AquaNES

Demonstrating Synergies in Combined Natural and Engineered Processes for Water Treatment Systems

Deliverable D5.2

Ecosystem services from cNES

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List of abbreviations

BF	Base flow
CBIOM	Carbon storage in biomass
CICES	Common international classification of ecosystem services
cNES	Combined natural and engineered treatment system
CTOT	Total carbon storage (soil and biomass)
CW	Constructed wetland
DESSIN	Demonstrate Ecosystem Services Enabling Innovation in the Water Sector
DPSIR	Drivers-Pressures-State-Impact-Response
ESs	Ecosystem services
EU-DEM	European Digital Elevation Model
FESs	Final ecosystem services
IESs	Intermediate ecosystem services
LULC	Land Use Land Cover
NEXP	Nitrogen export
NDR	Nutrient delivery ratio InVEST ecosystem services model
NRET	Nitrogen retention
PEXP	Phosphorus export
POLL	Pollination
PRET	Phosphorus retention
PP	Potabilisation plant
QF	Quick flow
RBF	Riverbank filtration
RSF	Retention soil filter
SAT	Soil Aquifer Treatment
SDR	Sediment delivery ratio InVEST ecosystem services model
SEDEXP	Sediment export
SRET	Sediment retention
ST	Sediment tank
SWY	Seasonal water yield InVEST ecosystem services model
WFD	Water framework directive
WP	Work package
WW	Water works
WWTP	Wastewater treatment plant

Executive Summary

The main purpose of this work was to determine the ecosystem services potential of three combined natural and engineered systems (cNES) for water and wastewater treatment: i) constructed wetlands (CW), ii) riverbank filtration (RBF) and iii) managed aquifer recharge/soil aquifer treatment; focussing on ecosystem services beyond water purification functions of these technologies, and by doing so demonstrating that these systems can exhibit potential for additional environmental benefits other than the ones typically associated with water and wastewater treatment. The ecosystem services potential was assessed for one case study site representative of each category of cNES. These were selected from the available case studies in the AquaNES project, and the selection was based on willingness of project partners to participate in the assessment, as well as ecosystem services potential as determined from initial descriptive assessments of the study areas. These case studies were Site 4 Poznan/Mosina for the RBF, Site 6 Basel/Lange Erlen for the MAR/SAT, and Site 11 Rheinbach/Erftverband for the CW technology. The assessment was carried out in two stages: first, the intermediate ecosystem services were quantified, and second, the final ecosystem services were elucidated by matching the intermediate ecosystem services with their possible beneficiaries.

We chose to carry out spatially explicit analyses using the InVEST suite of modelling tools for quantification of five ecosystem services: carbon storage, pollination, water retention, sediment retention and nutrient retention, as well as the Circuitscape model for habitat connectivity assessment. Modelling in the spatial domain allowed for the capture of any on-site and off-site environmental processes and ecological functions that would affect the actual ecosystem service potential of the areas within administrative boundaries of each case study site. We also designed an online survey to assess the aesthetic value of the CW and MAR/SAT technologies, comparing them to their engineered equivalents based on people's perception of these pairs of systems. We subsequently matched the quantified intermediate ecosystem services with possible beneficiaries using a systematic classification system designed for the purposes of economic valuation of ecosystem services and by doing so we indicated the relevance of the ecosystem services supplied by the cNES technologies to various aspects of human well-being.

Our results indicated that the RBF and MAR/SAT technologies supply an ecosystem services potential in delivering all services modelled, and that the CW could play a role in carbon storage and pollination. In most cases the amounts of ecosystem services generated from the sites were comparable to the amounts delivered from the surrounding wider landscape, with variation regarding the type of surrounding land use patches. The quantified ecosystem services potential of each technology may substantially differ with the spatial context in which each site is located as well as the land use properties and size of the sites themselves. Nevertheless, this study has shown that all cNES technologies can be treated as multifunctional entities delivering a range of tangible benefits reaching beyond their primary function of water and waste water purification. Maximisation of these benefits will depend on the type and management of the surrounding land use on the sites, their size as well as topographic and climatic context of a given location.

1 About this document

This report describes the outcomes of ecosystem services assessment carried out for exemplars of three cNES technologies for water and wastewater treatment – constructed wetlands (CW), riverbank filtration (RBF) and managed aquifer recharge/soil aquifer treatment (MAR/SAT). The assessment aims at identifying environmental and societal benefits of these technologies beyond benefits associated with water/wastewater purification. This document is linked to the milestone report MS28: Approach/methodology for ecosystem services analysis.

The entirety of this document is written in a form of a scientific manuscript and is intended for publication in a peer-reviewed journal:

Zawadzka, J., Gallagher, E., Smith, H., Corstanje, R. Ecosystem services from combined natural and engineered water and wastewater treatment systems: going beyond water quality enhancement, Ecosystem services or Ecological Engineering, In prep.

2 Introduction

Ecosystem services have been broadly defined as the benefits humans derive from nature (Millennium Ecosystem Assessment, 2005). Although initially natural or semi-natural environments have been considered as the main source of these benefits, today it is recognised that also non-pristine environments can supply them (Honey-Rosés et al., 2014). An example of ecosystem services derived from anthropogenically altered environments are the biogeochemical processes used in engineered water and wastewater treatment systems that use microbial ecosystems to remove biosolids and biochemicals, such as excess N and P, from effluent (Graham and Smith, 2004). In this context, ecosystem services are seen as an opportunity to lower the economic cost of water and wastewater treatment (Geber and Björklund, 2001).

Benefits resulting from improvement of water quality can be considered as primary ecosystem services from water and wastewater treatment technologies (Masi et al., 2016). The advent of ecological engineering, whereby engineered and natural treatment solutions are combined together into one system has initiated a potential for secondary ecosystem services that are not directly connected to water quality enhancement. Such combined natural and engineered systems (cNESs) include constructed wetlands (CW), riverbank filtration (RBF) and managed aquifer recharge/soil aquifer treatment (MAR/SAT). River bank filtration has been proven to be an inexpensive way of treatment of raw surface water (Tufenkji et al., 2002) for drinking water purposes. RBF utilises naturally occurring processes of adsorption, reduction, physicochemical filtration, and biodegradation within the unsaturated or saturated alluvial valley aquifer whilst water infiltrates from the riverbed to the pumping well located at a distance away. Similar processes are utilised in the managed aquifer recharge/soil aquifer treatment (MAR/SAT) technology that is used for recycling storm water or treated sewage effluent for non-potable and indirect potable reuse in urban and rural areas (Dillon et al., 2010). Managed aquifer recharge is conducted via "planned use of injection wells, and infiltration basins and galleries for rainwater, storm water, reclaimed water, mains water and water from other aquifers that is subsequently recovered for all types of uses" and often requires that water is pre-treated before it is allowed to infiltrate as well as undergoes post-treatment before it can be used. Constructed wetlands, on the other hand, use the emergent vegetation and filtering substrate's capacity to remove pollutants and nutrients from multiple types of wastewater (Almuktar et al., 2018; Arden and Ma, 2018; Wang et al., 2017).

Although each of these cNES technologies have been acclaimed for their role in delivering of the primary ecosystem services, their potential for the supply of secondary ecosystem services has not been fully explored and has been limited to constructed wetlands in terms of their recreational, educational, and habitat-creation potential (Ghermandi and Fichtman, 2015; Masi et al., 2016; Semeraro et al., 2015). These ecosystem services are associated not only with the water area of the constructed wetland, but also adjacent natural and semi-natural land use that is under administration for a given site and their surroundings.

In this paper, we hypothesise that all three cNES technologies have a good potential for delivering secondary ecosystem services, and by doing so can contribute wider societal values, but that this is dependent on the spatial context of the host landscape. We test this hypothesis for three selected sites located in Europe, one for each technology, using spatially explicit modelling tools and online surveys, looking at a broad range of ecosystem services. We then identify the beneficiaries for these services and discuss their potential economic value.

3 Materials and methods

3.1 Methodological approach

In this work we follow the ecosystem services cascade framework (Potschin-Young et al., 2018) that intuitively conceptualises the pathway of ecosystem services generation starting from the ecosystem itself and ending at the tangible benefits derived from it, including their potential economic value. The cascade is representative of the 'impact evaluation' part of the recently developed DESSIN approach (Anzaldua et al., 2018) designed to quantify water-related ecosystem services within the DPSIR (Drivers-Pressures-State-Impact-Response) framework that focuses on identification of environmental drivers and effects within a given study area, and in our opinion is better suited for comprehensive considerations of environmental impacts as a result of an intervention (i.e. land use or management change) within a given study area. Our approach, however, puts an emphasis on ecosystem services potential of specific cNES technologies for water/waste water treatment without consideration of alternative scenarios, and therefore we adopt the simpler conceptual approach, maintaining the key aspects of both frameworks (Figure 1). We maintained the nomenclature of ecosystem services used in the DESSIN framework, i.e. we refer to the intermediate ecosystem services (IESs) as ecosystem services that are provided but not necessarily utilised or appreciated by humans and final ecosystem services (FESs) as ecosystem services that are provided and directly utilised or appreciated and therefore can undergo economic evaluation. We also adopted the common international classification of ecosystem services (CICES) typology (Haines-Young and Potschin, 2013) to determine types of ecosystem services that can be derived from our case study areas.

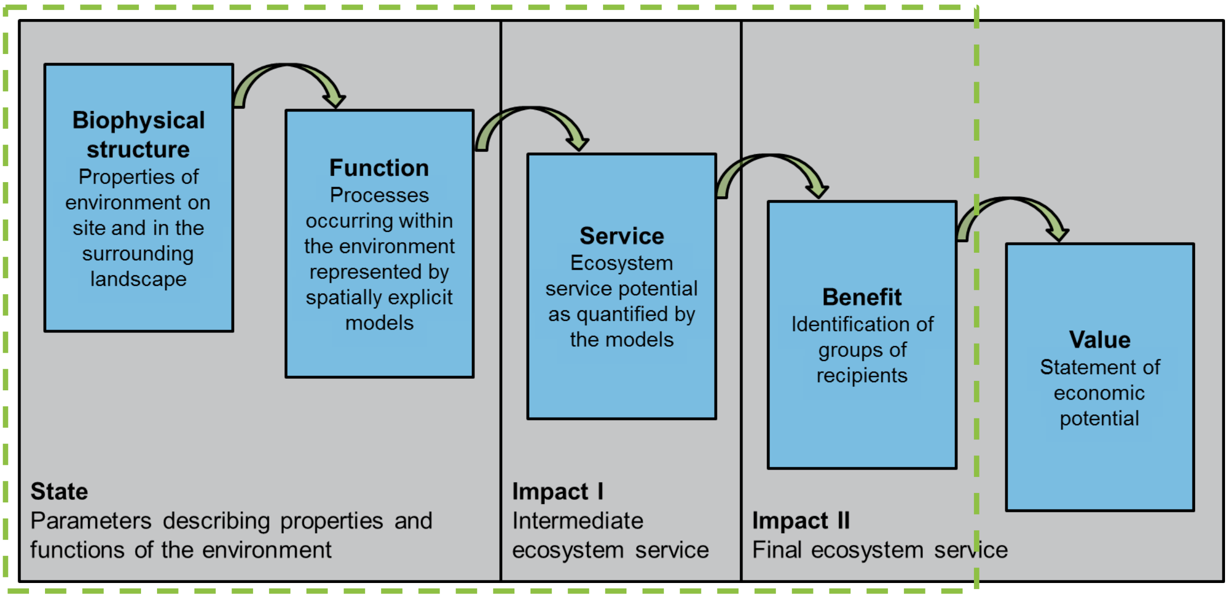

Figure 1 Theoretical approach to ESS assessment assumed this study incorporating both the ecosystem services cascade and DESSIN frameworks.
The green rectangle indicates the scope of the assessment carried out in this study.

Our assessment starts with the description of the biophysical structure and processes of our ecosystems, which is done via parameterisation of the models with relevant descriptors for the assessment of each ecosystem service under study. The models themselves represent the processes or ecosystem functions occurring within the ecosystems and their outputs determine the potential of each study area to deliver intermediate ecosystem services. Next, groups of beneficiaries for the intermediate ecosystem services specific to each case study area are identified using the final ecosystem goods and services (FEGS-CS) classification developed by Landers and Nahlik (2013), and potential economic value of key ecosystem services is discussed.

We chose to base our assessment on spatially-explicit models to quantify ecosystem services as these are capable of capturing multi-scale effects of ecosystem processes driving ecosystem services supply (Zulian et al., 2018) and provide information suitable for spatial planning and policy development (Maes et al., 2012). We therefore expanded the size of the study areas considered beyond the administrative boundaries of the sites, to which we refer to as the core case study area, with an attempt to capture any off-site effects that can be mitigated by each site. We chose to use watersheds as the wider case study areas as these would allow for capturing ecosystem services related to water flow in the landscape. Another benefit of such assessments is the ability to compare the amounts of ESS generated at each considered site to their wider-landscape setting, and by doing so, determine the role each cNES technology in ecosystem services provision in their local context.

For the ease of interpretation of the spatial outputs, we compared the mean amount of ESSs generated at each site to the mean value of ESSs generated at each land cover patch in the wider landscape as well as within the site, by calculation of the site/LULC-patch ratio, being an adaptation of the methodology for analysis of changes in ecosystem services presented in Zawadzka et al. (2017).

We also included the assessment of the aesthetic value of CW and MAR/SAT technologies via an online survey aiming at capturing respondents' perception of these technologies as compared to their engineered equivalents. In this case, biophysical structure of the cNES was represented by photographs of exemplars of given technologies.

3.2 Study areas

We determined the ecosystem services from three case study areas representing riverbank filtration (RBF), managed aquifer recharge/soil aquifer treatment (MAR/SAT) and constructed wetlands (CW) cNES for water and waste water treatment. The selection of the sites was determined by willingness of partners of AquaNES project to participate in the assessment and overall potential of the sites to supply ecosystem services determined from descriptions of all sites available at the beginning of the project. Locations of case study areas are shown in Figure 2.

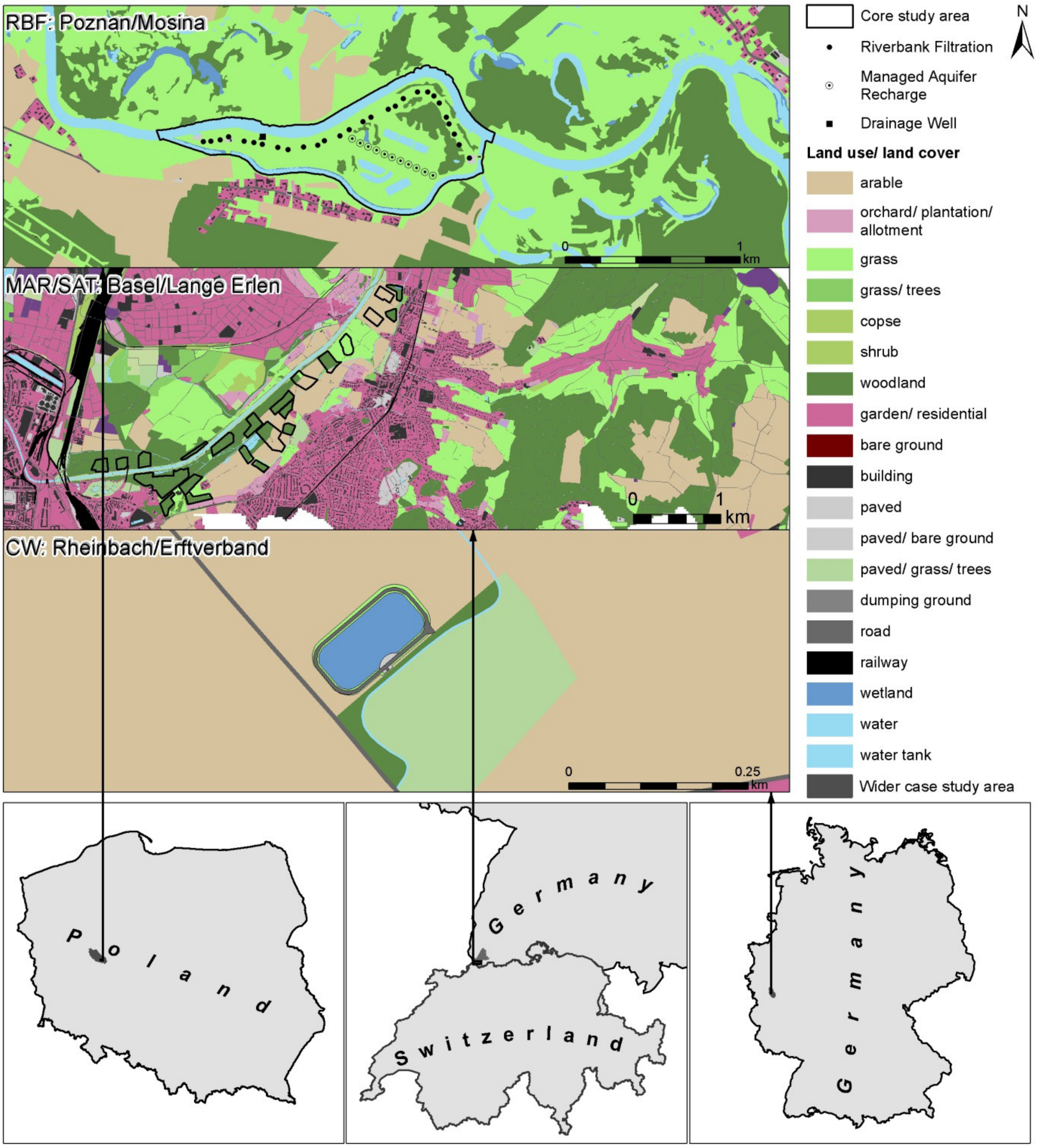

Figure 2 Core and wider study areas for the three case study sites undergoing ecosystem services assessment.
RBF – riverbank filtration, MAR/SAT – Managed aquifer recharge/soil aquifer treatment, CW – constructed wetland.

3.2.1 Riverbank filtration – Poznan/Mosina, Poland

The bank filtration site is located on the Krajkowska Island located on the right bank of the Warta River, in Wielkopolska Voivodship in Poland 30 km south-east from Poznan. The site is managed by the Water Company Aquanet SA, scientific research is overviewed by researchers from the Adam Mickiewicz University in the city of Poznan. The site comprises 28 riverbank filtration wells located in the floodplain 70-80 m away from the river bank and the extracted water at the rate of 44,750 m^3/day is supplied to the city of Poznan. The entire water capture system includes also a 7 km long series of 56 wells on the higher river terrace located at the distance of 480 to 1000 m from the river, four MAR basins located in the floodplain and one drainage well located 5m below the river bed – all of which together supply 60,000-70,000 m^3 of water per day, with maximum capacity of 150,000m^3/day.

Land cover on the Krajkowska Island includes a stretch of managed grass near the wells, as well as woodland and semi-natural grassland in the central area of the Island. A road formed from concrete slabs provides access to the wells along the river, and there is a pumping station on the eastern side of the site. The entire island is a water protection zone and as a result public access is forbidden.

The wider case study area is 502 km^2 in size and covers a variety of land covers. It also encompasses several Natura 2000 sites as well as national nature protection areas, and the core study area is located within the boundaries of these sites.

3.2.2 MAR/SAT – Basel/Lange Erlen – Switzerland

The Lange Erlen MAR/SAT site is located at the outskirts of the City of Basel, in the Basel-Stadt canton in Switzerland and it is used for the purpose of treating Rhine River water as part of the potable water treatment process. The site operator is Industrielle Werke Basel, and the scientific activities are carried out by Fachhochschule Nordwestschweiz Hochschule für Life Sciences. The Lange Erlen site comprises 23 recharge areas 1.2-10 ha in size that are covered mainly by woody vegetation and are located on either sides of the Wiese River that is a right-hand tributary of the Rhine. The recharge areas are not accessible to the public, however, adjacent park areas are open for recreation.

The wider case study area delimited as a watershed from DEM analysis extends largely to Baden-Württemberg German state and is 157 km^2 in size.

3.2.3 Constructed wetlands – Rheinbach/Erftverband – Germany

The Erftverband site is located near the City of Rheinbach in the state of North Rhine Westphalia in Germany. The constructed wetland is planned to be built over the duration of the project and is 4500 m^2 in size. Its purpose is dual – during dry weather it is going to provide advanced treatment of waste water treatment plant effluent, and during wet weather it will treat the effluent from combined sewer overflows. The secondary purpose of the wetland is to slow down the peak runoff and flood protection. The constructed wetland is going to be planted with common reed (*Phragmites australis*) and use retention soil filter for additional subsurface treatment of wastewater. Due to mounding and separation from the ground with a sealing membrane, the wetland is hydrologically disconnected from the wider landscape. The effluent from the wetland is discharged to the Rotterbach River.

The main stakeholders are the Erftverband waterboard (non-profit organization under public law) who is the operator of the WWTP as well as the inhabitants of the Rheinbach city and people potentially affected by the flooding.

The wider case study area is a watershed 302 km² in size encompassing a variety of land uses and extends onto the German state of Rhineland-Palatinate.

3.3 Methods

3.3.1 Quantitative assessment of ecosystem services from cNES

Quantitative ecosystem assessments were carried out in three modes. Firstly, relevant models from the suite of InVEST 3.4.4 (Tallis and Polasky, 2009) tools were deployed to quantify the amounts of ecosystem services generated from each case study site and their surrounding landscape. Five InVEST 3.4.4. models were run: pollination, carbon storage and sequestration, seasonal water yield (SWY), nutrient delivery ratio (NDR) and sediment delivery ratio (SDR). The models use land use/land cover (LULC) maps as the primary driver of ecosystem services, and due to local character of the selected case study site, we chose to use small scale maps capturing necessary detail of the land cover on sites as well as their surroundings. Consequently, we acquired the BDOT10k topographic map at 1:10 000 scale for the Poznan/Mosina case study, the Swiss TLM3D dataset for the Swiss part and the ALKIS DLM50 for the German part of the Basel/Lange Erlen wider case study area, and the basis DLM50 dataset for the Rheinbach/Erftverband case study area. The legends of original vector maps were simplified and the maps were converted to a raster format required by the InVEST models at 5 m spatial resolution. The SWY, NDR and SDR models also require the use of a digital elevation model, and for this purpose the European Environment Agency's 25 m resolution EU-DEM was used. Further details on parameterisation of these models are given in Supplementary Materials 1.

We also assessed the role that each site plays in terms of habitat connectivity for species of mammals and birds found within Natura 2000 areas present in the study area catchments in the case of CW and MAR/SAR, and the Natura 2000 site within which the RBF site is located. We used the Circuitscape 4.0 model (McRae et al., 2008) that describes species movement across the landscape through electrical current theory and requires assigning resistance values to LULC classes in order to determine the ease of movement across the landscape. In order to do so, we identified habitat preferences of each species, including their response to human threats, and assigned a value of 1, 25, 50, 75 or 100 (where 1 means high preference and 100 – avoidance) to each LULC class present in the wider study areas based on the information on the species in the IUCN Red List. We then calculated an average score for each LULC class to produce a single resistance map submitted to the model. The model also requires specification of nodes, i.e. points between which connectivity is assessed, and we chose 50 randomly placed points located at the outer edges of the Natura 2000 network patches (Figure 3). This was done in a random fashion as we wished to determine connectivity rather than habitat, and information on particular nesting sites was not available. Lists of species present and resistivity values assigned to each LULC class are shown in Supplementary Materials 2.

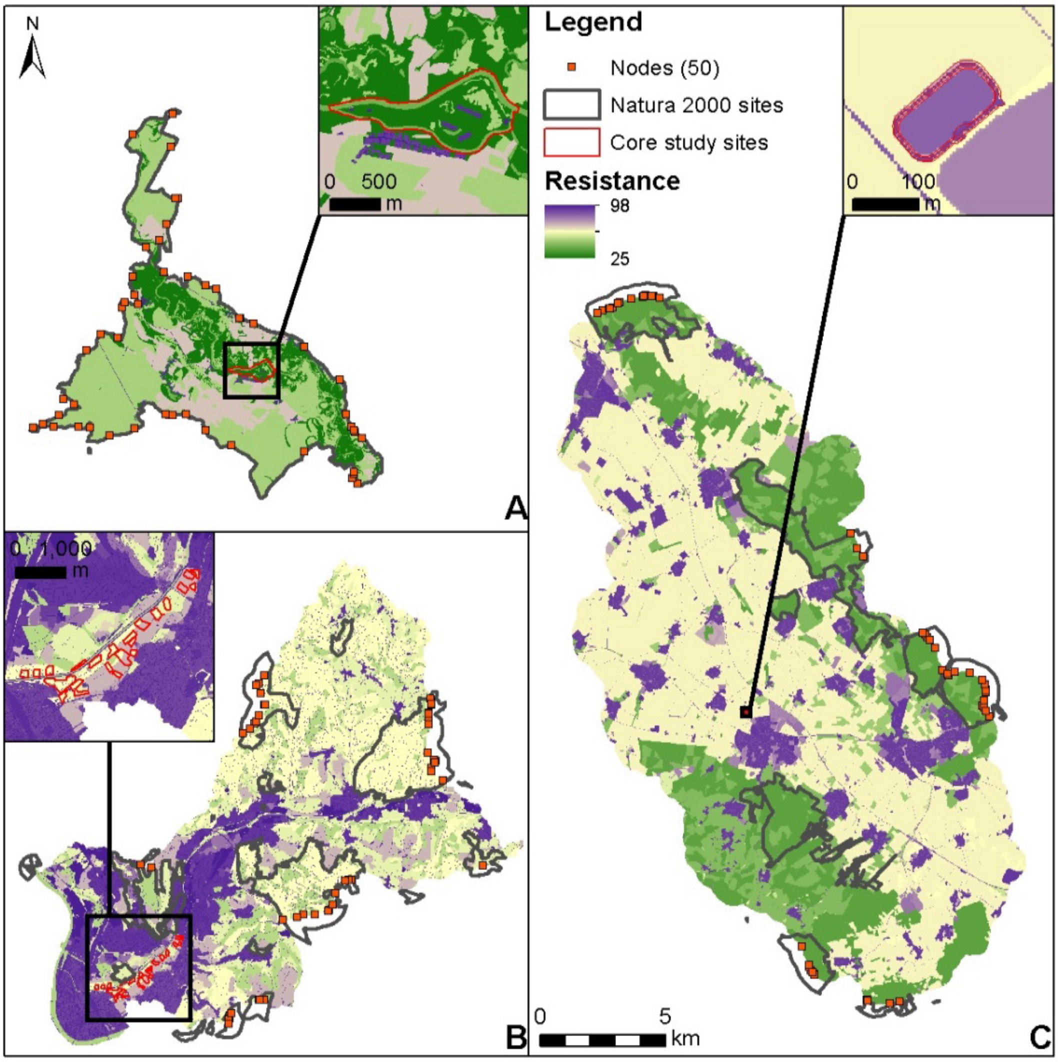

Figure 3 Resistance values assigned to each LULC class in the case study areas and habitat nodes used as the inputs to the Circuitscape habitat connectivity model:
A – RBF, B – MAR/SAT, C – CW. Lower values indicate a lower resistance to species movement.

The outputs of the spatially-explicit models, both the InVEST 3.4.4 and Circuitscape, were analysed in two manners. Firstly, the pixel-based spatial outputs of the models were summarised with the mean function within each individual LULC patch in the wider study area, for the cNES site and its immediate surroundings, with the purpose of contextual assessment of the levels of ecosystem service supplied by the site. Carbon stock potential in biomass (CBIOM) was determined from the output of the InVEST 3.4.4 Carbon Storage and Sequestration model and the total carbon stock (CTOT), including the carbon stocks in biomass and soils, was determined as the sum of CBIOM and carbon storage in soils derived from the SoilGrids (Hengl et al., 2017) dataset. We split the carbon stocks output into the two pools to make account of the fact that whilst carbon stocks in soil are difficult to amend, carbon stocks in biomass will depend on factors such as land cover and age and type of vegetation, and can be altered subject to appropriate management and planning. Pollination outputs (POLL) are shown as the mean value of pollinator supply and abundance layers returned by the InVEST 3.4.4. Pollinators model. We decided to show two outputs for the InVEST 3.4.4 Seasonal Water Yield model – quick flow and base flow – as both can depict important and at times contrasting ecosystem services, either of generation of flood risk or hydropower potential, and replenishing of ground waters. As for the InVEST 3.4.4 Nutrient Delivery Ratio model, we analysed the N and P export layers together with the N and P retention layers. The latter, although not part of the standard outputs, were derived as a difference from nutrient load layer and nutrient export layer. We argue that even in the case of the net positive nutrient export, it is also important to consider the part of nutrients that are retained within the landscape. For similar reasons both sediment export and retention outputs of the InVEST 3.4.4. Sediment Delivery Ratio model are shown. The habitat connectivity output depicting the cumulative current between habitat nodes from the Circuitscape model has also been summarised over individual LULC patches and displayed together with the InVEST models. It has to be noted that we only run the carbon, pollinator and connectivity models for the CW (Erftverband) site, as the constructed wetland should be treated as an isolated system from the water and nutrient cycling as well as sediment retention perspective. This is due to its sealing from the ground and surrounding landscape by an impermeable membrane and elevated banks preventing water and mass transport into and away from the CW by natural processes represented by the corresponding InVEST models.

The spatial layers subsequently formed a basis for numerical assessments whereby the amounts of services derived from each cNES site are tabularised and expressed in units per hectare and per entire site, where appropriate.

The third mode of assessment was done for the purpose of identifying people's perception on the aesthetic value of two out of three cNES technologies – CW and MAR/SAT – as compared to their engineered equivalents: sediment tank (ST) and potabilisation plant (PP) using a series of nine questions with 5-point Likert Scale response format ranging from 'strongly disagree' to 'strongly agree' (Supplementary Materials 3). This was done via an online survey designed in Qualtrics deployed to UK residents ensuring that the sample was representative of British demographics through stratification. The results were analysed using paired t-test and the Cramer's V statistic (Zawadzka et al., 2015) that can be used to compare categorical responses at the scale of 0 to 1, where 1 indicates a maximum agreement.

3.3.2 Identification of beneficiaries

Beneficiaries for the intermediate ecosystem services were determined during the qualitative assessment using the FEGS-CS classification of beneficiaries (Landers, D.H., Nahlik, 2013) to ensure IESs and their beneficiaries are systematically matched. Subsequently, presence of the potential beneficiaries specific to each case study site was evaluated. Identification of both potential and actual beneficiaries was essential for upscaling of our results that otherwise would be very case-specific and allowed for recognition of full ecosystem services potential of a given technology that may not be revealed in the case-specific assessment.

4 Results

4.1 Intermediate ecosystem services from cNES technologies

In this section the ecosystem services potential that can be attributed specifically to each case study area is discussed. The results of spatially explicit InVEST models are shown in Figures 4-6, and habitat connectivity maps are displayed in Figure 7. Concise summary of modelled amounts of ecosystem services from each site is available in Supplementary Materials 5.

4.1.1 Carbon storage

RBF case study site, due to its location in the floodplain, can store considerable amounts of carbon in the rich alluvial soils, amounting to 667 tC ha^{-1} or 37, 484 t per the entire site. The MAR/SAT site can store 274 tC $ha^{-1}$of carbon or 16,576 t per site in the soil, and the carbon storage underneath the constructed wetland was not assessed as due to the construction process the upper layers of the soil would have been removed.

Vegetation present on the RBF site can contribute a fair store of carbon which amounts to 15 tC ha^{-1}or 848 t per site, whereas the MAR/SAT site could potentially store 85 tC ha^{-1}or 5,145 t per site. The reed beds planted in the CW could store 32 tC ha^{-1}, assuming total aboveground biomass in common reed of 17 tC ha^{-1} and belowground biomass of 80 tC ha^{-1} (Tripathee and Schäfer, 2015), and the carbon content usually amounting to 45-50% of the weight of over-dry biomass (Schlesinger, 1991). All other assumptions with regards to the parameterisation of the InVEST carbon model followed published values and is discussed in detail in Supplementary Materials 1.

Spatial assessment of the total carbon stocks revealed that the RBF site blends in with the surrounding landscape very well and only carbon stored in biomass may appear lower than in the adjacent land cover classes. The contextual character of this site has to be considered here as the entire area belongs to areas of nature protection and has a fairly natural character – the carbon stock in biomass on site that is managed for operational use may therefore be slightly lower than in the surrounding landscape. In the case of the other case study sites – MAR/SAT and CW, carbon stocks are comparable or higher. This is due to the fact that the MAR/SAT site is largely covered by woodland that is a much better carbon pool than arable land, grassland or urban land. The CW, on the other hand, is located within intensive arable land and can contribute higher carbon storage capacity in biomass than arable land.

4.1.2 Pollination

The InVEST 3.4.4 Pollinators model assesses the suitability of land cover in a given area to support the presence of user-defined pollinators in the landscape based on the availability of nesting and foraging grounds as well as mean foraging distance the species can typically cover. In this study we chose to use six species of bumble bees (*Bombus sp.*) (Table S1.7) as key pollinators of wild flowers and commercial crops (Carvell et al., 2017) and assumed springtime and early summer conditions for availability of floral resources. The spatial interpretation of the output maps, that were generated by averaging the pollinator supply and abundance output maps for all six pollinator species, leads to a conclusion that each site can provide supporting grounds for these pollinators. The RBF site has comparable pollinator capacity to adjacent semi-natural grasslands and the MAR/SAT site stands out from its mainly agricultural and urbanised matrix. The model parameterisation for the CW site assumed that there is little nesting or foraging ground availability within the area of the reed bed, however, there is some capacity to support pollinators within the grassed banks of the wetland, and that capacity appears to exceed the capacity of the surrounding agricultural land in the modelling output.

4.1.3 Regulation of hydrological cycles

Contributions to the hydrological cycle of each cNES technologies was assessed with the InVEST 3.4.4 Seasonal water yield model. The model has the capacity to determine both the amount of surface runoff, or quick flow (QF), that can potentially enter the stream and the amount of water infiltrating into the aquifer, or the base-flow (BF), allowing for capturing of a more balanced view of the water cycle within the study area. Spatial assessment of the RBF site reveals that it can contribute relatively high amounts of run-off to the neighbouring Warta River, which can be justified by primarily grassy land cover that has lower evapotranspiration coefficient than woody vegetation. Due to the closeness to the river, the generated quick flow cannot be retained within the landscape and therefore enters the stream. The higher amount of available quick flow corresponds to the higher capacity of the site to generate base flow, which appears to be relatively high as compared to the wider case study area. In absolute terms, the modelled amount of water entering the stream is 290 m^3 ha^{-1} or 16,240 m^3 per site, and the amounts of generated base flow are 7.7 m^3 $ha^{-1}$and 431.2 m^3 per site on a yearly basis. Quick flow generated from the MAR/SAT recharge areas is low as compared to the wider case study area, which corresponds well to the primary woody character of the land cover. As a result, the amount of base flow infiltrating into the ground is also lower than from the surrounding landscape. It has to be noted here that these results do not take into account the amount of water purposefully directed into the ground as part of the water treatment process, as well as the fact that the modelled high amounts of base flow from residential areas surrounding the site would normally be captured by the storm drainage system. Nevertheless, given that the MAR/SAT site has a natural character, the modelling results can be representative of the actual amounts of quick flow and base flow generated, and these amount to 190 m^3 ha^{-1}or 11400 m^3 per site in terms of the surface run-off, and 20 m^3 ha^{-1}or 1200 m^3 per site for the groundwater recharge.

The results of the SWY model indicate that although the amounts of surface run-off generated from precipitation on the sites greatly exceed the amount of water infiltrating of to the ground, they allow for recognising the fact that infiltration of water can occur on these sites, which is not usually the case in anthropogenic environments characterised with considerable soil sealing. As to the amounts of surface run-off, these could potentially contribute to increased flooding risk – and their actual role in this respect would need to be studied further in their local and regional contexts.

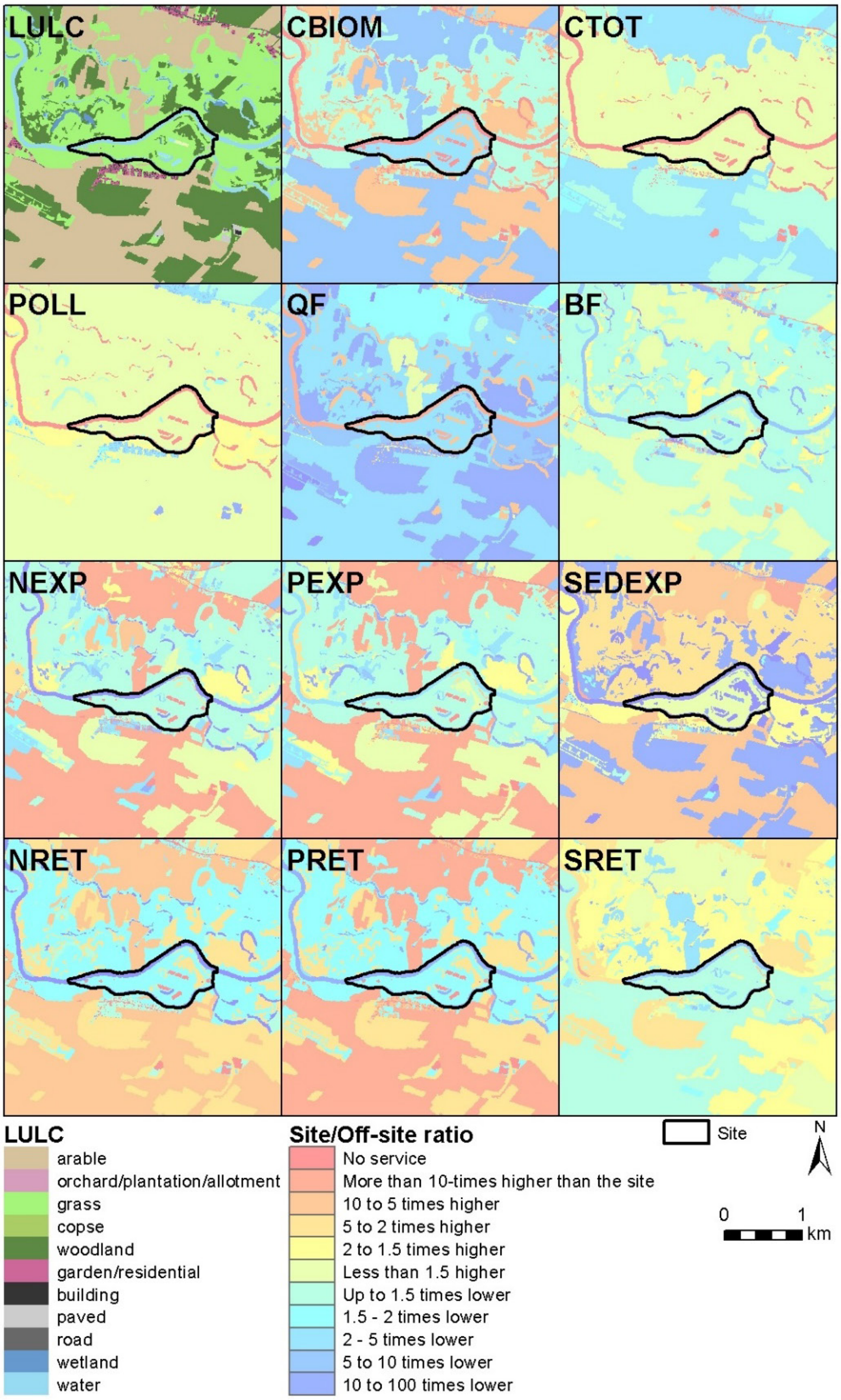

Figure 4 **Ecosystem services ratio between the mean value of each IES on site and the means of surrounding land use patches for the RBF Poznan/Mosina site.**
CBIOM – carbon storage in biomass; CTOT – total carbon storage (biomass+soil); CONN – habitat connectivity; POLL – mean of pollination abundance and supply; QF – quick flow; BF – base flow; NEXP, PEXP, SEDEXP –nitrogen, phosphorus and sediment export NRET, PRET, SRET – nitrogen, phosphorus and sediment retention. Shades of yellow to orange indicate areas with higher values of modelled amounts than the average for the site; shades of blue indicate areas of lower values of modelled amounts.

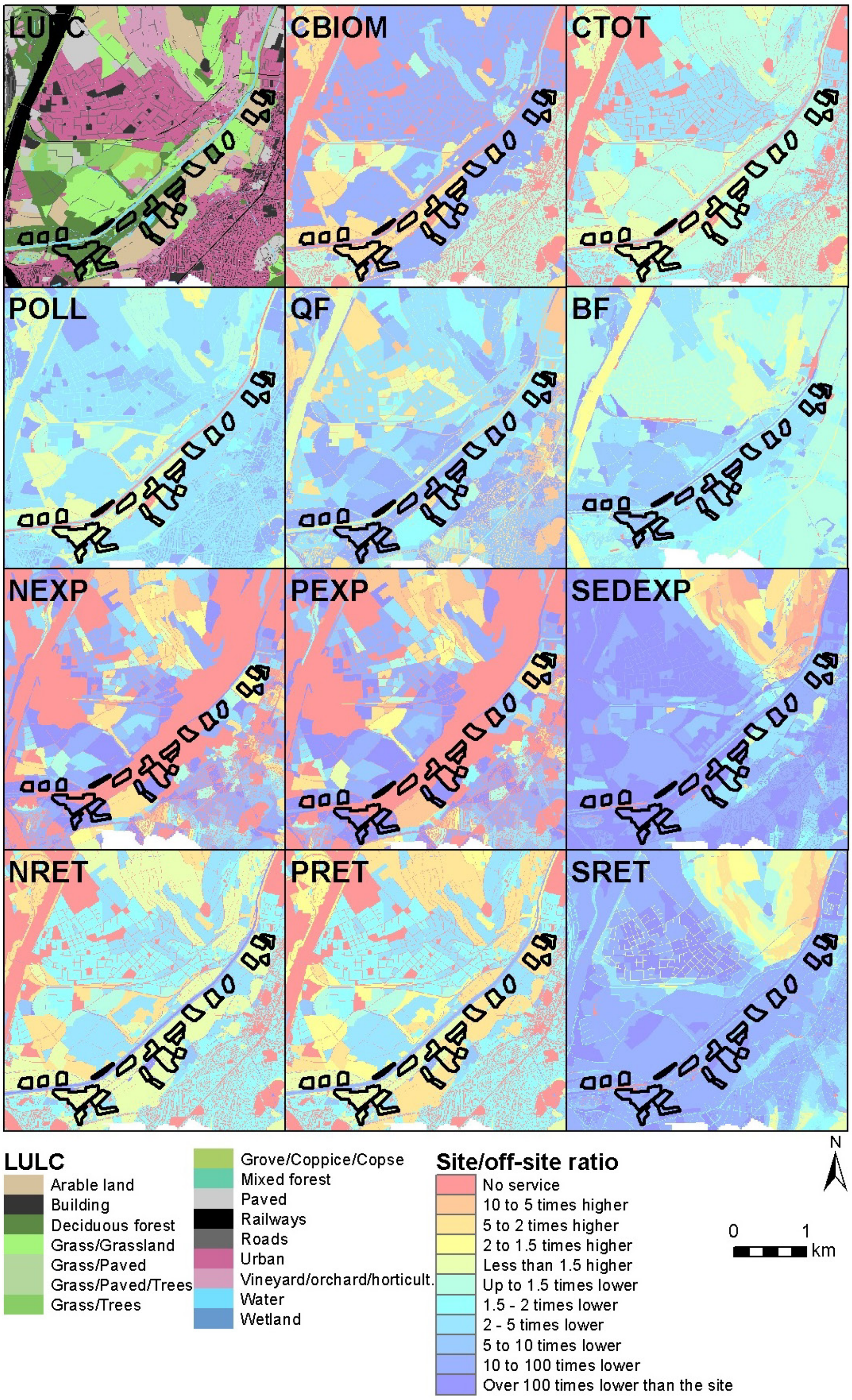

Figure 5 Ecosystem services ratio between the mean value of each IES on site and the means of surrounding land use patches for the MAR/SAT Basel/Lange Erlen site.
CBIOM – carbon storage in biomass; CTOT – total carbon storage (biomass+soil); CONN – habitat connectivity; POLL – mean of pollination abundance and supply; QF – quick flow; BF – base flow; NEXP, PEXP, SEDEXP –nitrogen, phosphorus and sediment export NRET, PRET, SRET –nitrogen, phosphorus and sediment retention. Shades of yellow to orange indicate areas with higher values of modelled amounts than the average for the site; shades of blue indicate areas of lower values of modelled amounts.

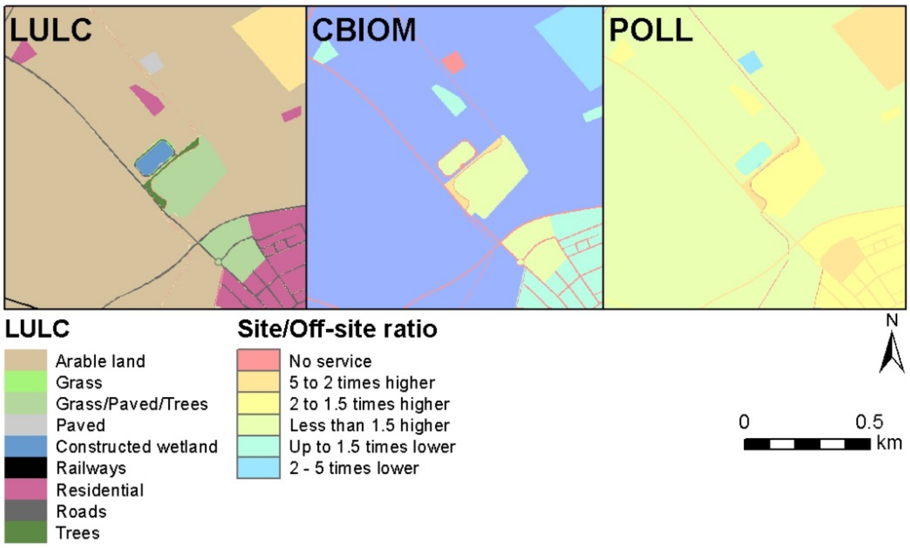

Figure 6 **Ecosystem services ratio between the mean value of each IES on site and the means of surrounding land use patches for the CW Rheinbach/Erftverband site.**
CBIOM – carbon storage in biomass; CTOT – total carbon storage (biomass+soil); CONN – habitat connectivity; POLL – mean of pollination abundance and supply; QF – quick flow; BF – base flow; NEXP, PEXP, SEDEXP –nitrogen, phosphorus and sediment export NRET, PRET, SRET –nitrogen, phosphorus and sediment retention. Shades of yellow to orange indicate areas with higher values of modelled amounts than the average for the site; shades of blue indicate areas of lower values of modelled amounts.

4.1.4 Nutrient and sediment balance

Nutrient balance at the RBF and MAR/SAT sites was modelled with the InVEST 3.4.4 Nutrient Delivery Ratio model. The model analyses the fate on nutrients within the landscape based on the topography of the terrain represented by the digital elevation model, the amount of available water for surface run-off, represented by the quick flow output of the InVEST Seasonal Water Yield model, and the land cover capacity to be both a source and sink of nutrients. The main model output, the nutrient export map specifies how much of N or P at a given location can reach the nearest stream. The amount of nutrients that were prevented from entering the stream can also be derived from the model outputs and here is referred to as nutrient retention.

The spatial analysis for the RBF site reveals that despite relatively high amounts of surface water run-off, both N and P export from the site is relatively low. This is likely due to low nutrient loadings assigned to grass, which covers a substantial area of the site as well as the protection channel encompassing the site from the south that prevents nutrients mobilised ex-situ from entering the site. Low nutrient loadings and the site's separation from the wider landscape have contributed to the relatively low amounts of nutrients retained on site as compared to other land cover classes present in the wider case study area. Table 1 shows, however, that the amounts of nutrients captured on site as compared to the amounts exported to the river are circa 40-times higher, indicating a great potential of the site to capture excess nutrients.

Table 1 **Modelled amounts of nitrogen, phosphorus and sediment exported from and retained within the riverbank filtration (RBF) and managed aquifer recharge/soil aquifer recharge (MAR/SAT) sites.**

	N export		N retention		P export		P retention	
Site	kg/ha	kg/site	kg/ha	kg/site	kg/ha	kg/site	kg/ha	kg/site
RBF	0.630	35	24	1345	0.013	0.726	0.530	29
MAR/SAT	0.187	11	86	5144	0.007	0.436	2.330	140

In the case of the MAR/SAT site, the spatial analysis shows that both N and P export from the recharge areas is lower than from the surrounding landscape, and that numerous recharge areas do not generate P export. The recharge areas, however, show higher capacity for nutrient retention than the surrounding land cover classes, and therefore can act as a buffer for neighbouring urban areas for nutrient retention. This is confirmed by the absolute modelled values of nutrient export and retention from the site (Table 1), showing that nutrient retention is 300 to 460 times higher than nutrient export.

4.1.5 Sediment balance

Sediment export is modelled by the InVEST 3.4.4 Sediment delivery ratio model based on the USLE equation that can determine erosion rates from an area based on the properties of rainfall, soil susceptibility to erosion, topography and land cover impact on the likelihood of dislocation of soil particles (Wischmeier and Smith, 1978). Sediment retention, on the other hand, determines the role of land cover present within the study area to retain sediments by comparison of the amount of sediment delivered by the current study area to the same study is covered with bare soil only. The model takes also into account the connectivity of the landscape, making assumptions of how much sediment may be dislocated from one location to another.

The spatially-explicit results from the SDR model show that the RBF site generates and retains low amounts of sediment as compared to the wider landscape, which, as in the case of nutrient modelling, can be explained partly by the unique topographic setting of the site whereby the protective channel prevents external sources of sediment from entering to the site. The type of land cover and very low slopes also contribute to low sediment loads that can be generated from the site, corresponding to high capacity to retain any excess sediment. Modelled values summarised for the site reveal that, on yearly basis, very little sediment is generated from the site, and that the amount of sediment retained there is circa 40 times higher.

Table 2 **Modelled outputs of the InVEST 3.4.4 SDR model for the riverbank filtration (RBF) and managed aquifer recharge/soil aquifer recharge (MAR/SAT) sites.**

	Sediment export		Sediment retention	
Site	t/ha	t/site	t/ha	t/site
RBF	0.006	0.353	0.266	15
MAR/SAT	0.018	1.054	0.933	56

The spatial analysis of the results obtained from the MAR/SAT site reveals that in its geographical setting dominated by flat slopes, the site and the surrounding landscape generate very little sediment that could eventually enter surface water bodies. As a result, some of the recharge areas as well as surrounding land cover patches that would normally have sediment retention potential do not retain sediment, the reason for which being lack of sediment dislocated from areas located upslope from those locations. The absolute values of sediment export and retention on the site are shown in Table 2, and reveal similar pattern as in the case of the RBF site, of sediment retention capacity being circa 50 times higher than sediment export from the site.

4.1.6 Habitat connectivity

The analysis of the results for the contribution of each site to habitat connectivity across the wider landscape obtained from the Circuitscape model reveals that the RBF site has the highest capacity to provide a stepping stone for modelled species. Both MAR/SAT and CW sites appear to have more marginal roles in that respect. These results should be treated with caution as the outcomes of the model can depend on multiple factors including the type of species for which assessment is made and their habitat requirements, habitats present on site as well as in the areas surrounding the site, providing potential ecological corridors, and the location of nodes, i.e. the species source points for which the model assesses connectivity. In this study, the emphasis was put on species that are present within the Natura 2000 sites located within the wider case study areas, oftentimes characterised with specific habitat requirements pertaining to the Natura 2000 sites themselves, and therefore difficult to find elsewhere. This could be the reason for the RBF site to appear most connected, which can be explained by the fact that this site is located within a Natura 2000 site, and contains habitats favoured by multiple species, as seen from low resistance values (Figure 3). In the case of the MAR/SAT, the resistance values are low, however, the site is located away from Natura 2000 sites and is separated from them by urban areas that prevent species movements to and from the site. In the case of the CW, it is surrounded by agricultural land with medium resistance values, is characterised with high resistance to species movement, and is located away from the Natura 2000 sites, which amounted to its overall low role in habitat connectivity. Should the assessment be based on more common species that are used to anthropogenic influences, the result of the model could have been much different.

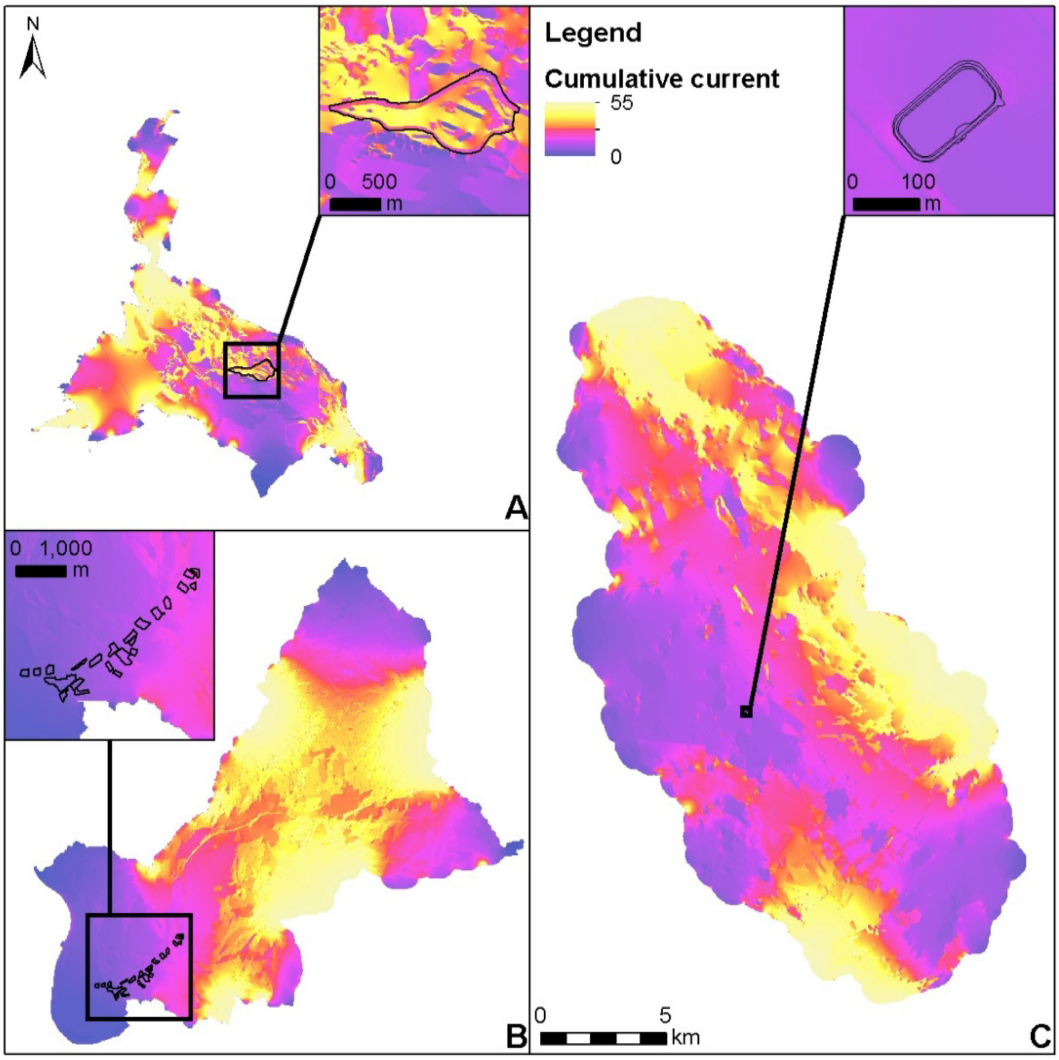

Figure 7 Habitat connectivity within A – the Natura 2000 area within which the RBF case study site is located, B – MAR/SAT, and C – CW case study sites as seen by the Circuitscape model.

4.1.7 Aesthetic quality

Aesthetic value of CW and MAR/SAR cNES technologies was assessed from the responses received to the online survey aiming at comparison of these technologies to their engineered equivalents (sediment tank for CW and potabilisation plant for MAR/SAR). The survey received the total of 760 responses.

A series of paired t-tests (Tables S4.1-S4.2 Supplementary materials 4) were run to determine preference of the engineered or natural treatment option on a number of dimensions which are presented below. It can be seen that on all dimensions, there was greater preference for the constructed wetland (CW) than for the engineered equivalent primary sediment tank (ST). It was also shown that there was greater preference on all dimensions for MAR/SAT over the potabilisation plant (PP). These results were confirmed by low values of Cramer's V statistic that ranged between 0.07-0.09 and 0.16-0.21 for each question for the CW-ST and MAR/SAT-PP indicating a marked difference in people's perception of these paired technologies. The distribution of the responses revealed that indeed they were largely positive for the cNES technologies (Figure 8 A-D).

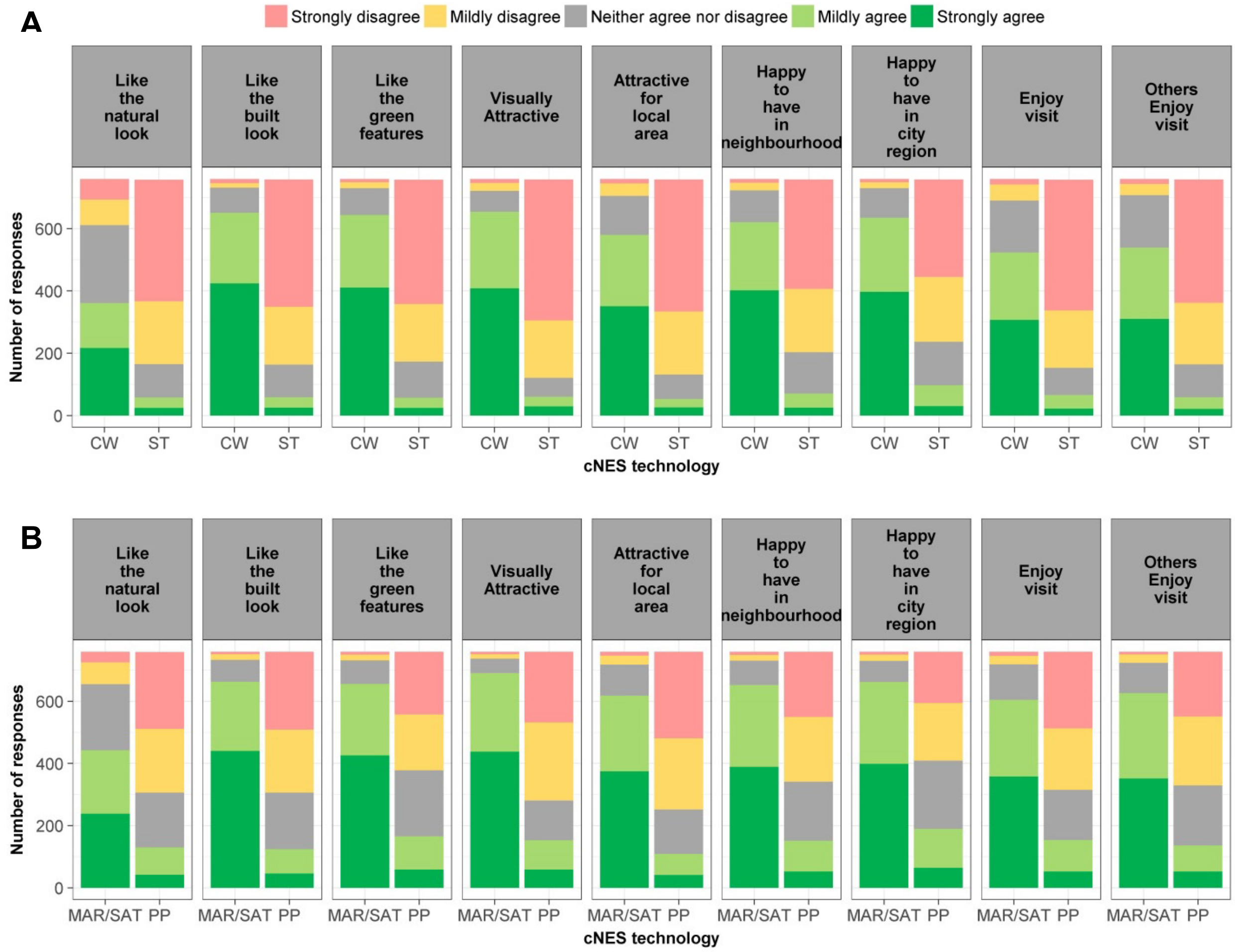

Figure 8 **Responses to the online surveys regarding comparisons between cNES and their engineered equivalents.**
A – distribution of the responses for the CW/ST pair, and B – for the MAR/SAT PP pair of technologies responses in the negative (red and yellow), neutral (grey) and positive categories (green) indicating that people's perception was mostly positive for the cNES categories and mostly negative for their engineered equivalents.

4.2 Final ecosystems services from cNES technologies

In this section, main ecosystem services beneficiaries for the previously identified intermediate ecosystem services are determined (Table 3), full list of potential beneficiaries is given in Table S5.3 in Supplementary Materials 5. Each cNES technology played a certain role in terms of carbon storage, and as such may contribute to the regulation of global climate and therefore may benefit all humanity. The sites are also facilitators for pollinator supply, which can have a role in terms of pollinating crops, either commercial, such as apples in orchards found within the wider case study areas of the CW and RBF cNES technologies, plantations of blueberries and black currants (RBF), or recreational in allotments (CW, MAR/SAT) and private gardens (RBF). Due to the media attention that the issue of maintaining populations of pollinators has been receiving, the general public or 'people who care' can also be included in the group of beneficiaries. Pollinators also play a role in maintenance of wildflower populations which can contribute to the aesthetic value of the wider landscape, which can be especially important for the RBF site, surrounded by semi-natural grasslands. Similarly, the role of the sites in habitat connectivity can be appreciated by people who care, as well as people who appreciate outdoors biodiversity as part of recreation, artistic inspiration, or as a medium for education. Strengthening of ecological corridors can also be appreciated by administrative bodies of nature protection areas as well as businesses that depend on the presence of particular species that can attract visitors to the area.

The beneficiaries of sediment and nutrient retention include people who use water bodies for recreation, such as swimming, bathing, fishing or boating or hiking in their proximity; as well as water treatment plants benefitting from better quality of surface water. Sediment retention can also contribute to reduced siltation of water bodies, which can have tangible benefits for users of surface waters for irrigation, commercial fresh-water fish catchers, or energy generators requiring pure water for their cooling systems.

Generation of quick flow that would enter water bodies, in non-excessive amounts, can contribute to the maintenance of the sufficient water levels that in turn could promote commercial use for transportation purposes, irrigation, electricity generation (hydropower and cooling), as well as recreation, inspiration and drinking water production. On the other hand, excess surface run-off may contribute to increased flood risk and cause damages to home owners and industry.

Water retention, however, can contribute to aquifer recharge and water storage that can be subsequently extracted for drinking and industrial purposes as well as contribute to the maintenance of adequate groundwater levels for plant growth utilised in agriculture and forestry.

Good aesthetic value of the cNES technologies can be important for people living nearby, visiting the area for recreational purposes or in any other way benefiting from pleasing landscapes.

Our study identified potential groups of beneficiaries of modelled intermediate ecosystem services whose importance in the context of each study area may vary. We did not attempt economic valuation of identified FESs; instead, we discuss relevant examples from literature to give a notion of monetary value of ESs assessed here. Pollination by wild bees has been shown to improve the quality, shelf life and commercial value of strawberries (Klatt et al., 2013), and apples (Garratt et al., 2014), as well as increase yield of oil seed rape (Stanley et al., 2013), among others. The economic value of this service can be assessed based on the prices and dependence ratio for crops directly used for human consumption (Gallai et al., 2009), the cost of alternative pollination sources, such as managed bees, and the value of production resulting from bee pollination (Winfree et al., 2011), or by willingness to pay methods. Using the latter method, Breeze et al. (2015) estimated the value of pollination in the UK in the context of local produce supply and wildflower pollination to be £25.5-£12.6 per person. The value of insect pollinators to agricultural production on an oceanic island of Terceira (Azores), was approximated at €170,291 for the entire island using data on producer prices and assuming crop dependency ratio of 10.5% (Picanço et al., 2017). Sediment retention services and resulting reduced siltation of surface waters can be monetised by assessing costs associated with change in water withdrawal due to sedimentation in watersheds, as well as avoided costs of flood damage (Alam, 2018). For example, the national costs associated with flood damage and flood risk management due to soil erosion in England and Wales were estimated at £168 million (Graves et al., 2015b). The economic value of water retention due to forested land can be estimated from costs of technical substitutes such as dam construction that would store the equivalent amounts of water, and the value of one hectare of woodland was estimated at 43US$ (2007) in a watershed located in Iran (Mashayekhi et al., 2010). Flood protection ecosystem service could also be valuated from avoided cost of damage to buildings, infrastructure, crop failure, production stoppage and costs of emergency services and others (Barth and Döll, 2016) and such cost could amount up to £1.4 billion in the UK (Graves et al., 2015b). Reduced export of nutrients to surface water bodies could be evaluated based on replacement costs of constructed wetlands (La Notte et al., 2015) as well as avoided losses to fish production due to avoided eutrophication as a result of nutrient buffering capacity natural wetlands (Simonit and Perrings, 2011). Carbon storage in carbon pools could be evaluated based on the abated social cost of carbon which measures the present value of future economic damages cause by an additional ton of carbon emissions (Yang et al., 2018). The aesthetic value and habitat connectivity services could be indirectly monetised with the use of economic benefits associated with recreational activities, such as for example travel costs (Ezebilo, 2016) to the areas affected by the sites.

Table 3 **Final ecosystem services and their beneficiaries for the three cNES technologies mapped into the CICES and FEGS-CS classification systems at case study sites.**
Y – presence of a beneficiary, POS – high possibility of presence of a beneficiary, MAR – marginal role, N – beneficiary not present, n/a – not applicable due to lack of IES. Continued on next page.

IESs	CICES section (IESs)	CICES class (IESs)	CICES section (FESs)	CICES class (FESs)	Beneficiary (FEGS-CS)	RBF	MAR /SAT	CW
Pollination	Regulation and maintenance	Pollination and seed dispersal	Provisioning	Cultivated crops	Farmers	Y	POS	POS
				Wild plants, algae and their outputs	Food Pickers and Gatherers	Y	POS	POS
			Cultural	Experiential use of plants, animals and land-/seascapes in different environmental settings	Experiencers and Viewers	Y	Y	POS
				Existence	All humans	Y	Y	Y
Carbon storage	Regulation and maintenance	Global climate regulation by reduction of greenhouse gas concentrations	Regulation and maintenance	Global climate regulation by reduction of greenhouse gas concentrations	All humans	Y	Y	Y
Habitat connectivity	Regulation and maintenance	Lifecycle maintenance, habitat and gene pool protection	Cultural	Experiential use of plants, animals and land-/seascapes in different environmental settings	Experiencers and Viewers	Y	Y	MAR
				Intellectual and representative interactions: Scientific, educational, aesthetic	Educators and Students	POS	POS	MAR
					Researchers	POS	POS	N
				Other cultural outputs (Existence)	People who care (Existence)	POS	POS	POS
Sediment retention	Regulation and maintenance	Filtration/sequestration/storage/accumulation by ecosystems	Cultural	Physical use of land-/seascapes in different environmental settings	Anglers	POS	POS	n/a
				Physical use of land-/seascapes in different environmental settings	Boaters	POS	MAR	n/a

IESs	CICES section (IESs)	CICES class (IESs)	CICES section (FESs)	CICES class (FESs)	Beneficiary (FEGS-CS)	RBF	MAR /SAT	CW
Nutrient retention	Regulation and maintenance	Filtration/sequestration/storage/ accumulation by ecosystems	Cultural	Experiential use of plants, animals and land-/seascapes in different environmental settings	Experiencers and Viewers	Y	Y	n/a
				Physical use of land-/seascapes in different environmental settings	Anglers	POS	POS	n/a
				Physical use of land-/seascapes in different environmental settings	Boaters	POS	MAR	n/a
Water yield (quick flow)	Regulation and maintenance	Hydrological cycle and water flow maintenance	Cultural	Experiential use of plants, animals and land-/seascapes in different environmental settings	Experiencers and Viewers	Y	Y	n/a
				Physical use of land-/seascapes in different environmental settings	Anglers	POS	POS	n/a
				Physical use of land-/seascapes in different environmental settings	Boaters	POS	POS	n/a
Water retention (base flow)	Regulation and maintenance	Hydrological cycle and water flow maintenance	Provisioning	Groundwater for drinking purposes	Municipal Drinking Water Plant Operators	Y	Y	n/a
Aesthetics	Not applicable	Not applicable	Cultural	Experiential use of plants, animals and land-/seascapes in different environmental settings	Experiencers and Viewers	Y	Y	n/a
				Other cultural outputs (Existence)	People who care (Existence)	POS	POS	POS

5 Discussion

In this study, we deployed spatially explicit ecosystem services models in order to map and quantify the ecosystem services potential of three cNES technologies: riverbank filtration, managed aquifer recharge/soil aquifer treatment, and constructed wetlands with the overall aim of determining their contribution to societal well-being beyond that of potable water and wastewater purification, and by doing so, we have demonstrated the multifunctional character of these technologies. The choice of the InVEST modelling tools was dictated by their ability to not only allocate the ecosystem services supply potential in spatial domain, but also incorporate the spatial context into the modelling process. The latter feature of the models is particularly important for ecosystem services depending on flows of ecological functions, or landscape processes, underpinning the ecosystem's capacity to supply services (Kreiling et al., 2018; López-Pintor et al., 2018), highlighting the importance of the situational context of the study area. For example, the capacity of a given study area to retain sediments or nutrients will not only depend on the retention capacity of land cover present in this area, but also the amount of material entering the site determined by retention capacity of land cover located upslope of that study area, steepness of slopes, and amount of available water to carry the material downhill. Moreover, the SDR and NDR models attempt at quantification of the amounts of sediments or nutrients dislocated from a given area and entering surface water bodies, highlighting the importance of the land surface properties downslope from the site. Conversely, the amount of water yield generated at the site and entering water bodies will depend on the topography of the wider study area and water retention capacity due to soil type, evapotranspiration and amount of precipitation, all of which are taken into account in the SWY model. The landscape context is also important for the quantification of pollination and habitat connectivity services. The former is modelled by the InVEST Pollinators model incorporating not only suitability of habitats, represented by the LULC map, to host pollinators, but also the pollinators' ability to cover distances and the spatial arrangement of LULC patches providing support for pollinators. We chose to use the Circuitscape model for habitat connectivity estimation due to its ability to reflect the flows of species movement throughout the landscape (Grafius et al., 2017). From the modelled services, only carbon storage can be treated as independent from ex-situ processes.

The estimated carbon stock in biomass reflects the expected published values of carbon storage found in literature for various land uses, and therefore actual amounts may differ somewhat from the modelled values due to differences in species composition, age of woody vegetation as well as duration of land use, management practices and local climate. It is also important to recognise that we did not account for possible greenhouse gas emissions from frequently inundated sites, and especially constructed wetlands, which under specific conditions may contribute significant emissions to the atmosphere (Maucieri et al., 2017). Although the carbon stocks in soil were estimated from the global SoilGrids dataset, which is a predictive dataset with overall 61% accuracy (Hengl et al., 2017), we consider the estimates as accurate for relative comparisons of soil carbon between the sites and their wider landscape. The predicted amounts of sediment export on both RBF and MAR/SAT sites were low and were set within the typical values of soil erosion estimated by various authors for England and Wales (Graves et al., 2015b) for land cover classes dominant on both sites – woodland or grassland. The modelled values are interpretable in average annual terms, and actual soil losses from the sites may vary with the year-to-year changes in the state of vegetation or weather conditions (Guerra et al., 2014). In terms of nutrient export, the NDR model has been shown to perform well in terms of relative magnitudes of N and P export from catchments rather than absolute amounts (Redhead et al., 2018a) and therefore spatially explicit maps of nutrient export derived for each wider study area can be reliably used to interpret the relative contributions of each site to the overall nutrient loss from the landscape. The SWY model has only been recently developed and therefore no studies from similar geographic areas to this study exist in literature. Nevertheless, the performance of the SWY model was found to be satisfactory in case studies located in Rwanda (Bagstad et al., 2018) and Australia (Wang et al., 2018) with a recommendation that fine resolution of the input spatial data, as is the case in this study, corresponded with higher reliability of the modelling outputs. The results of the pollination model indicated that all sites can promote wild pollinator abundance in the landscape, however, the InVEST model has been shown to be particularly sensitive to parameters describing the availability of nesting grounds and the mean foraging distance covered by the pollinators (Groff et al., 2016), and therefore specific local conditions that were not captured during the study may alter the significance of the case study areas in pollinator supply.

In this work we have refrained from conducting full economic valuation of ecosystem services from cNES technologies as our modelled results are only indicative of the possible amounts of ecosystem services derived from the sites, did not undergo rigorous ground-truthing with measured data, and depend on the environmental contexts of each site. Nevertheless, should an economic valuation be required for a given decision context, Boithias et al. (2016) offer a compendium of guidelines that could be followed to achieve an accurate estimation of the monetary value of ecosystem services in a given socio-economic context with consideration of main sources of uncertainty including the number of ecosystem services and their benefits considered, valuation methods used, and uncertainty around the valuation metrics applied. For example, aspects such as costs of N and P treatment, costs of health and environmental damages per unit of the nutrient as well as the value of land cover resulting from water purification for drinking purposes could be considered to determine the value of nutrient retention. However, economic valuation should not be limited to a single IES, and rather embrace multiple IESs and all associated benefits to avoid underestimations in the assessment.

6 Conclusions

The presented modelling study of ecosystem services derived from three types of cNES technologies for water and waste water treatment revealed their multifunctional potential in terms of secondary ecosystem services supply, i.e. ecosystem services above that of water purification due to natural processes inherent to the natural components of the treatment methods. These services are derived from natural and semi-natural land cover classes present within the sites formed as a result of extensive use and presence of protection zones restricting intensive use of the sites. From the three investigated cNES technologies, the riverbank filtration (RBF) and managed aquifer recharge/soil aquifer treatment (MAR/SAT) proved to play a role in all seven ecosystem services assessed here: carbon storage, pollination, water retention, sediment retention, nutrient retention and habitat connectivity for biodiversity. The constructed wetland (CW) had a role in carbon storage and pollination services. These results are highly sensitive to the local conditions of the sites as well as their wider landscape context, such as the type of land cover on-site and off-site, management practices on-site affecting the state of vegetation, the spatial extent of the site and the natural/semi-natural land cover on-site, as well as topography of the wider study area and climate. Due to these considerations, the results of this study cannot be generalised to overall guidance concerning ecosystem potential of these cNES technologies. For the same reasons, any comparisons between the ecosystem services potential of the studied sites were avoided, as the same technology in different environmental settings can have different potential to deliver ecosystem services. Our study also indicated that people's perception of the aesthetic value of the CW and MAR/SAT technologies as compared to their engineered equivalents can be largely positive, subject to the sensitivities around the type of land cover on the site. In conclusion, cNES technologies for water and wastewater treatment can make important contributions to ecosystem services supply subject to widespread implementation in appropriate environmental settings and land cover management promoting ecological functioning of ecosystems present on the sites.

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8 Supplementary materials

8.1 S1 Parameterisation of the InVEST models

8.1.1 Carbon stocks in biomass

InVEST 3.4.4 Carbon

The InVEST 3.4.4. Carbon model was deployed with the purpose of assessing current (BF and MAR/SAT) or potential (CW) carbon stocks stored within the biomass on the case study sites as well as the wider landscape. Tables S1.1-S1.3 show parameterisation of the carbon model for LULC classes in each of the three study areas.

Table S1.1 Parameters for the InVEST 3.4.4 Carbon model regarding carbon storage in biomass for the BF case study – Poznan/Mosina [t/ha]. LULC class names with the "k_" prefix refer to the BF site.

lucode	LULC_name	C_above	C_below	C_dead
0	arable	1	1.33	0.1
1	arable natural	1	1.33	0.1
2	bare ground	0	0	0
3	building	0	0	0
4	k_building	0	0	0
5	copse	9.4	4.32	7.3
6	dumping ground	0	0	0
7	garden	30	55.11	0
8	grass	1	4	0
9	k_grass	1	4	0
10	grass/trees	47	13.16	0
11	natural grassland	2.4	9.6	0
12	orchard	7	4.6	0
13	paved	0	0	0
14	k_paved	0	0	0
15	paved/bare ground	0	0	0
16	paved/grass/trees	31.33	8.77	0
17	plantation	8.7	3	0
18	railway	0	0	0
19	road	0	0	0
20	sand	0	0	0
21	shrub	9.4	4.32	7.3
22	water	0	0	0
23	k_water	0	0	0
24	water tank	0	0	0
25	k_water tank	0	0	0
26	wetland	8	38	0
27	k_wetland	8	38	0
28	woodland	93	22.32	7.3
29	k_woodland	56.4	12.97	7.3

Table S1.2 Parameters for the InVEST 3.4.4 Carbon model regarding carbon storage in biomass for the MAR/SAT case study – Basel/Lange Erlen [t/ha]. LULC class names with the "RA_" prefix refer to the MAR/SAT site.

lucode	LULC_name	C_above	C_below	C_dead
0	Allotment	1	1.33	0.1
1	Arable land	1	1.33	0.1
2	Building	0	0	0
3	Coniferous forest	89.25	17.85	6.9
4	Deciduous forest	96	22.08	7.7
5	Grass	1	4	0
6	Grass/Paved	0.5	2	0
7	Grass/Paved/Trees	31.33	8.77	0
8	Grass/Trees	47	13.16	0
9	Grassland	1	4	0
10	Grassland/Allotment	1	2.67	0.05
11	Grassland/Arable land	0.5	2	0
12	Grove/Coppice/Copse	9.4	4.32	7.3
13	Horticulture	1	1.33	0.1
14	Industrial and commercial site - Paved	0	0	0
15	Mixed forest	93	22.32	3.5
16	Orchard	7	4.6	0
17	Paved	0	0	0
18	Quarry	0	0	0
19	RA_Allotment	1	1.33	0.1
20	RA_Arable land	1	1.33	0.1
21	RA_Building	0	0	0
22	RA_Deciduous forest	96	22.08	7.7
23	RA_Grass/Paved	0.5	2	0
24	RA_Grassland	1	4	0
25	RA_Mixed forest	93	22.32	0.05
26	RA_Roads	0	0	0
27	RA_Urban - Grass/Paved/Trees	31.33	8.77	0
28	RA_Water	0	0	0
29	RA_Water - Rivers	0	0	0
30	RA_Wetland	8	38	0
31	Railways	0	0	0
32	Residential (Paved <50% of the area)	0.3	1.2	0
33	Residential (Paved >50% of the area)	0.2	0.8	0
34	Roads	0	0	0
35	Sports area - Grass/Paved/Trees	31.33	8.77	0
36	Tree nursery	9.4	4.32	0
37	Trees	9.4	4.32	7.3
38	Unpaved or lightweight road - Roads	0	0	0
39	Urban - Grass/Paved/Trees	31.33	8.77	0
40	Vineyard - Vineyard	8.7	3	0
41	Water	0	0	0
42	Water - Rivers	0	0	0

43	Water tank	0	0	0

Table S1.3 Parameters for the InVEST 3.4.4 Carbon model regarding carbon storage in biomass for the CW case study – Rheinbach/Erftverband [t/ha]. LULC class names with the "Site-" prefix refer to the MAR/SAT site.

lucode	LULC_name	C_above	C_below	C_dead
0	Allotment	1	1.33	0.1
1	Allotment/Grass/Paved/Trees	23.75	6.91	0.025
2	Arable land	1	1.33	0.1
3	Arable land/Paved	0.5	0.67	0.05
4	Bare ground	0	0	0
5	Bare ground/Grass	0.5	2	0
6	Bare ground/Grass/Paved	0.33	1.32	0
7	Bare ground/Grass/Trees	31.02	8.7	0
8	Bare ground/Paved	0	0	0
9	Coniferous forest	89.25	17.85	6.9
10	Coniferous trees	89.25	17.85	6.9
11	Deciduous forest	96	22.08	7.7
12	Deciduous trees	96	22.08	7.7
13	Grass	1	4	0
14	Grass/Paved	0.5	2	0
15	Grass/Paved/Trees	31.02	8.7	2.41
16	Grass/Trees	47	13.16	0
17	Grassland	1	4	0
18	Grove/Coppice/Copse	9.4	4.32	3.65
19	Mixed forest	93	22.32	7.3
20	Moor	93	22.32	7.3
21	Orchard	7	4.6	0
22	Paved	0	0	0
23	Paved/Arable	0.5	0.67	0.05
24	Paved/Horticulture	0.5	0.67	0.05
25	Paved/Orchard	3.5	2.3	0
26	Paved/Trees	46.5	11.16	0
27	Paved/Trees/Water	30.69	7.36	0
28	Quarry	0	0	0
29	Railways	0	0	0
30	Residential	18.8	5.26	0
31	Roads	0	0	0
32	Site-Grass	0.33	1.32	0
33	Site-Paved	0	0	0
34	Site-Reedbeds	8	38	0
35	Site-Roads	0	0	0
36	Tree nursery	9.4	4.32	0
37	Trees	93	22.32	0
38	Vineyard	8.7	3	0
39	Water	0	0	0
40	Water - Rivers	0	0	0

8.1.2 Carbon stocks in soil

Carbon stock in soil up to the 100cm depth was estimated from the OCSTHA SoilGrids layers (Hengl et al., 2017) using Equation 1.

Equation 1

$$\frac{1}{b-a}\int_{a}^{b} f(x)dx \approx \frac{1}{(b-a)}\frac{1}{2}\sum_{k=1}^{N-1}(x_{k+1}-x_{k})(f(x_{k}+f(x_{k+1}))$$

a, b – upper most and lower most depth of the profile in consideration

N – number of depths

x_k – k^{th} depth

$F(x_k)$ – value of the target variable at the depth x_k

All necessary calculations of raster SoilGrids layers were carried out in Raster Calculator of ArcGIS 10.5.1 software. The resulting raster layer stored soil stocks values in t/ha.

With the purpose of removing the 250x250m blocky artefacts from the resulting map, the 250m resolution raster map was interpolated, using the radial basis completely regularized spline function in Geostatistical Analyst of ArcGIS 10.5.1 software, and subsequently saved at 5m resolution to match the spatial resolution of LULC maps. The choice of the interpolation function was based on the smallest root-mean-square error, which was 0.025 for BF, 0.013 for MAR/SAT and 0.014 CW case study sites (t/ha).

8.1.3 InVEST 3.4.4 Pollination

The focus of modelling is on bumble bees (*Bombus spp.*) as key pollinators of wild flowers and commercial crops (Carvell et al., 2017). The Pollination model requires attribution of the available land use map with the probability of occurrence of nesting sites and floral resources. It also requires that each pollinator species is attributed with mean foraging distance and activity levels in time periods for which the model is run. In this case, springtime conditions have been assumed.

The assignment of nesting sites occurrence within LULC classes in the wider case study area, which for bumble bees are located in the ground, was based on the following findings from literature. Carvell et al. (2017) assessed the suitability of land parcels as nesting habitats for bumblebees by estimating average vegetation height across the whole parcel, whether tussocky vegetation was present, the extent of plant litter or moss within the sward and whether there were signs of small mammal activity such as the presence of burrows, runs or faeces. Redhead et al. (2016) excluded cropped arable fields, roads, buildings and water as suitable nesting habitat classes in a study area that otherwise was composed of short grass, mixed, non-woody, semi-natural vegetation, garden and urban vegetation, woody vegetation, ELS field margin, water, and bare soil.

Tables S1.4-S1.6 show the nesting ground suitability scores as well as availability of floral resources used in this study.

Table S1.4 Availability of nesting sites and floral resources in LULC classes within the BF Poznan/Mosina wider case study.

lucode	LULC_desc	nesting_ground_availability_index	floral_resources_spring_index
0	arable	0	0
1	bare ground	0.25	0
2	building	0	0
3	copse	0.5	0.25
4	dumping ground	0	0
5	garden	0.5	0.5
6	grass	0.5	0.5
7	grass/trees	0.5	0.5
8	orchard	0.25	0.75
9	paved	0	0
10	paved/bare ground	0	0
11	paved/grass/trees	0.25	0.25
12	plantation	0.25	0.75
13	railway	0	0
14	road	0	0
15	sand	0	0
16	shrub	0.5	0
17	water	0	0
18	water tank	0	0
19	wetland	0	0.5
20	woodland	0.25	0.25

Table S1.5 Availability of nesting sites and floral resources in LULC classes within the MAR/SAT Basel/Lange Erlen case study.

lucode	LULC_desc	nesting_ground_availability_index	floral_resources_spring_index
0	Allotment	0.5	0.75
1	Arable land	0.1	0
2	Building	0	0
3	Coniferous forest	0.5	0.25
4	Deciduous forest	0.5	0.25
5	Grass	0.5	0.5
6	Grass/Paved	0.25	0.25
7	Grass/Paved/Trees	0.33	0.25
8	Grass/Trees	0.5	0.375
9	Grassland	0.75	0.75
10	Grassland/Allotment	0.625	0.75
11	Grassland/Arable land	0.43	0.375
12	Grove/Coppice/Copse	0.5	0.25
13	Horticulture	0.5	0.75
14	Industrial and commercial site - Paved	0	0
15	Mixed forest	0.5	0.25
16	Orchard	0.25	0.75
17	Paved	0	0
18	Quarry	0	0
19	RA_Allotment	0.5	0.75
20	RA_Arable land	0.1	0
21	RA_Building	0	0
22	RA_Deciduous forest	0.5	0.25
23	RA_Grass/Paved	0.25	0.25
24	RA_Grassland	0.75	0.75
25	RA_Mixed forest	0.5	0.25
26	RA_Roads	0	0
27	RA_Urban - Grass/Paved/Trees	0.33	0.25
28	RA_Water	0	0
29	RA_Water - Rivers	0	0
30	RA_Wetland	0	0.5
31	Railways	0	0
32	Residential (Paved <50% of the area)	0.33	0.25
33	Residential (Paved >50% of the area)	0.165	0.125
34	Roads	0	0
35	Sports area - Grass/Paved/Trees	0.165	0.125
36	Tree nursery	0.25	0.1
37	Trees	0.5	0.25
38	Unpaved or lightweight road - Roads	0	0
39	Urban - Grass/Paved/Trees	0.33	0.25

40	Vineyard - Vineyard	0.25	0.75
41	Water	0	0
42	Water - Rivers	0	0
43	Water tank	0	0

Table S1.6 Availability of nesting sites and floral resources in LULC classes within the MAR/SAT Basel/Lange Erlen wider case study.

lucode	LULC_desc	nesting_ground_availability_index	floral_resources_spring_index
0	Grassland	0.75	0.75
1	Arable land	0.1	0
2	Grass	0.5	0.5
3	Grass/Trees	0.5	0.375
4	Grass/Paved/Trees	0.33	0.25
5	Grass/Paved	0.25	0.25
6	Paved/Trees	0.25	0.125
7	Paved	0	0
8	Deciduous forest	0.5	0.25
9	Paved/Trees/Water	0.17	0.08
10	Arable land/Paved	0.05	0
11	Coniferous forest	0.5	0.25
12	Coniferous trees	0.5	0.25
13	Deciduous trees	0.5	0.25
14	Grove/Coppice/Copse	0.5	0.25
15	Bare ground	0.25	0
16	Bare ground/Paved	0.125	0
17	Paved/Orchard	0.125	0.375
18	Bare ground/Grass/Paved	0.25	0.17
19	Trees	0.5	0.25
20	Paved/Horticulture	0.125	0.375
21	Residential	0.33	0.25
22	Paved/Arable	0.05	0
23	Allotment/Grass/Paved/Trees	0.375	0.44
24	Bare ground/Grass/Trees	0.42	0.25
25	Bare ground/Grass	0.375	0.25
26	Roads	0	0
27	Water - Rivers	0	0
28	Mixed forest	0.5	0.25
29	Moor	0	0.5
30	Quarry	0	0
31	Orchard	0.25	0.75
32	Railways	0	0
33	Allotment	0.5	0.75
34	Water	0	0
35	Tree nursery	0.25	0.1
36	Vineyard	0.25	0.75

37	Reedbed	0	0

Foraging distance was estimated for six species of bumblebees with widespread occurrence ranges in Europe (Rasmont and Iserbyt, 201X) Table S1.7.

Table S1.7 Guild table used in parameterisation of the InVEST 3.4.4 Pollination model. Alpha relates to the mean foraging distance.

SPECIES	nesting_suitability_ground_index	foraging_activity_spring_index	alpha	relative_abundance	Reference
B_pratorum	1	1	674	1	Knight et al. (2005)
B_hortorum	1	1	273	1	Redhead et al. (2016)
B_lapidarius	1	1	493	1	
B_pascuorum	1	1	393	1	
B_ruderatus	1	1	502	1	
B_terrestris	1	1	655	1	

8.1.4 InVEST 3.4.4 Seasonal Water Yield (SWY) model

Threshold flow accumulation

In all case study sites this setting was set to 10000 grid cells

Potential evapotranspiration

Monthly Global PET rasters at 1km spatial resolution downloaded from Global Aridity and PET Database at https://cgiarcsi.community/data/global-aridity-and-pet-database/#download. Further description of the dataset is available from (Zomer et al., 2008, 2006)

Precipitation

Monthly mean precipitation layers were downloaded as 30 sec resolution rasters from the global WorldClim v2.0 dataset that holds average monthly climate data for years 1970-2000 (Fick and Hijmans, 2017).

Digital elevation model

EU-DEM was downloaded from the European Environment Agency at https://www.eea.europa.eu/data-and-maps/data/copernicus-land-monitoring-service-eu-dem and clipped to the extent of wider case study areas increased by a 2000m buffer.

The original spatial resolution of the DEM is 25m - this was changed to 5m to match the spatial resolution of the LULC maps. First, the DEM was resampled to 5m resolution using the Nearest Neighbour method using the 'Resample tool' in ArcGIS 10.5.1. Second, with the aim of smoothing the dataset, focal mean raster within a circle of 5 grid cell radius was derived with the 'Focal statistics tool'.

Land use/Land cover

LULC maps were submitted to the models as 5m resolution rasters derived from datasets described in the main text of this paper.

Soil group

Hydrologic soil group is determined based on soil depth and hydraulic conductivity.

Soil depth form the SoilGrids dataset at 250m resolution (Hengl et al., 2017) was used.

Saturated hydraulic conductivity layers at the depth of 0-200cm were obtained from the KS dataset available from the 3D soil hydraulic database of Europe at 250m resolution (Tóth et al., 2017) were used. Equation 1 was used to calculate the total KS for the entire 0-200cm soil profile.

The SWY model requires that the units of hydraulic conductivity are mc/s. KS is supplied in cm/day times 100, and therefore the KS raster was multiplied by 0.11574 to bring it to the required units.

Hydrologic soil groups to each pixel in the maps was assigned according to the criteria listed in the help file for the model.

AOI/Watershed

The outline of the wider study areas was used as the AOI.

Biophysical table

The biophysical tables used in the study are shown in tables S1.8-S1.10. The biophysical table contains information on the curve number (CN) and evapotranspiration coefficient (Kc) for each LULC class in the study area.

Curve number is an indicator of runoff potential of a complex, formed by the combination of a hydrologic soil group, land use and treatment class, during periods when the soil is not frozen. The parameterisation was based on values listed in the USDA handbook (NRCS-USDA, 2007 Chap. 9). In all cases, were applicable, good hydrological conditions were assumed. Further assumptions as to the parameterisation of the CN values are given in tables S1.11-S1.12.

Table S1.8 Biophysical table submitted to the InVEST 3.4.4 SWY model for the Poznan/Mosina wider case study area.

lucode	Description	CN_A	CN_B	CN_C	CN_D	Kc_1	Kc_2	Kc_3	Kc_4	Kc_5	Kc_6	Kc_7	Kc_8	Kc_9	Kc_10	Kc_11	Kc_12
0	arable	0	0	80	84	0.4	0.4	0.6	1.15	1.15	1.15	1.15	0.7	0.4	0.4	0.4	0.4
3	copse	0	0	70	77	0.2	0.2	0.3	0.9	1.2	1.2	1.2	1.2	1.2	1.1	0.5	0.2
5	garden	0	0	72	79	0.2	0.2	0.3	0.9	1.2	1.2	1.2	1.2	1.2	1.1	0.5	0.2
6	grass	0	0	71	78	0.4	0.4	0.56	0.95	0.95	1.01	1.05	1.05	1	1	0.86	0.4
7	grass/trees	0	0	72	79	0.2	0.2	0.3	0.9	1.2	1.2	1.2	1.2	1.2	1.1	0.5	0.2
8	orchard	0	0	72	79	0.2	0.2	0.3	0.9	1.2	1.2	1.2	1.2	1.2	1.1	0.5	0.2
11	paved/grass/trees	0	0	85	89	0.27	0.27	0.35	0.68	0.78	0.8	0.82	0.82	0.8	0.77	0.52	0.27
12	plantation	0	0	72	79	0.2	0.2	0.3	0.9	1.2	1.2	1.2	1.2	1.2	1.1	0.5	0.2
16	shrub	0	0	70	77	0.2	0.2	0.3	0.9	1.2	1.2	1.2	1.2	1.2	1.1	0.5	0.2
19	wetland	0	0	99	99	0.6	1.2	1.2	1.2	1.2	1.2	1.2	1.2	0.7	0.3	0.3	0.3
20	woodland	0	0	70	77	0.2	0.2	0.3	0.9	1.2	1.2	1.2	1.2	1.2	1.1	0.5	0.2
1	bare ground	0	0	91	94	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
2	building	0	0	98	98	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
4	dumping ground	0	0	82	86	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
9	paved	0	0	98	98	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
10	paved/bare ground	0	0	95	96	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
13	railway	0	0	89	91	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
14	road	0	0	92	93	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
15	sand	0	0	91	94	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
17	water	0	0	98	98	0.65	0.65	0.65	0.65	0.65	0.65	1.25	1.25	1.25	0.65	0.65	0.65
18	water tank	0	0	98	98	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05

Table S1.9 Biophysical table submitted to the InVEST 3.4.4 SWY model for the Basel/Lange Erlen wider case study area.

lucode	Description	CN_A	CN_B	CN_C	CN_D	Kc_1	Kc_2	Kc_3	Kc_4	Kc_5	Kc_6	Kc_7	Kc_8	Kc_9	Kc_10	Kc_11	Kc_12
0	Allotment	0	0	77	83	0.4	0.4	0.54	0.93	0.93	0.93	0.93	0.61	0.4	0.4	0.4	0.4
1	Arable land	0	0	82	86	0.4	0.4	0.6	1.15	1.15	1.15	1.15	0.7	0.4	0.4	0.4	0.4
2	Building	0	0	98	98	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
3	Coniferous forest	0	0	70	77	0.2	0.2	0.3	0.9	1.2	1.2	1.2	1.2	1.2	1.1	0.5	0.2
4	Deciduous forest	0	0	70	77	0.2	0.2	0.3	0.9	1.2	1.2	1.2	1.2	1.2	1.1	0.5	0.2
5	Grass	0	0	74	80	0.2	0.2	0.3	0.9	1.2	1.2	1.2	1.2	1.2	1.1	0.5	0.2
6	Grass/Paved	0	0	86	89	0.2	0.2	0.25	0.55	0.7	0.7	0.7	0.7	0.7	0.65	0.35	0.2
7	Grass/Paved/Trees	0	0	81	85	0.2	0.2	0.27	0.67	0.87	0.87	0.87	0.87	0.87	0.8	0.4	0.2
8	Grass/Trees	0	0	72	79	0.2	0.2	0.3	0.9	1.2	1.2	1.2	1.2	1.2	1.1	0.5	0.2
9	Grassland	0	0	71	78	0.4	0.4	0.56	0.95	0.95	1.01	1.05	1.05	1	1	0.86	0.4
10	Grassland/Allotment	0	0	74	81	0.3	0.3	0.42	0.91	1.06	1.06	1.06	0.91	0.8	0.75	0.45	0.3
11	Grassland/Arable land	0	0	77	82	0.4	0.4	0.58	1.05	1.05	1.08	1.1	0.88	0.7	0.7	0.63	0.4
12	Grove/Coppice/Copse	0	0	70	77	0.2	0.2	0.3	0.9	1.2	1.2	1.2	1.2	1.2	1.1	0.5	0.2
13	Horticulture	0	0	77	83	0.4	0.4	0.54	0.93	0.93	0.93	0.93	0.61	0.4	0.4	0.4	0.4
14	Industrial and commercial site - Paved	0	0	98	98	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
15	Mixed forest	0	0	70	77	0.2	0.2	0.3	0.9	1.2	1.2	1.2	1.2	1.2	1.1	0.5	0.2
16	Orchard	0	0	72	79	0.2	0.2	0.3	0.9	1.2	1.2	1.2	1.2	1.2	1.1	0.5	0.2
17	Paved	0	0	98	98	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
18	Quarry	0	0	98	98	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
19	RA_Allotment	0	0	77	83	0.4	0.4	0.54	0.93	0.93	0.93	0.93	0.61	0.4	0.4	0.4	0.4
20	RA_Arable land	0	0	82	86	0.4	0.4	0.6	1.15	1.15	1.15	1.15	0.7	0.4	0.4	0.4	0.4
21	RA_Building	0	0	98	98	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
22	RA_Deciduous forest	0	0	70	77	0.77	0.77	0.8	1	1.1	1.1	1.1	1.1	1.1	1.067	0.86	0.767

																7	
23	RA_Grass/Paved	0	0	86	89	0.2	0.2	0.25	0.55	0.7	0.7	0.7	0.7	0.7	0.65	0.35	0.2
24	RA_Grassland	0	0	71	78	0.83	0.83	0.89	1.02	1.02	1.04	1.05	1.05	1.03	1.033	0.987	0.833
25	RA_Mixed forest	0	0	70	77	0.77	0.77	0.8	1	1.1	1.1	1.1	1.1	1.1	1.067	0.867	0.767
26	RA_Roads	0	0	98	98	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
27	RA_Urban - Grass/Paved/Trees	0	0	81	85	0.2	0.2	0.27	0.67	0.87	0.87	0.87	0.87	0.87	0.8	0.4	0.2
28	RA_Water	0	0	98	98	0.65	0.65	0.65	0.65	0.65	0.65	1.25	1.25	1.25	0.65	0.65	0.65
29	RA_Water - Rivers	0	0	98	98	0.65	0.65	0.65	0.65	0.65	0.65	1.25	1.25	1.25	0.65	0.65	0.65
30	RA_Wetland	0	0	98	98	0.6	1.2	1.2	1.2	1.2	1.2	1.2	1.2	0.7	0.3	0.3	0.3
31	Railways	0	0	89	91	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
32	Residential (Paved <50% of the area)	0	0	83	87	0.2	0.2	0.25	0.55	0.7	0.7	0.7	0.7	0.7	0.65	0.35	0.2
33	Residential (Paved >50% of the area)	0	0	90	92	0.2	0.2	0.24	0.48	0.6	0.6	0.6	0.6	0.6	0.56	0.32	0.2
34	Roads	0	0	98	98	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
35	Sports area - Grass/Paved/Trees	0	0	81	85	0.2	0.2	0.27	0.67	0.87	0.87	0.87	0.87	0.87	0.8	0.4	0.2
36	Tree nursery	0	0	72	79	0.2	0.2	0.3	0.9	1.2	1.2	1.2	1.2	1.2	1.1	0.5	0.2
37	Trees	0	0	70	77	0.2	0.2	0.3	0.9	1.2	1.2	1.2	1.2	1.2	1.1	0.5	0.2
38	Unpaved or lightweight road - Roads	0	0	87	89	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
39	Urban - Grass/Paved/Trees	0	0	81	85	0.2	0.2	0.27	0.67	0.87	0.87	0.87	0.87	0.87	0.8	0.4	0.2
40	Vineyard - Vineyard	0	0	82	86	0.4	0.4	0.4	0.4	0.37	0.5	0.64	0.7	0.7	0.5	0.4	0.4
41	Water	0	0	98	98	0.65	0.65	0.65	0.65	0.65	0.65	1.25	1.25	1.25	0.65	0.65	0.65
42	Water - Rivers	0	0	98	98	0.65	0.65	0.65	0.65	0.65	0.65	1.25	1.25	1.25	0.65	0.65	0.65
43	Water tank	0	0	98	98	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05

Table S1.10 Biophysical table submitted to the InVEST 3.4.4 SWY model for the Rheinbach/Erftverband wider case study area.

lucode	Description	CN_A	CN_B	CN_C	CN_D	Kc_1	Kc_2	Kc_3	Kc_4	Kc_5	Kc_6	Kc_7	Kc_8	Kc_9	Kc_10	Kc_11	Kc_12
0	Grassland	0	0	71	78	0.4	0.4	0.56	0.95	0.95	1.01	1.05	1.05	1	1	0.86	0.4
1	Arable land	0	0	80	84	0.4	0.4	0.6	1.15	1.15	1.15	1.15	0.7	0.4	0.4	0.4	0.4
2	Grass	0	0	74	80	0.2	0.2	0.3	0.9	1.2	1.2	1.2	1.2	1.2	1.1	0.5	0.2
3	Grass/Trees	0	0	80	79	0.2	0.2	0.3	0.9	1.2	1.2	1.2	1.2	1.2	1.1	0.5	0.2
4	Grass/Paved/Trees	0	0	81	85	0.2	0.2	0.27	0.67	0.87	0.87	0.87	0.87	0.87	0.8	0.4	0.2
5	Grass/Paved	0	0	88	91	0.2	0.2	0.25	0.55	0.7	0.7	0.7	0.7	0.7	0.65	0.35	0.2
6	Paved/Trees	0	0	84	88	0.2	0.2	0.25	0.55	0.7	0.7	0.7	0.7	0.7	0.65	0.35	0.2
7	Paved	0	0	98	98	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
8	Deciduous forest	0	0	70	77	0.2	0.2	0.3	0.9	1.2	1.2	1.2	1.2	1.2	1.1	0.5	0.2
9	Paved/Trees/Water	0	0	89	91	0.35	0.35	0.38	0.58	0.68	0.68	0.88	0.88	0.88	0.65	0.45	0.35
10	Arable land/Paved	0	0	89	91	0.3	0.3	0.4	0.68	0.68	0.68	0.68	0.45	0.3	0.3	0.3	0.3
11	Coniferous forest	0	0	70	77	0.2	0.2	0.3	0.9	1.2	1.2	1.2	1.2	1.2	1.1	0.5	0.2
12	Coniferous trees	0	0	70	77	0.2	0.2	0.3	0.9	1.2	1.2	1.2	1.2	1.2	1.1	0.5	0.2
13	Deciduous trees	0	0	70	77	0.2	0.2	0.3	0.9	1.2	1.2	1.2	1.2	1.2	1.1	0.5	0.2
14	Grove/Coppice/Copse	0	0	70	77	0.2	0.2	0.3	0.9	1.2	1.2	1.2	1.2	1.2	1.1	0.5	0.2
15	Bare ground	0	0	91	94	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
16	Bare ground/Paved	0	0	95	96	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
17	Paved/Orchard	0	0	85	89	0.2	0.2	0.25	0.55	0.7	0.7	0.7	0.7	0.7	0.65	0.35	0.2
18	Bare ground/Grass/Paved	0	0	88	91	0.27	0.27	0.3	0.5	0.6	0.6	0.6	0.6	0.6	0.567	0.367	0.267
19	Trees	0	0	70	77	0.2	0.2	0.3	0.9	1.2	1.2	1.2	1.2	1.2	1.1	0.5	0.2
20	Paved/Horticulture	0	0	88	91	0.3	0.3	0.37	0.56	0.56	0.56	0.56	0.41	0.3	0.3	0.3	0.3
21	Residential	0	0	90	92	0.2	0.2	0.24	0.48	0.6	0.6	0.6	0.6	0.6	0.56	0.32	0.2
22	Paved/Arable	0	0	89	91	0.3	0.3	0.4	0.68	0.68	0.68	0.68	0.45	0.3	0.3	0.3	0.3
23	Allotment/Grass/Paved/Tre	0	0	80	85	0.25	0.25	0.34	0.73	0.88	0.88	0.88	0.8	0.75	0.7	0.4	0.25

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24	Bare ground/Grass/Trees	0	0	78	84	0.27	0.27	0.33	0.73	0.93	0.93	0.93	0.93	0.93	0.867	0.467	0.267
25	Bare ground/Grass	0	0	83	87	0.3	0.3	0.35	0.65	0.8	0.8	0.8	0.8	0.8	0.75	0.45	0.3
26	Roads	0	0	98	98	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
27	Water - Rivers	0	0	98	98	0.65	0.65	0.65	0.65	0.65	0.65	1.25	1.25	1.25	0.65	0.65	0.65
28	Mixed forest	0	0	70	77	0.2	0.2	0.3	0.9	1.2	1.2	1.2	1.2	1.2	1.1	0.5	0.2
29	Moor	0	0	65	73	0.2	0.2	0.3	0.9	1.2	1.2	1.2	1.2	1.2	1.1	0.5	0.2
30	Quarry	0	0	98	98	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
31	Orchard	0	0	72	79	0.2	0.2	0.3	0.9	1.2	1.2	1.2	1.2	1.2	1.1	0.5	0.2
32	Railways	0	0	89	91	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
33	Allotment	0	0	77	83	0.4	0.4	0.54	0.93	0.93	0.93	0.93	0.61	0.4	0.4	0.4	0.4
34	Water	0	0	98	98	0.65	0.65	0.65	0.65	0.65	0.65	1.25	1.25	1.25	0.65	0.65	0.65
35	Tree nursery	0	0	72	79	0.2	0.2	0.3	0.9	1.2	1.2	1.2	1.2	1.2	1.1	0.5	0.2
36	Vineyard	0	0	82	86	0.4	0.4	0.4	0.4	0.37	0.5	0.64	0.7	0.7	0.5	0.4	0.4
37	Reedbeds	0	0	98	98	0.6	1.2	1.2	1.2	1.2	1.2	1.2	1.2	0.7	0.3	0.3	0.3

Table S1.11 Assumptions as to assignment of CN numbers in the Poznan/Mosina case study.

LULC	CN_A	CN_B	CN_C	CN_D	Comments
arable	N/A	N/A	80	84	Assumption that small grain crops are grown, with straight row (SR) and some crop residue cover(CR) under good hydrologic conditions, i.e. with factors improving run-off infiltration
copse	N/A	N/A	70	77	Copse is treated as woods under good hydrologic conditions
garden	N/A	N/A	72	79	Treated as woods-grass combination (orchard or tree farm) with good hydrologic conditions
grass	N/A	N/A	71	78	Grass treated as meadow-continuous grass protected from grazing and generally mowed for hay, good hydrologic conditions
grass/trees	N/A	N/A	72	79	Treated as woods-grass combination (orchard or tree farm) with good hydrologic conditions
orchard	N/A	N/A	72	79	Treated as woods-grass combination (orchard or tree farm) with good hydrologic conditions

paved/grass/trees	N/A	N/A	85	89	An average between paved, and grass/trees
plantation	N/A	N/A	72	79	Treated as woods-grass combination (orchard or tree farm) with good hydrologic conditions
shrub	N/A	N/A	70	77	Shrub is treated as woods under good hydrologic conditions
wetland	N/A	N/A	99	99	Treated as water
woodland	N/A	N/A	70	77	Treated as woodland, good hydrologic conditions
bare ground	N/A	N/A	91	94	Treated as bare soil
building	N/A	N/A	98	98	Treated as impervious areas, paved parking lots, roofs, driveways, etc
dumping ground	N/A	N/A	82	86	Treated as farmstead
paved	N/A	N/A	98	98	Treated as impervious areas, paved parking lots, roofs, driveways, etc
paved/bare ground	N/A	N/A	95	96	An average between paved and bare ground
railway	N/A	N/A	89	91	Treated as gravel road, right of way
road	N/A	N/A	92	93	Treated as streets and roads, paved with open ditches
sand	N/A	N/A	91	94	Treated as bare soil
water	N/A	N/A	98	98	Recommendation for water
water tank	N/A	N/A	98	98	Recommendation for water

Table S1.12 Assumptions as to assignment of CN numbers in the Basel/Lange Erlen and Rheinbach/Erftverband case studies.

ID	LULC	CN_C	CN_D	Comments
1	Allotment	77	83	As minor crops
2	Allotment/Grass/Paved/Trees	80	85	Mean of respective LULC classes
3	Arable land	80	84	Assumption that small grain crops are grown, with straight row (SR) and some crop residue cover(CR) under good hydrologic conditions, i.e. with factors improving run-off infiltration
4	Arable land/Paved	90	92	Mean of respective LULC classes
5	Bare ground	91	94	As Fallow/bare soil
6	Bare ground/Grass	83	87	Mean of respective LULC classes
7	Bare ground/Grass/Paved	88	91	Mean of respective LULC classes
8	Bare ground/Grass/Trees	78	84	Mean of respective LULC classes
9	Bare ground/Paved	95	96	Mean of respective LULC classes
10	Building	98	98	Paved parking lots, roofs, driveways, etc.
11	Coniferous forest	70	77	Woods, good hydro conditions
12	Coniferous trees	70	77	Woods, good hydro conditions
13	Deciduous forest	70	77	Woods, good hydro conditions
14	Deciduous trees	70	77	Woods, good hydro conditions
15	Grass	74	80	Open space, good condition
16	Grass/Paved	86	89	Mean of grass and paved
17	Grass/Paved/Trees	81	85	Mean of grass, paved, and trees
18	Grass/Trees	72	79	Mean of grass and trees
19	Grassland	71	78	Meadow-continuous grass
20	Grassland/Allotment	74	81	Mean of respective LULCs
21	Grassland/Arable land	76	81	Mean of respective LULCs
22	Grove/Coppice/Copse	70	77	Woods, good hydro conditions
23	Horticulture	77	83	As minor crops (Puerto Rico)
24	Industrial and commercial site - Paved	98	98	Paved; curbs and storm sewers
25	Mixed forest	70	77	Woods, good hydro conditions
26	Moor	65	73	As brush-brush-forbs-grass mixture, good conditions
27	Orchard	72	79	Woods-grass combination, good conditions
28	Paved	98	98	Paved; curbs and storm sewers
29	Paved/Arable	90	92	Mean of respective LULC classes
30	Paved/Horticulture	88	91	Mean of respective LULC classes
31	Paved/Orchard	85	89	Mean of respective LULC classes
32	Paved/Trees	84	88	Mean of respective LULC classes
33	Paved/Trees/Water	89	91	Mean of respective LULC classes
34	Reedbeds (CW in Erftverband)	98	98	As water
35	Quarry	98	98	Assumption of quick runoff
36	RA_Allotment	77	83	As minor crops
37	RA_Arable land	82	86	Small grain, Contoured, good hydro conditions

38	RA_Building	98	98	Paved parking lots, roofs, driveways, etc.
39	RA_Deciduous forest	70	77	Woods, good hydro conditions
40	RA_Grass/Paved	86	89	Mean of grass and paved
41	RA_Grassland	71	78	Meadow-continuous grass
42	RA_Mixed forest	70	77	Woods, good hydro conditions
43	RA_Roads	98	98	Paved; curbs and storm sewers (excluding right-of-way)
44	RA_Urban - Grass/Paved/Trees	81	85	Mean of grass, paved, and trees
45	RA_Water	98	98	Recommendation for water
46	RA_Water - Rivers	98	98	Recommendation for water
47	RA_Wetland	98	98	Recommendation for water
48	Railways	89	91	Gravel (including right-of-way)
49	Residential	90	92	as residential with 65 percent impervious land cover
50	Residential (Paved <50% of the area)	83	87	Residential areas, 1/4 acre, 38% of impervious area
51	Residential (Paved >50% of the area)	90	92	1/8 acre or less (town houses), 65% of impervious area
52	Roads	98	98	Paved; curbs and storm sewers (excluding right-of-way)
53	Sports area - Grass/Paved/Trees	81	85	Mean of grass, paved, and trees
54	Tree nursery	72	79	Woods-grass combination, good conditions
55	Trees	70	77	Woods, good hydro conditions
56	Unpaved or lightweight road - Roads	87	89	Dirt (including right-of-way)
57	Urban - Grass/Paved/Trees	81	85	Mean of grass, paved, and trees
58	Vineyard - Vineyard	82	86	Row crops, contoured, good conditions
59	Water	98	98	Recommendation for water
60	Water - Rivers	98	98	Recommendation for water
61	Water tank	98	98	Recommendation for water

Assumptions regarding the parameterisation of the Kc coefficient for the initial, mid- and end- of growing stages were based on the FAO guidelines (Allen, 1998). In all case studies, it was assumed that the growing season starts on 22 March and ends on 13 November (236 days) and duration of growth stages were adapted from Table 11 in that reference. For arable land, the assumed crop was winter wheat. For grassland, estimates for rye grass hay with cutting effects were assumed. In Lange Erlen site, recharge areas that are inundated with water received the Kc calculated as two parts of water and one part of the respective LULC. Vineyards were parameterised as wine for grapes with duration of growing season of 180, planting in May. Outside of growing season Kc was set to arable land equivalent (0.4). Allotment and horticulture was parameterised as arable land with the exception that outside of growing season the coefficient of 0.3 was assumed due to possible lower ground cover than in winter wheat. Quarries were treated as paved, and moors as grass.

Rain events table

Rain events table specifies the number of rain events per month. These were obtained from the International Water Management Institute World Water and Climate Atlas at http://wcatlas.iwmi.org/ for points located in the centroids of the core case study sites. The database used data summaries for the years 1961-1990.

Alpha m parameter

Set to the default value of 1/12.

Beta i parameter

Set to the default value of 1.

Gamma parameter

Set to the default value of 1.

8.1.5 InVEST 3.4.4 Nutrient Delivery Ratio (NDR) model

DEM Raster

As in the case of the SWY model

Land Use

As in the case of the SWY model

Nutrient Runoff Proxy

Set to the quick flow (QF) raster generated by the SWY model.

Watersheds

Set to the outline of the wider study area.

Biophysical table

The parameters used in the biophysical table for LULC classes found within all three case study sites are shown in Table S1.13. Model is parameterised with adapted N and P loadings used in Redhead et al. (2018), and given in the supplementary materials for the paper. Woodland and copse parameterised as the mean between Broadleaf and Coniferous woodland. Grass uses the value for neutral grassland. Values dedicated to urban/suburban are assigned to dumping ground, garden, grass/trees, paved/bare ground, paved/grass/trees. Building, paved, railway, road, sand and bare ground are assigned a value of 0. Orchard and plantation are assigned the values for arable and horticulture. Shrub is parameterised as woodland, Wetland as Fen, Marsh, Swamp. Water is treated as freshwater. Water tank acquires the value of 0 as it is disconnected from the landscape.

Arable (arable land in Poznan/Mosina site) is parameterised with average application rates of N and P for the Wielkopolska Voivodship and in the other study areas, the values from Redhead et al. (2018) are used.

Nutrient retention (eff_n and eff_p) within each LULC type is also adapted from Redhead et al. (2018).

The critical length, i.e. the distance after which it is assumed that a patch of LULC retains nutrients at its maximum capacity was set to 25m, which was the minimum distance used in the Redhead et al. (2018) study.

Table S1.13 Parameters used in the biophysical table of the InVEST 3.4.4 NDR model for all three case study sites.

LULC_desc	load_n	eff_n	crit_len_n	proportion_subsurface_n	load_p	eff_p	crit_len_p	proportion_subsurface_p
Allotment	35.24	0.25	25	0	1.52	0.25	25	0
Allotment/Grass/Paved/Trees	20.18	0.36	25	0	0.64	0.36	25	0
arable	90.3	0.25	25	0	12.7	0.25	25	0
Arable land	35.24	0.25	25	0	1.52	0.25	25	0
Arable land/Paved	17.62	0.12	25	0	0.76	0.12	25	0
Bare ground	0	0	25	0	0	0	25	0
Bare ground/Grass	3.75	0.2	25	0	0.08	0.2	25	0
Bare ground/Grass/Paved	2.5	0.13	25	0	0.05	0.13	25	0
Bare ground/Grass/Trees	15.15	0.4	25	0	0.35	0.4	25	0
Bare ground/Paved	0	0	25	0	0	0	25	0
Building	0	0	25	0	0	0	25	0
Coniferous forest	10.9	0.8	25	0	0.73	0.8	25	0
Coniferous trees	10.9	0.8	25	0	0.73	0.8	25	0
Copse	37.95	0.8	25	0	0.9	0.8	25	0
Deciduous forest	65	0.8	25	0	1.07	0.8	25	0
Deciduous trees	65	0.8	25	0	1.07	0.8	25	0
Dumping ground	7.63	0.05	25	0	2.22	0.05	25	0
Garden	7.63	0.05	25	0	2.22	0.05	25	0
Grass	7.5	0.4	25	0	0.15	0.4	25	0
Grass/Paved	3.75	0.2	25	0	0.08	0.2	25	0
Grass/Paved/Trees	15.15	0.4	25	0	0.35	0.4	25	0
Grass/Trees	22.72	0.6	25	0	0.52	0.6	25	0
Grassland	7.5	0.4	25	0	0.15	0.4	25	0
Grassland/Allotment	21.37	0.32	25	0	0.84	0.32	25	0
Grassland/Arable land	21.37	0.32	25	0	0.84	0.32	25	0
Grove/Coppice/Copse	65	0.8	25	0	1.07	0.8	25	0
Horticulture	35.24	0.25	25	0	1.52	0.25	25	0
Industrial and commercial site - Paved	0	0	25	0	0	0	25	0
Mixed forest	37.95	0.8	25	0	0.9	0.8	25	0
Moor	7.5	0.4	25	0	0.15	0.4	25	0
Orchard	35.24	0.25	25	0	1.52	0.25	25	0
Paved	0	0	25	0	0	0	25	0
Paved/Arable	17.62	0.12	25	0	0.76	0.12	25	0
paved/bare ground	7.63	0.05	25	0	2.22	0.05	25	0
paved/grass/trees	7.63	0.05	25	0	2.22	0.05	25	0
Paved/Horticulture	17.62	0.12	25	0	0.76	0.12	25	0
Paved/Orchard	17.62	0.12	25	0	0.76	0.12	25	0
Paved/Trees	18.98	0.4	25	0	0.45	0.4	25	0
Paved/Trees/Water	12.65	0.27	25	0	0.30	0.27	25	0
plantation	35.24	0.25	25	0	1.52	0.25	25	0
Quarry	0	0	25	0	0	0	25	0

Railways	0	0	25	0	0	0	25	0
Residential	9.09	0.24	25	0	0.21	0.24	25	0
Residential (Paved <50% of the area)	13.64	0.36	25	0	0.32	0.36	25	0
Residential (Paved >50% of the area)	9.09	0.24	25	0	0.21	0.24	25	0
Roads	0	0	25	0	0	0	25	0
sand	0	0	25	0	0	0	25	0
shrub	37.95	0.8	25	0	0.9	0.8	25	0
Sports area - Grass/Paved/Trees	15.15	0.4	25	0	0.35	0.4	25	0
Tree nursery	37.95	0.8	25	0	0.9	0.8	25	0
Trees	37.95	0.8	25	0	0.9	0.8	25	0
Unpaved or lightweight road - Roads	0	0	25	0	0	0	25	0
Urban - Grass/Paved/Trees	15.15	0.4	25	0	0.35	0.4	25	0
Vineyard	35.24	0.25	25	0	1.52	0.25	25	0
Water	0.01	0	25	0	0.01	0	25	0
Water - Rivers	0.01	0	25	0	0.01	0	25	0
Water tank	0	0	25	0	0	0	25	0
wetland	10	0.8	25	0	0.14	0.8	25	0
woodland	37.95	0.8	25	0	0.9	0.8	25	0

Threshold flow accumulation

Set as in the case of the SWY model.

Borselli k parameter

0.5

Subsurface critical length (Nitrogen and Phosphorus)

25m (Redhead et al. (2018))

Subsurface Maximum Retention Efficiency (Nitrogen and Phosphorus)

0.5

8.1.6 Invest 3.4.4 Sediment Delivery Ratio (SDR) model

Digital Elevation Model

As in the case of the SWY model

Rainfall Erosivity Index R

Sourced from the European rainfall erosivity map at 500m resolution (Panagos et al., 2015a).

Soil Erodibility Index K

Sourced from the European soil erodibility map at 500m resolution (Panagos et al., 2014). Gaps under urban areas were filled with the mean value of K for the wider study areas to avoid areas with missing data in the model output.

Land-use/Land-Cover

As in the case of the SWY model

Watersheds

As in the case of the SWY model

Biophysical table

The cover management (C) and support practice (P) factors used in this study for all case study sites are show in Table S1.14.

P factor is set to 1 for all land cover classes, assuming that there are no practices in place that would mitigate erosion.

The values of the C factor are largely based on Table 2 in (Panagos et al., 2015b).

Table S1.14 Cover management (C) and support practice (P) factors used in all case studies.

LULC	usle_c	usle_p
Allotment	0.07	1
Allotment/Grass/Paved/Trees	0.043	1
Arable land	0.2	1
Arable land/Paved	0.1005	1
Bare ground	0.5	1
Bare ground/Grass	0.3	1
Bare ground/Grass/Paved	0.267	1
Bare ground/Grass/Trees	0.2007	1
Bare ground/Paved	0.2505	1
Building	0.001	1
Coniferous forest	0.002	1
Coniferous trees	0.002	1
copse	0.002	1
Deciduous forest	0.002	1
Deciduous trees	0.002	1
dumping ground	0.001	1
garden	0.1	1
Grass	0.1	1
Grass/Paved	0.0505	1
Grass/Paved/Trees	0.034	1
Grass/Trees	0.051	1
Grassland	0.1	1
Grassland/Allotment	0.085	1
Grassland/Arable land	0.15	1
Grove/Coppice/Copse	0.002	1

Horticulture	0.07	1
Industrial and commercial site - Paved	0.001	1
Mixed forest	0.002	1
Moor	0.01	1
Orchard	0.3	1
Paved	0.001	1
Paved/Arable	0.1005	1
paved/bare ground	0.001	1
paved/grass/trees	0.057167	1
Paved/Horticulture	0.0355	1
Paved/Orchard	0.1505	1
Paved/Trees	0.0015	1
Paved/Trees/Water	0.0013	1
plantation	0.1	1
Quarry	0.5	1
RA_Allotment	0.07	1
RA_Arable land	0.2	1
RA_Building	0.001	1
RA_Deciduous forest	0.002	1
RA_Grass/Paved	0.0505	1
RA_Grassland	0.1	1
RA_Mixed forest	0.002	1
RA_Roads	0.001	1
RA_Urban - Grass/Paved/Trees	0.034	1
RA_Water	1	1
RA_Water - Rivers	1	1
RA_Wetland	1	1
Railways	0.001	1
Residential	0.021	1
Residential (Paved <50% of the area)	0.031	1
Residential (Paved >50% of the area)	0.021	1
Roads	0.001	1
sand	0.001	1
shrub	0.0001	1
Sports area - Grass/Paved/Trees	0.034	1
Tree nursery	0.002	1
Trees	0.002	1
Unpaved or lightweight road - Roads	0.1	1
Urban - Grass/Paved/Trees	0.034	1
Vineyard	0.15	1
Water	0.001	1
Water - Rivers	0.001	1
Water tank	0.001	1
Wetland	0.001	1
Woodland	0.0001	1

Threshold Flow Accumulation

As in the case of the SWY model

Drainages

A raster depicting the spatial location of water bodies derived from the LULC map using GIS operations (ArcGIS 10.5).

Borselli k Parameter

2 (Default)

Borselli ICo Parameter

0.5 (Default)

Max SDR value

0.8 (Default)

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8.2 S2 Parameterisation of the Circuitscape model for habitat connectivity assessment

Connectivity modelling was based on lists of species of birds and mammals available from Natura 2000 network obtained from the European Environment Agency at https://www.eea.europa.eu/data-and-maps/data/natura-9.

Shapefiles for Natura 2000 network were downloaded from https://www.eea.europa.eu/data-and-maps/data/nationally-designated-areas-national-cdda-12/gis-data/cdda-shape-file and clipped to the extent of the wider study areas with a 500m buffer.

Natura 2000 networks that were present within the study areas are listed in Table S2.1 Species lists and resistivity values associated with each LULC class for each case study site are given in Tables S2.2-2.4 (Excel file).

Table S2.1 Natura 2000 network sites located within the wider case study areas.

SITECODE	SITENAME	MS	Site	Area_ha
DE5308401	Vogelschutzgebiet Kottenforst-Waldville	DE	Rheinbach/Erftverband	1930.77
DE5207301	Waldville	DE		1117.76
DE5308303	Waldreservat Kottenforst	DE		813
DE5207304	Villewälder bei Bornheim	DE		620.46
DE5307301	Laubwald südlich Rheinbach*	DE		550.7
DE5507401	Ahrgebirge	DE		352.2
DE5407301	Wiesen bei Ruine Tomberg	DE		107.12
DE5408302	Ahrtal	DE		11.24
DE8312311	Dinkelberg und Röttler Wald	DE	Basel/Lange Erlen	2624.54
DE8311441	Tüllinger Berg und Gleusen	DE		545.65
DE8311341	Tüllinger Berg und Tongrube Rümmingen	DE		329.36
DE8411341	Wälder bei Wyhlen	DE		188.53
FR4211812	Vallée du Rhin d'Artzenheim à Village-Neuf**	FR		33.06
FR4202000	Secteur Alluvial Rhin-Ried-Bruch, Haut-Rhin**	FR		13.73
DE8211401	Rheinniederung Haltingen - Neuenburg mit Vorbergzone	DE		12.28
DE8311342	Markgräfler Rheinebene von Weil bis Neuenburg	DE		11.01
PLB300017	Ostoja Rogalinska***	PL	Poznan/Mosina	16823.13
PLH300012	Rogalinska Dolina Warty	PL		9288.87
PLH300010	Ostoja Wielkopolska	PL		8434.18
PLH300039	Bedlewo-Bieczyny	PL		752.59

*No species data were available for this site

** Sites located in France on the other bank of the Rhine River (excluded from analysis)

*** Model run for the area covering this site only since the BF site (Krajkowska Island) is located within this Natura 2000 area.

8.3 S3 Online survey design

	Strongly agree	Mildly agree	Neither agree nor disagree	Mildly disagree	Strongly disagree	Strongly agree	Mildly agree	Neither agree nor disagree	Mildly disagree	Strongl disagre
I find it visually attractive	○	○	○	○	○	☐	☐	☐	☐	☐
I would enjoy visiting it	○	○	○	○	○	☐	☐	☐	☐	☐
I think others would enjoy visiting it	○	○	○	○	○	☐	☐	☐	☐	☐
I would be happy to have it in my neighbourhood	○	○	○	○	○	☐	☐	☐	☐	☐
I would be happy to have it in my city / region	○	○	○	○	○	☐	☐	☐	☐	☐
It's an attractive feature for the local area	○	○	○	○	○	☐	☐	☐	☐	☐
I particularly like the green features	○	○	○	○	○	☐	☐	☐	☐	☐
I particularly like the natural look	○	○	○	○	○	☐	☐	☐	☐	☐
I particularly like the built look	○	○	○	○	○	☐	☐	☐	☐	☐

Figure S3.1 Online survey questions regarding the comparison of aesthetic value of constructed wetland (CW) and primary sediment tank (ST)

	Strongly agree	Mildly agree	Neither agree nor disagree	Mildly disagree	Strongly disagree	Strongly agree	Mildly agree	Neither agree nor disagree	Mildly disagree	Stror disag
I find it visually attractive	○	○	○	○	○	☐	☐	☐	☐	☐
I would enjoy visiting it	○	○	○	○	○	☐	☐	☐	☐	☐
I think others would enjoy visiting it	○	○	○	○	○	☐	☐	☐	☐	☐
I would be happy to have it in my neighbourhood	○	○	○	○	○	☐	☐	☐	☐	☐
I would be happy to have it in my city / region	○	○	○	○	○	☐	☐	☐	☐	☐
It's an attractive feature for the local area	○	○	○	○	○	☐	☐	☐	☐	☐
I particularly like the green features	○	○	○	○	○	☐	☐	☐	☐	☐
I particularly like the natural look	○	○	○	○	○	☐	☐	☐	☐	☐
I particularly like the built look	○	○	○	○	○	☐	☐	☐	☐	☐

Figure S3.2 Online survey questions regarding the comparison of aesthetic value of managed aquifer recharge/soil aquifer treatment (MAR/SAT) and potabilisation plant (PP)

8.4 S4 Paired t-test analysis of the online survey

Table S4.1 Paired t-test results for the responses aiming at comparison between aesthetic value of constructed wetland (CW) and primary sediment tank (ST)

	Paired Differences							
				95% Confidence Interval of the Difference				
	Mean	Std. Deviation	Std. Error Mean	Lower	Upper	t	df	Sig. (2-tailed)
Pair 1 CW_Attractive - ST_Attractive	-2.644	1.428	.052	-2.746	-2.543	-51.011	758	.000
Pair 2 CW_Enjoy_Visit - ST_Enjoy_Visit	-2.208	1.517	.055	-2.317	-2.100	-40.092	757	.000
Pair 3 CW_Others_Enjoy_Visit - ST_Others_Enjoy_visit	-2.225	1.466	.053	-2.330	-2.121	-41.827	758	.000
Pair 4 CW_Happy_Neighbour - ST_Happy_Neighbour	-2.345	1.449	.053	-2.448	-2.242	-44.588	758	.000
Pair 5 CW_Happy_City_Region - ST_Happy_City_Region	-2.232	1.492	.054	-2.338	-2.126	-41.214	758	.000
Pair 6 CW_Attractive_Local_Area - ST_Attractive_Local_Area	-2.411	1.465	.053	-2.515	-2.307	-45.329	758	.000
Pair 7 CW_Green_Features - ST_Green_Features	-2.521	1.421	.052	-2.622	-2.420	-48.837	757	.000
Pair 8 CW_Built_Look - ST_Built_Look	-2.569	1.404	.051	-2.669	-2.469	-50.415	758	.000
Pair 9 CW_Natural_Look - ST_Natural_Look	-1.661	1.631	.059	-1.777	-1.545	-28.037	757	.000

Table S4.2 Paired t-test results for the responses aiming at comparison between aesthetic value of managed aquifer recharge/soil aquifer treatment (MAR/SAT) and potabilisation plant (PP)

	Paired Differences							
	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper	t	df	Sig. (2-tailed)
Pair 1 LE_Attractive - PP_Attractive	-2.093	1.496	.054	-2.200	-1.987	-38.606	760	.000
Pair 2 LE_Enjoy_visit - PP_Enjoy_Visit	-1.832	1.530	.055	-1.941	-1.723	-33.033	760	.000
Pair 3 LE_Others_Enjoy_visit - PP_Others_Enjoy_Visit	-1.820	1.489	.054	-1.926	-1.714	-33.725	760	.000
Pair 4 LE_Happy_neighbourhood - PP_Happy_Neighbourhood	-1.876	1.477	.054	-1.982	-1.771	-35.043	760	.000
Pair 5 LE_Happy_City_Region - PP_Happy_City_Region	-1.687	1.491	.054	-1.793	-1.581	-31.217	760	.000
Pair 6 LE_Attractive_Local_area - PP_Attractive_Local_Area	-2.070	1.542	.056	-2.179	-1.960	-37.024	760	.000
Pair 7 LE_Green_Features - PP_Green_Features	-1.844	1.483	.054	-1.949	-1.738	-34.305	760	.000
Pair 8 LE_Built_look - PP_Built_Look	-2.106	1.509	.055	-2.214	-1.999	-38.510	760	.000
Pair 9 LE_Natural_Look - PP_Natural_Look	-1.409	1.570	.057	-1.521	-1.297	-24.752	759	.000

8.5 S5 Quantitative and qualitative results for intermediate and final ecosystem services at case study sites

Table S5.1 Modelled mean amounts of intermediate ecosystem services – values per hectare per year.

Ecosystem service	Mosina (RBF)	Lange Erlen (MAR/SAT)	Erftverband (CW)
C biomass [t/ha]	15	85	32
C total [t/ha]	667	274	47
N export [kg/ha]	0.630	0.187	n/a
N retention [kg/ha]	24	86	n/a
P export [kg/ha]	0.013	0.007	n/a
P retention [kg/ha]	0.53	2.33	n/a
Pollinator abundance [-]	0.071	0.030	0.004
Pollinator supply [-]	0.069	0.035	0.012
Quick flow [mm]	29	19	n/a
Baseflow [mm]	7.7	20	n/a
Sediment export [t/ha]	0.006	0.018	n/a
Sediment retention [t/ha]	0.266	0.933	n/a

Table S5.2 Modelled total amounts of intermediate ecosystem services – values per site per year.

Ecosystem service	Mosina (RBF)	Lange Erlen (MAR/SAT)	Erftverband (CW)
C biomass [t/site]	848	5145	48
C total [t/site]	37484	16576	71
N export [kg/site]	35	11	n/a
N retention [kg/site]	1345	5144	n/a
P export [kg/site]	0.726	0.436	n/a
P retention [kg/site]	29	140	n/a
Quick flow [mm]	29	19	n/a
Base flow [mm]	431.2	1200	n/a
Sediment export [t/site]	0.353	1.054	n/a
Sediment retention [t/site]	15	56	n/a
Area [ha]	56	60	1.5

Table S5.3 **Potential beneficiaries of intermediate ecosystem services identified for the three cNES technologies mapped into the CICES and FEGS-CS classification systems.** (continued on next page)

IESs	CICES section (IESs)	CICES class (IESs)	CICES section (FESs)	CICES class (FESs)	Beneficiary (FEGS-CS)
Pollination	Regulation and maintenance	Pollination and seed dispersal	Provisioning	Cultivated crops	Farmers
				Wild plants, algae and their outputs	Food Pickers and Gatherers
			Cultural	Experiential use of plants, animals and land-/seascapes in different environmental settings	Experiencers and Viewers
			Cultural	Existence	All humans
Carbon storage	Regulation and maintenance	Global climate regulation by reduction of greenhouse gas concentrations	Regulation and maintenance	Global climate regulation by reduction of greenhouse gas concentrations	All humans
Habitat connectivity	Regulation and maintenance	Lifecycle maintenance, habitat and gene pool protection	Cultural	Experiential use of plants, animals and land-/seascapes in different environmental settings	Resource-Dependent Businesses
					Experiencers and Viewers
				Intellectual and representative interactions: Scientific, educational, aesthetic	Artists
					Educators and Students
					Researchers
				Other cultural outputs (Existence)	People who care (Existence)
				Physical use of land-/seascapes in different environmental settings	Hunters
Sediment retention	Regulation and maintenance	Filtration/sequestration/storage /accumulation by ecosystems	Provisioning	Surface water for non-drinking purposes	Irrigators Food Extractors
					Electric and other Energy Generators
				Surface water for non-drinking and drinking purposes	Waste Water Treatment Plant Operators
			Cultural	Physical use of land-/seascapes in different environmental settings	Anglers
					Waders, Swimmers, and Divers
					Boaters

IESs	CICES section (IESs)	CICES class (IESs)	CICES section (FESs)	CICES class (FESs)	Beneficiary (FEGS-CS)
Nutrient retention	Regulation and maintenance	Filtration/sequestration/storage / accumulation by ecosystems	Provisioning	Surface water for non-drinking and drinking purposes	Municipal Drinking Water Plant Operators
					Waste Water Treatment Plant Operators
			Cultural	Experiential use of plants, animals and land-/seascapes in different environmental settings	Experiencers and Viewers
				Physical use of land-/seascapes in different environmental settings	Anglers
					Waders, Swimmers, and Divers
					Boaters
Water yield (quick flow)	Regulation and maintenance	Hydrological cycle and water flow maintenance	Provisioning	Surface water for non-drinking purposes	Irrigators
					Electric and other Energy Generators
				Surface water for drinking purposes	Municipal Drinking Water Plant Operators
			Regulation and maintenance	Hydrological cycle and water flow maintenance	Businesses/Industry
					Residential Property Owners
					Transporter of goods
					Transporters of people
			Cultural	Experiential use of plants, animals and land-/seascapes in different environmental settings	Experiencers and Viewers
				Physical use of land-/seascapes in different environmental settings	Anglers
					Waders, Swimmers, and Divers
					Boaters
					Artists
Water retention (base flow)	Regulation and maintenance	Hydrological cycle and water flow maintenance	Provisioning	Surface water for non-drinking purposes	Irrigators
					Livestock Grazers
					Farmers
					Foresters
				Groundwater for drinking purposes	Municipal Drinking Water Plant Operators
				Hydrological cycle and water flow maintenance	Residential Property Owners
					Businesses/Industry

IESs	CICES section (IESs)	CICES class (IESs)	CICES section (FESs)	CICES class (FESs)	Beneficiary (FEGS-CS)
Aesthetics	Not applicable	Not applicable	Cultural	Physical use of land-/seascapes in different environmental settings	Resource-Dependent Businesses
				Experiential use of plants, animals and land-/seascapes in different environmental settings	Residential Property Owners
					Experiencers and Viewers
				Other cultural outputs (Existence)	People who care (Existence)