advisory services and authorities). Distributed modelling offers us a unique opportunity to assess wetland multi-functionality and climate resilience. We will use the tool developed in this task to support dialogue in the stakeholder workshops (WP4.3). We will extend our approach to highlight wetland water storage volume[26,32], both in WP4 and as an input to WP5.

WP4: **Social and institutional factors** (**MB**, DC, FD, MF, PG)

In this WP, we will assess social and institutional factors that facilitate or hinder the use of wetlands in the agricultural landscape for delivery of hydrological ES. We will assess the perceptions of farmers, land owners, water managers, authorities, regulatory bodies, academics and NGOs on the potential for agricultural wetlands to deliver multiple ES with specific focus on hydrologic ES which enhances landscape-scale resilience to extreme events (task 1) and organize a series of workshops to facilitate dialogue amongst relevant actors (task 2). An additional aim of the workshops will be to raise the awareness of relevant stakeholders, and particularly farmers, on the hydrological ES benefits that can be derived from wetlands with respect to maintaining water balances for drought and flood risk mitigation.

Task 1: *Practitioner Survey*. A survey will be conducted to assess factors which influence farmers' willingness to create and maintain wetlands, their perceptions of the role of wetlands for climate mitigation and adaptation, and the potential ES delivery from constructed wetlands. The survey will also cover the factors that either motivate or discourage farmers in implementation of wetland NBS. The survey will target two populations: the farmers and land owners responsible for the 40 wetlands we plan to monitor during the project and an equivalent sized population of farmers and land owners who do not currently have constructed wetlands on their properties to account for potential differences in perceptions between these two groups.

Task 2: *Stakeholder Workshops* We will organise workshops in the Mälardalen region to encourage dialogue between key stakeholders involved in wetland creation and management in Sweden. We will invite land owners, farmers, public water managers, local authorities working with water (municipalities), academics and NGOs. We will conduct workshops to:

(i) Facilitate dialogue between land owners and land managers: About 2/3 of agricultural land in Sweden is not farmed by landowners but is leased to farmers. Leases are typically long term and difficult to change without mutual consent. Since wetland restoration and creation often imply changes in the terms of the lease contract, both the land owner and the land user need to be in agreement. This obstacle to establishment of wetlands has not yet been addressed. Establishing a forum for dialogue where these two types of stakeholders can meet will promote a better understanding of how agreement can be achieved.

(ii) Explore wetland implementation barriers and enabling factors. We will use earlier Swedish work highlighting pathways and barriers to wetland creation for ES delivery[13], studies of farmer attitudes towards wetlands[44,45,] as well as results of the practitioner survey (Task 1) will be used as a foundation in preparing for the workshops. The focus will be on social, economic and institutional factors that either enable or hinder wetlands' creation in agricultural landscapes. We will discuss with stakeholders potential ways forward in using wetlands as NBS, ways to remove the existing barriers and opportunities to build on existing enabling factors.

(iii) Co-develop and test the decision support tool developed in WP1.4 and WP3.2. The workshops will be used for development of an AE-Footprint decision support tool[17]. Stakeholders will be presented with information from the project (from goals ii and iii in the project description) and asked to use these to develop an assessment matrix that can be used for critical evaluation (ranking) of prospective wetland sites based on multiple criteria. The assessment matrix will be included in the projects web-based handbook. When the project is concluded, the matrix, a guide to its use and the film developed within the project will be combined into a package designed to be used in future local workshop settings organized to support establishment of wetlands.

WP5: **Communication** (**JH**, JA, MB, DC, FD, MF, PG, MP)

This WP will present the new knowledge generated in WP1-4 to Swedish and international audiences. This WP has two tasks: the production of a ca. 30-minute broadcast-quality film about hydrological ES from multifunctional wetlands in the agricultural landscape (task 1) and an interactive 'story map' web based learning environment (task 2).

Task 1: *The Film* The goal of this task is to produce a film for general audiences in which we raise awareness about the multifunctional role of agricultural wetlands in the hydrological cycle and highlight successful "made in Sweden" solutions. We will produce Swedish and English language versions of the film so as to reach national and international audiences. We want to show how wetlands can help us to steward our water and aid us in improving its quality. In the film, we will interview farmers and land owners with wetlands on their properties, as well as other groups with an interest in the issue (scientists, NGOs, water managers, etc.). We will identify candidates for interviews based on our existing contact networks and advice from SWaM, HaV and the project reference group.

Task 2: *Interactive learning environment*: Based on project results, we will produce a web-based interactive learning environment using the ESRI 'Story map' platform (https://storymaps.arcgis.com/en/). The learning environment will describe in more detail the various issues and how these could be addressed. The learning environment will be a mixture of text, photos, illustrations and animations describing the problems of drought, water scarcity, flooding and eutrophication in depth. The learning environment will also give example on how problems could be solved bearing in mind local and climatic differences. The story map platform also enables the use of a 'what-if' approach. Main target groups of this task include farmers, water managers, land owners and academics.

The film and learning environment will be 'stand-alone' products but will form a united package with similar design and narrative style. They will be released at an event at KSLA in Stockholm with invitees from various stakeholder groups. All material will be presented at Havs och Vatten forum. After the release, all material will be freely available on the Internet, with links from all participating organizations.

Data Publication Plan

This project will generate new biophysical data on wetland functioning and new social science data on stakeholder perceptions and attitudes. All scientific data generated during the project will be archived on figshare.net or another publicly accessible repository. This will ensure that all data are available to SwAM, the Swedish EPA and the research community. All scientific papers arising from the project will be published with full open access.

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