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Mapping favorability to the implementation of nature-based solutions for agricultural water management in Europe

Constraints, demand, effectiveness and costs

Pistocchi, A.

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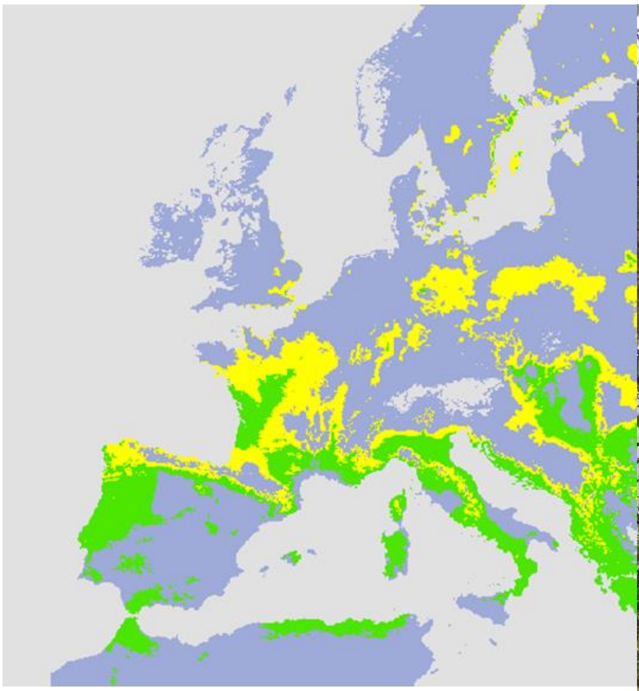


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Authors
This report was prepared by Alberto Pistocchi (JRC). Anacleto Rizzo and Giulio Conte (IRIDRA) supported the definition of criteria for mapping, based on the following reports provided by IRIDRA srl:

1) Riccardo Bresciani, Giulio Conte, Nicola Martinuzzi, Fabio Masi, Andrea Nardini, Anacleto Rizzo. Nature-based solutions for climate change adaptation and water pollution in agricultural regions: services supporting the synthesis and dissemination of results. Final report (deliverable D2), 21 may 2021.
2) Riccardo Bresciani, Giulio Conte, Nicola Martinuzzi, Fabio Masi, Andrea Nardini, Anacleto Rizzo. Nature-based solutions for climate change adaptation and water pollution in agricultural regions: services supporting the synthesis and dissemination of results. Internal report on D4.1 activities. May 2021.

The above reports are provided as annexes to this technical report.

Bruna Grizzetti, Olga Vigiak and Alberto Aloe are kindly acknowledged for providing recent GREEN model output to map manure application and diffuse emissions of nutrients used to represent demands of nature-based solutions.

This report describes a spatial evaluation for the mapping of favourability for the implementation of nature-based solutions, including multiple criteria of technical, economic, social and ecological nature. The work has been developed in the context of Administrative Arrangement N ° 34027704/2018/789016/Aa/Env.C.1 between DG Environment and the Joint Research Centre (JRC Contract Number 35003).

Abstract

This report documents the criteria proposed to map the favourability to investments in nature-based solutions (NBS) for agricultural water management, the costs and effectiveness of various types of NBS. We address selected typologies of NBS, including treatment wetlands for the removal of excess nutrients from manure and the stabilization of sludge; buffer strips, ponds and vegetated drainage ditches for diffuse pollution control; and ponds for water storage and managed aquifer recharge to address irrigation demand. We identify areas where these typologies of NBS can be implemented, taking into account various constraints. We introduce indicators representing the intensity of "demand" for NBS, i.e. presence of diffuse pollution, excess manure and sewage sludge, soil erosion and pesticide, summer deficit of precipitation with respect to potential evapotranspiration, lack of biodiversity at the landscape scale, and intensity of extreme precipitation requiring flood buffering. We propose an approach based on these information to build scenarios of implementation of NBS, which can be applied for the appraisal of programmes of measures at the regional and European scale.

1 Introduction

Water management is essential to agriculture: crops require sufficient water of appropriate quality to balance their evapotranspiration, and agricultural activities may be a significant source of pollution for surface and groundwater. Water management requires adequate infrastructure, including treatment plants and storage volumes. These can be designed in order to exploit natural processes, using biological and geological materials, so that they provide the service required while they contribute to improve the agricultural landscape and to support biodiversity. In this case, we speak about "nature-based solutions" (NBS).
We consider the following types of NBS:

1) Treatment wetlands for the removal of excess nutrients originating from manure and sewage sludge;
2) Landscape elements, such as buffer strips, ponds and vegetated ditches, for the mitigation of diffuse nutrient pollution;
3) Ponds for the storage of runoff, or its infiltration in aquifers (managed aquifer recharge), in order to support irrigation.

More in detail, we address the types and categories of NBS listed in **Table 1**.

Table 1. NBS types and categories considered in this report.

NBS Type	NBS category
NBS A1 – Wetlands	NBS A1.1 – Surface flow (SF)
	NBS A1.2 – Hybrid SF + subsurface flow (SSF)
NBS B1 – Free water surface wetland (FWS)	No categories
NBS B2 – Vegetated drainage ditch (VDD)	No categories
NBS B3 – Buffer strip (BS)	NBS B3.1 – buffer strips to address runoff (BS - R)
	NBS B3.2 – buffer strips to address groundwater (BS - G)
	NBS B3.3 – BS - Integrated
NBS C1 – Storage	NBS C1.1 – Storage pond
	NBS C1.2 – Pre-treatment pond + Storage pond
	NBS C1.3 – Pre-treatment wetland + Storage pond
NBS C2 – Managed aquifer recharge (MAR)	NBS C2.1 – Infiltration pond
	NBS C2.2 – Pre-treatment pond + Infiltration pond
	NBS C2.3 – Pre-treatment wetland + Infiltration pond
	NBS C2.4 – Infiltration wooded area

This technical report describes a spatial evaluation for the mapping of favourability to implement the above types of NBS for agricultural water management in the European Union (EU), according to multiple technical, economic, social and ecological criteria. The analysis aims at quantifying the overall benefits, as well as the investment requirements, for each type of solutions.
The analysis is organized in three steps: 1) Identification of areas compatible with the implementation of NBS (Section 2); 2) Evaluation of the extent of NBS required to meet a demand for nutrient removal or water storage, as well as additional benefits such as biodiversity support (Section 3); 3) Quantification of the effectiveness and costs of NBS (Section 4 and 5).

The methods and results of our analysis are presented and discussed in detail in the following sections.

2 Areas compatible with the implementation of NBS

We consider the NBS types listed in **Table 2**. Each type of NBS requires specific landscape conditions. We mapped these conditions using available data, and combined these condition maps in a map of modelled constraints (**Table 2**).

For flood hazards [`floodmap`], we consider the map of areas subject to flooding with a return period of 50 years developed by the JRC at a resolution of 100 m (Dottori et al., 2021).

For Land Cover we use the Corine Land Cover 100 m resolution raster map [`CLC`] referred to the year 2018, **Table 3**. The Euclidean distance from urban areas is evaluated using CLC urban areas as sources.

For aquifer productivity, we refer to the units mapped in the Hydrogeological Map of Europe 1:1,500,000 ([1]), **Table 4**.

Elevation and slope [`elev, Slope`] are extracted from the 100-m resolution digital elevation model (DEM) developed by Vogt et al., 2007 based on the Shuttle Radar Topography Mission (SRTM) data.

For the water table depth [`WTD`] we use the dataset by Pistocchi et al., 2022a ("version 1" of the interpolation, see Pistocchi et al., 2022a). Illustrative examples of the maps are shown in **Figure 1**.

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1 https://www.bgr.bund.de/EN/Themen/Wasser/Projekte/laufend/Beratung/Ihme1500/ihme1500_projektbeschr_en.html

Table 2. Typologies of NBS considered in the analysis, and representation of constraints to their implementation.

NBS type	Landscape conditions	Modelled constraints (ArcGIS 10.7 © Raster calculator expression)
A1: wetlands	• Slope ≤ 15% • Elevation ≤ 1700 m asl • No Flood hazard • Land cover: agriculture, mining sites • Distance from urban areas ≥ 300 m	`( ( "CLC" == 7 ) + ( ( "CLC" >= 12 ) * ( "CLC" <= 22 ) ) ) * (Tan( "Slope " * 3.14 / 360 ) <= 0.15 ) * ("urb_dist " >= 300 ) * ("elev" <= 1700 ) * IsNull ("floodmap")`
B1: free water surface (FWS) wetlands	• Slope ≤ 5%, • Elevation ≤ 2000 m asl • No Flood hazard • Land cover: agriculture, mining sites; distance from urban areas ≥ 300 m • Water table depth (WTD) >=1m	`( ( "CLC" == 7 ) + ( ( "CLC" >= 12 ) * ( "CLC" <= 22 ) ) ) * (Tan( "Slope" * 3.14 / 360 ) <= 0.05 ) * ("urb_dist" >= 300 ) * ("elev" <= 2000 ) * IsNull("floodmap") * ("WTD" >= 1)`
B2: vegetated drainage ditches	• Elevation ≤ 2000 m asl • No Flood hazard • Land cover: agriculture	`( ( ( "CLC" >= 12 ) * ( "CLC" <= 22 ) ) ) * ("elev" <= 2000 ) * IsNull("floodmap")`
B3.1: buffer strips for runoff	• Slope ≤ 10%, • Elevation ≤ 1000 m asl • WTD >=2 m • Land cover: agriculture	`( ( ( "CLC" >= 12 ) * ( "CLC" <= 22 ) ) ) * (Tan( "Slope" * 3.14 / 360 ) <= 0.10 ) * ("elev" <= 1000 ) * ("WTD" >= 2)`
B3.2: buffer strips for groundwater	• Slope ≤ 5% • Elevation ≤ 1000 m asl • WTD <=2 m • Land cover: agriculture	`( ( ( "CLC" >= 12 ) * ( "CLC" <= 22 ) ) ) * (Tan( "Slope" * 3.14 / 360 ) <= 0.05 ) * ("elev" <= 1000 ) * ("WTD" <= 2)`
C1: ponds	• Slope ≤ 5%, • No Flood hazard • Land cover: agriculture, mining sites • WTD≥ 1m	`( ( "CLC" == 7 ) + ( ( "CLC" >= 12 ) * ( "CLC" <= 22 ) ) ) * (Tan( "Slope" * 3.14 / 360 ) <= 0.05 ) * IsNull("floodmap") * ("WTD" >= 1)`
C2: managed aquifer recharge	• Slope ≤ 5%, • No Flood hazard • Land cover: agriculture, mining sites • Highly productive aquifers (porous and fissured) • WTD≥ 5m	`( ( "CLC" == 7 ) + ( ( "CLC" >= 12 ) * ( "CLC" <= 22 ) ) ) * (Tan( "Slope" * 3.14 / 360 ) <= 0.05 ) * IsNull("floodmap") * ("WTD" >= 5) * ("HyME" == 4 +"HyME" == 6)`

Pixel Value	Land cover class description	code
1	Continuous urban fabric	111
2	Discontinuous urban fabric	112
3	Industrial or commercial units	121
4	Road and rail networks and associated land	122
5	Port areas	123
6	Airports	124
7	Mineral extraction sites	131
8	Dump sites	132
9	Construction sites	133
10	Green urban areas	141
11	Sport and leisure facilities	142
12	Non-irrigated arable land	211
13	Permanently irrigated land	212
14	Rice fields	213
15	Vineyards	221
16	Fruit trees and berry plantations	222
17	Olive groves	223
18	Pastures	231
19	Annual crops associated with permanent crops	241
20	Complex cultivation patterns	242
21	Land principally occupied by agriculture, with significant areas of natural vegetation	243
22	Agro-forestry areas	244
23	Broad-leaved forest	311
24	Coniferous forest	312
25	Mixed forest	313
26	Natural grasslands	321
27	Moors and heathland	322
28	Sclerophyllous vegetation	323
29	Transitional woodland-shrub	324
30	Beaches, dunes, sands	331
31	Bare rocks	332
32	Sparsely vegetated areas	333
33	Burnt areas	334
34	Glaciers and perpetual snow	335
35	Inland marshes	411
36	Peat bogs	412
37	Salt marshes	421
38	Salines	422
39	Intertidal flats	423
40	Water courses	511
41	Water bodies	512
42	Coastal lagoons	521
43	Estuaries	522

Table 3. Legend of the Corine Land Cover raster map.

Pixel value	Description
1	Locally aquiferous rocks, porous or fissured
2	Low and moderately productive porous aquifers
3	Practically non-aquiferous rocks, porous or fissured
4	Highly productive porous aquifers
5	Low and moderately productive fissured aquifers (including karstified rocks)
6	Highly productive fissured aquifers (including karstified rocks)
7	Inland water
8	Snow field / ice field

Table 4. Legend of the Hydrogeological map of Europe (HyME).

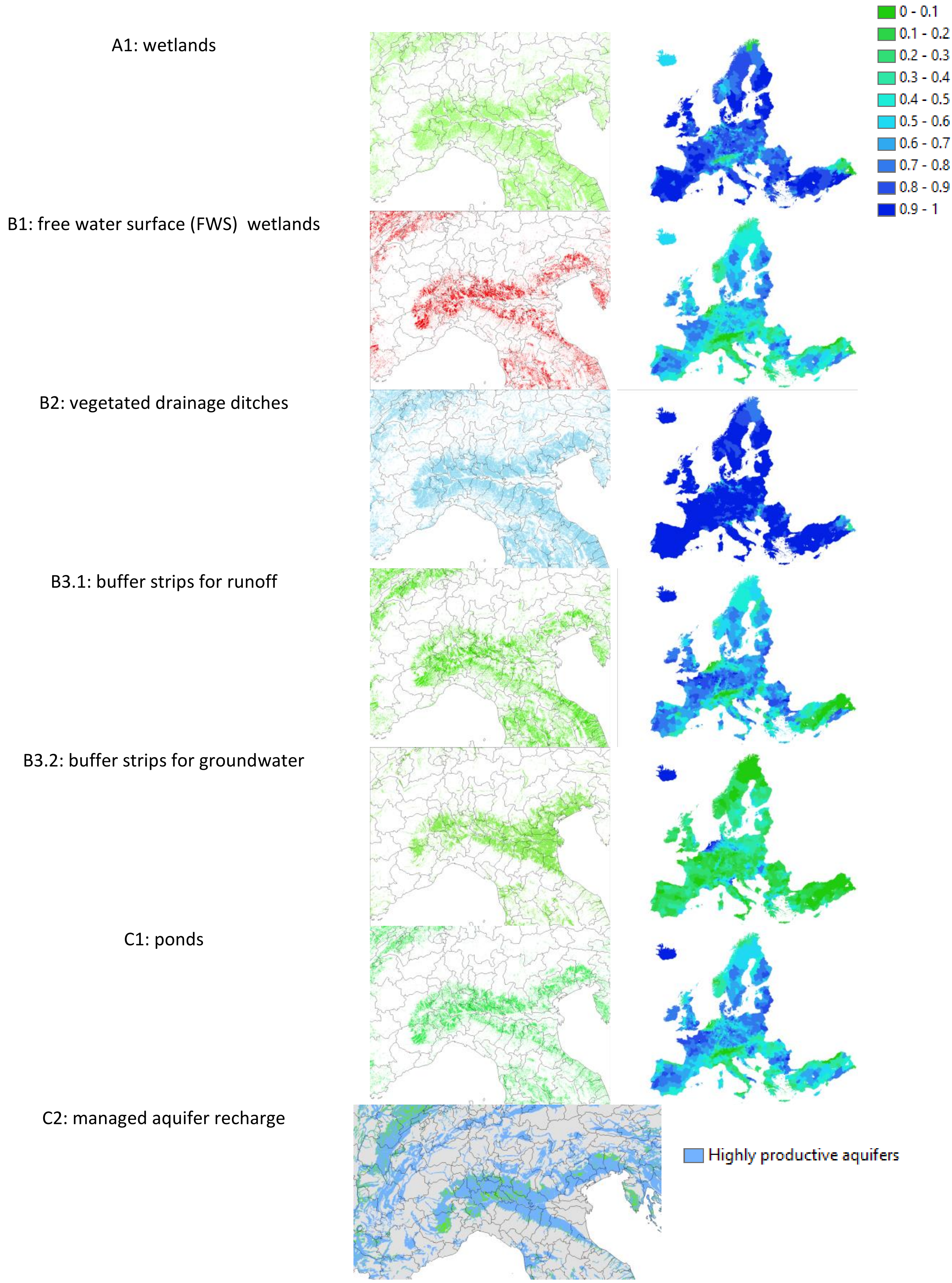


Figure 1. Illustrative maps of areas compatible with the various types of NBS: example at 100 m resolution (left) and suitable fraction of agricultural land cover by NUTS3 region (right). For type C2, we only show part of the map of compatible areas with a background of highly productive aquifers.

3 Demand for NBS

The typologies of NBS listed in **Table 2** are implemented in order to meet a demand for primary services expected from NBS:

- control of discharges of nutrients related to sludge or manure
- control of diffuse releases of nutrients (N and P) from agriculture
- provision of water for irrigation

Besides these primary services, NBS may contribute to address demands for secondary (additional) services providing co-benefits including :

- retention of sediments eroded from agricultural fields
- buffering of local floods due to extreme precipitation
- support to biodiversity by provision of habitat
- control of diffuse pollution due to pesticides.

The various NBS should be implemented where compatible, and to an extent sufficient to meet their demand, with a priority to areas with higher demand.

For each of the above demands, we define an indicator in order to support the mapping of favourability for different NBS.

Treatment of sewage sludge

NBS of type A1 (treatment wetlands) should be implemented to treat sewage sludge where the likelihood of sludge application to land is higher. We produced a map of potential sludge application rates as follows.

1) We compute the sum of population equivalents (PE) treated by European wastewater treatment plants (WWTPs) within a circular moving neighbourhood of 10 km radius. We call this map $P_N(x,y)$ (**Figure 2** A)
2) We compute the sum of hectares of arable land and pasture (assumed to be those land cover classes suitable for sludge spreading) within the same moving neighbourhood. We call this map $A_N(x,y)$ (**Figure 2** B)
3) We estimate the probability that a site (x,y) receives sludge on agricultural land as:

$$P(x,y) = \frac{\frac{P_N(x,y)}{A_N(x,y)}}{\int_{Region(x,y)} \frac{P_N(\sigma,\tau)}{A_N(\sigma,\tau)} d\sigma\, d\tau}$$

Where $\int_{Region(x,y)} f(\sigma,\tau) d\sigma d\tau$ is the area integral of function f(σ,τ) over Region(x,y), the region site (x,y) is assigned to.

4) We estimate a potential quantity of sludge applied to site (x,y) as:

$$D(x,y) = \frac{Pop\big(Region(x,y)\big)}{Pop\big(Country(x,y)\big)} Sludge\big(Country(x,y)\big) AgriApp\big(Country(x,y)\big) P(x,y)$$

Where Country(x,y) is the country site (x,y) is assigned to, and Pop(Region(x,y) is the total population equivalents of Region(x,y) and Country(x,y), respectively, Sludge(Country(x,y)) is the production of sludge in the country and $AgriApp\big(Country(x,y)\big)$ the share of the sludge that is applied to agriculture.

For our calculation we refer to the NUTS2 level regions of the EU as regions, and we use the sludge production information summarized in **Table 5**.

The land cover information for map $A_N(x,y)$ is derived from the Corine Land Cover (CLC) 2018 map while the capacity of WWTPs is derived from the European database[2] containing data used for the 10th report on the implementation of the Urban Waste Water Treatment Directive (UWWTD)[3].

Country	Sludge production (tonnes per year)	Share applied on land (%)	Population equivalents	Source
AT	234,400	21	20,670,206	EUROSTAT[4] , year 2018
BE	153,000	65	9,214,898	EUROSTAT[4], year 2017
BG	52,857	56	7,032,204	UWWTD 10th implementation report[3]
HR	27,368	6	2,649,847	UWWTD 10th implementation report[3]
CY	8,406	11	834,746	UWWTD 10th implementation report[3]
CZ	163,478	31	8,774,435	UWWTD 10th implementation report[3]
DK	141000	50	11,598,945	EUROSTAT[4], year 2010
EE	33,371.49	71	1,580,684	UWWTD 10th implementation report[3]
FI	146,621	44	5,057,300	UWWTD 10th implementation report[3]
FR	856,248	35	72,495,719	UWWTD 10th implementation report[3]
DE	1,794,443	15	110,737,394	EUROSTAT[4], year 2016
EL	105,823	20	10,700,983	UWWTD 10th implementation report[3]
HU	85,312	7	11,648,962	EUROSTAT[4], year 2018
IE	55,226	99	4,895,692	UWWTD 10th implementation report[3]
IT	1,102,700	29	73,344,630	EUROSTAT[4], year 2010
LV	24,591	17	1,542,142	UWWTD 10th implementation report[3]
LT	44,192	14	2,825,679	EUROSTAT[4], year 2018
LU	8,565	21	635,845	update to UWWTD 10th implementation report
MT	8280	0	789,039	EUROSTAT[4], year 2018
NL	341000	4	19,444,506	EUROSTAT[4], year 2018
PL	583,070	20	38,164,849	UWWTD 10th implementation report[3]
PT	165673	2	12,243,937	UWWTD 10th implementation report
RO	131,988	33	12,719,360	update to UWWTD 10th implementation report
SK	55,929	0	3,554,953	UWWTD 10th implementation report[3]
SI	38,079	0	1,324,520	UWWTD 10th implementation report[3]
ES	1,174,000	78	64,180,481	UWWTD 10th implementation report[3]
SE	210,881	39	12,517,265	UWWTD 10th implementation report[3]

Table 5. Sludge produced and applied in agriculture by the EU Member States (MS).

[2] https://www.eea.europa.eu/data-and-maps/indicators/urban-waste-water-treatment/urban-waste-water-treatment-assessment-5
[3] https://ec.europa.eu/environment/water/water-urbanwaste/legislation/directive_en.htm
[4] http://appsso.eurostat.ec.europa.eu/nui/show.do?lang=en&dataset=env_ww_spd

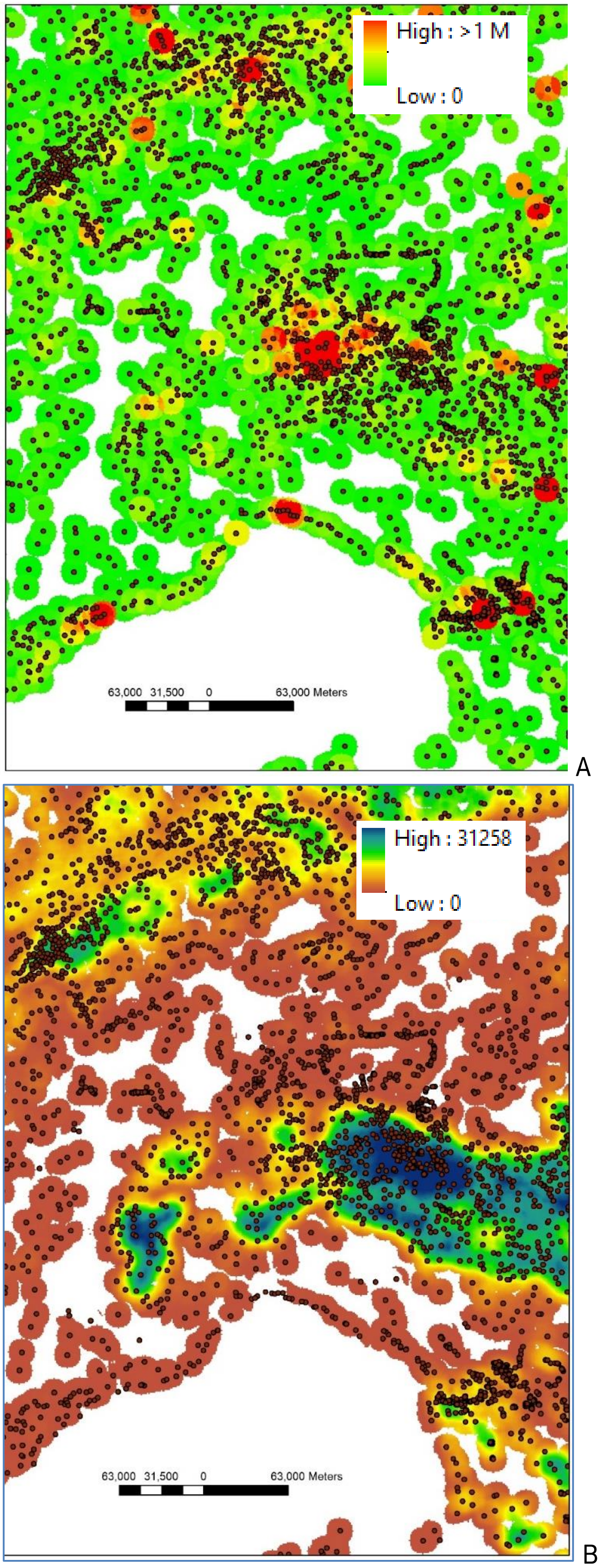


Figure 2. A: excerpt of map $P_N(x,y)$ (values in PE). B: excerpt of map $A_N(x,y)$ (values in ha). Black points represent WWTPs. Explanations in the text.

Treatment of manure

NBS of type A1 (treatment wetlands) should be implemented to reduce the loads of N and P with manure where the likelihood of excess manure application to land is higher. The GREEN model (Grizzetti et al., 2021) considers as input the total amount of N and P applied with manure in each sub-basin of the European stream network. This can be regarded as a proxy for the prioritization of NBS implementation.

Diffuse nutrient pollution

NBS of type B1 (free water surface wetlands), B2 (vegetated drainage ditches) and B3.1/B3.2 (buffer strips for runoff and for groundwater) should be implemented to remove excess nutrients from diffuse sources where the likelihood of diffuse emissions is higher. The GREEN model (Grizzetti et al., 2021) considers as input the total amount of N and P discharged to water bodies from diffuse sources in each sub-basin of the European stream network. This can be regarded as a proxy for the prioritization of NBS implementation.

Diffuse pesticide pollution

NBS of types B1, B2, B3 may provide a service of pesticide retention and attenuation. In order to map areas with higher demand for pesticide retention, we refer to the estimate of total potential pesticide loss derived by Pistocchi et al., 2022c, see **Figure 3**. Total potential pesticide loss is presented as:

$$L_{pest} = \sum_{i=1}^{n} \frac{Leros_i + Lrunoff_i + \alpha E_i}{Tox_i}$$

Where:

- n is the number of pesticides,
- $Leros_i, Lrunoff_i, E_i$ are the losses of a pesticide due to erosion and leaching/runoff and the total use of a pesticide, respectively
- α is the fraction of the total amount of a pesticide applied to the field that is lost directly to water before reaching the soil (in this exercise we set α=0.5%)
- Tox_i is the toxicity threshold for a pesticide. In this exercise we refer to the values of median effect concentration (EC50) of the species sensitivity curves (SSD) presented in Posthuma et al., 2019.

L_{pest} comes in “toxic units” that represent the toxic mass equivalents of a loss of a pesticide with an EC50 of 1 ug/L. **Figure 3** presents L_{pest} as conventional grams (g*) per hectare per year.

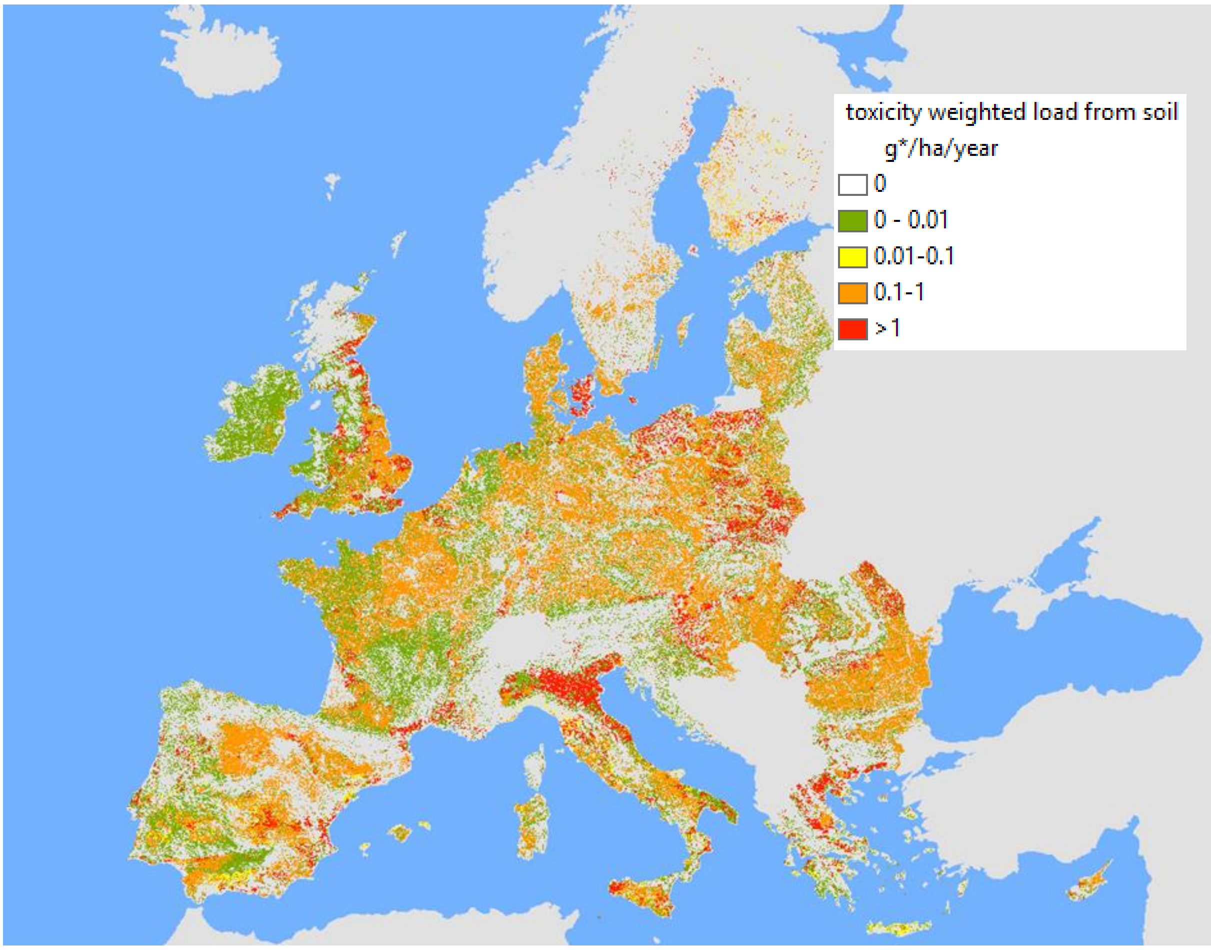


Figure 3. Diffuse emissions of pesticides from agricultural application.

Sediment retention

NBS of types B1, B2, B3 may also provide a service of sediment retention in areas with higher erosion. In order to map areas with higher demand for sediment retention, we refer to the map of potential soil erosion by water produced Panagos et al., 2015, see **Figure 4**.

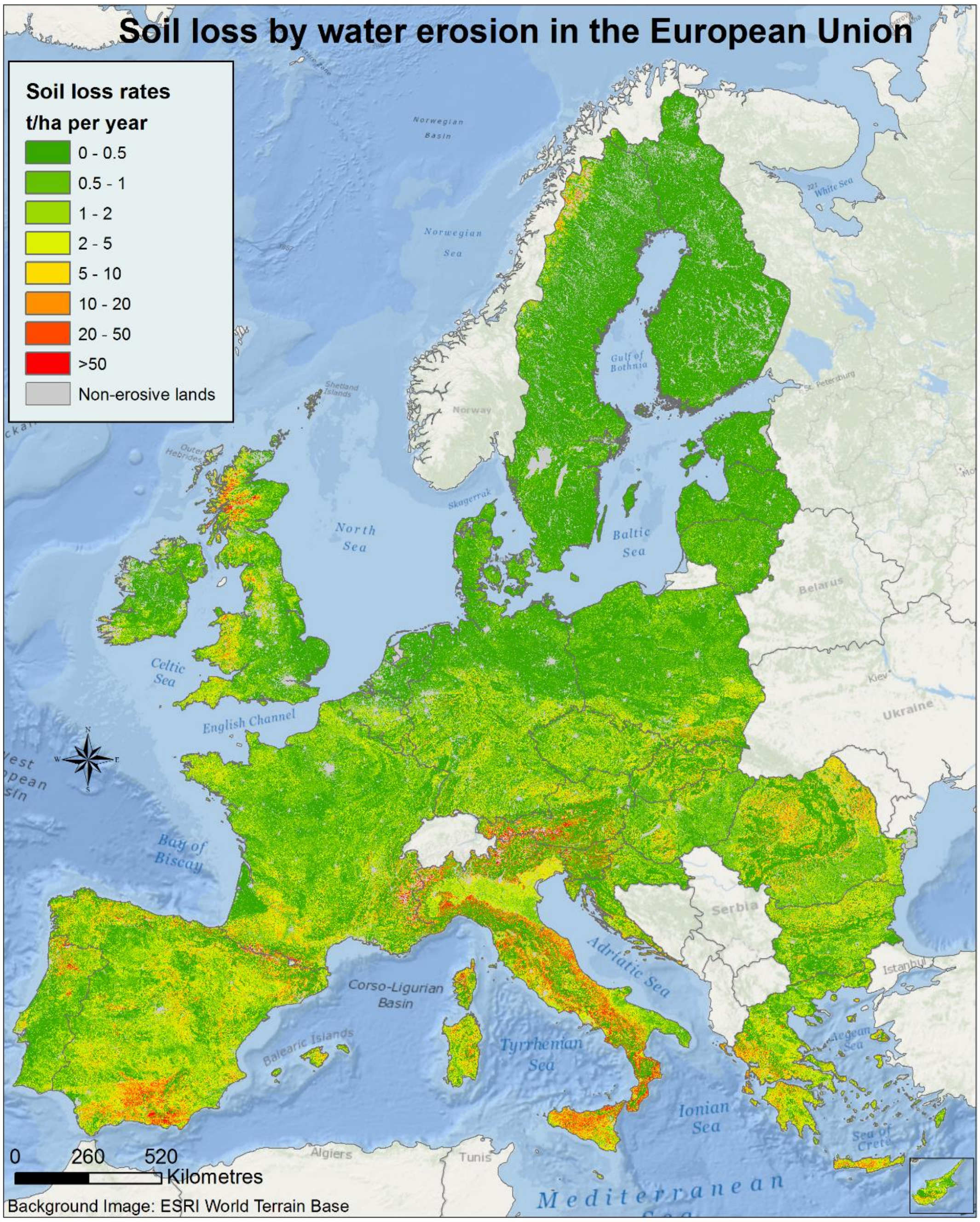


Figure 4. Map of potential soil erosion by water.

Source : JRC. https://esdac.jrc.ec.europa.eu/content/soil-erosion-water-rusle2015

Flood buffering

All NBS types may provide a capacity to buffer local floods caused by extreme precipitation intensity. In order to identify areas with high demand for flood buffering, we refer to the 10-year return period precipitation of duration 24 hours, that Pistocchi et al., 2022b, estimate by fitting a Gumbel distribution to the series of annual maxima from Thiemig et al., 2022 (**Figure 5**).

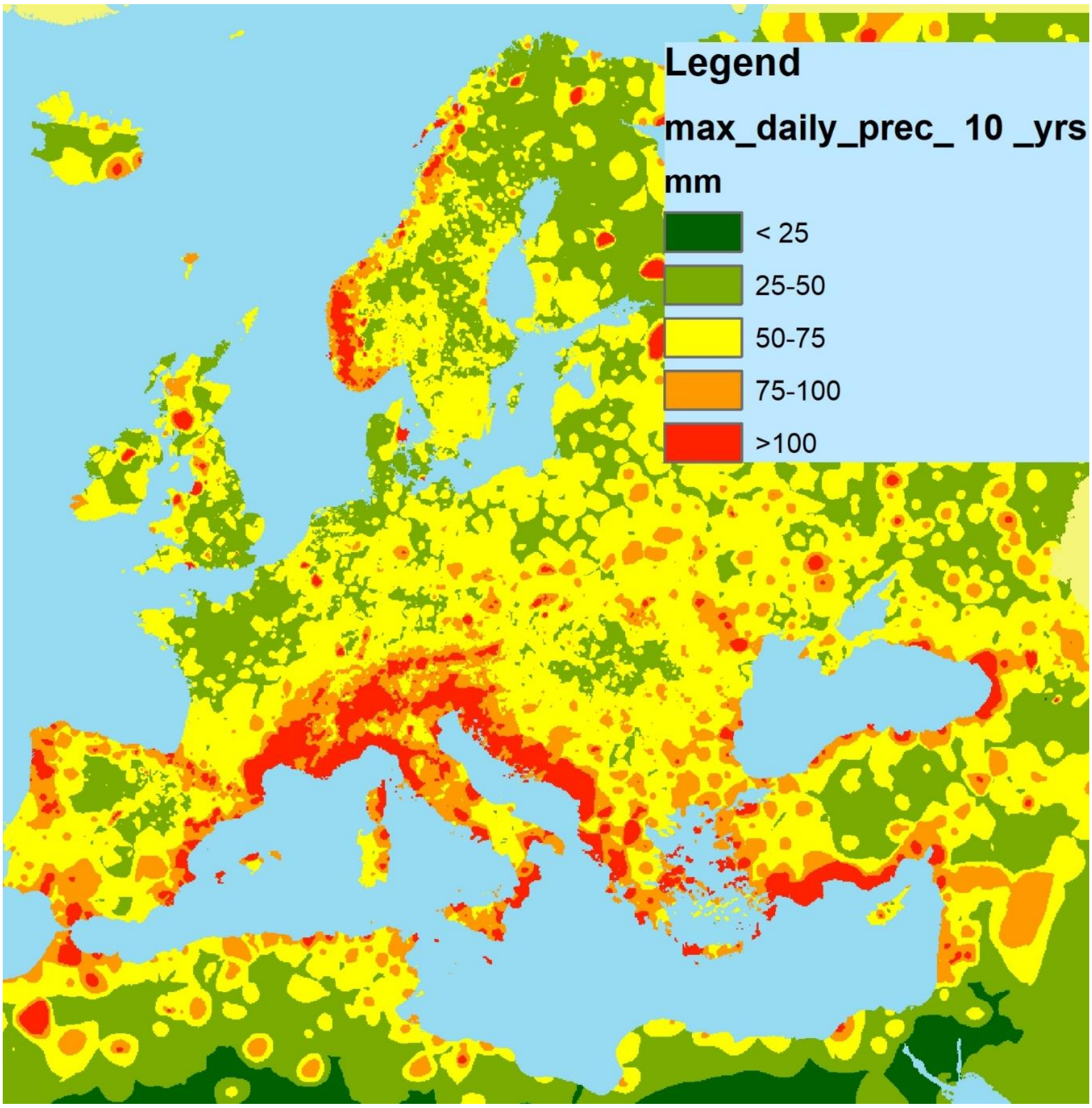


Figure 5. Map of 10-year return period daily precipitation. Source : Pistocchi et al., 2022b.

Irrigation

The demand for irrigation may be estimated from the difference of precipitation and potential evapotranspiration (deficit). As a first approximation, in this exercise we refer to the "climatological" average of monthly values of precipitation and temperature from the WorldClim dataset (years 2010-2018)[5] (Fick and Hijmans, 2017; Harris et al., 2014).

From temperatures we estimate monthly values of potential evapotranspiration (PET) using the formula of Thornthwaite (e.g. Pistocchi et al., 2008). For a given month we compute the average of minimum temperatures and maximum temperatures, and the average of the two is assumed to represent the monthly average temperature of the i-th month, T_i. We then compute a monthly value of conventional PET for the i-th month, PET^*_i, based solely on this temperature and depending on the sun declination δ, latitude φ and number of days in the month d_i, according to the empirical Thornthwaite's formula:

$$PET^*_i \sim \frac{d_i}{30} Acos(-tan\delta \tan\varphi) \times \left(\frac{10T_i}{\sum_{i=1}^{12} \left(\frac{T_i}{5}\right)^{1.514}} \right)^{0.000000675\left(\sum_{i=1}^{12}\left(\frac{T_i}{5}\right)^{1.514}\right)^3 - 0.0000771\left(\sum_{i=1}^{12}\left(\frac{T_i}{5}\right)^{1.514}\right)^2 + 0.01792\left(\sum_{i=1}^{12}\left(\frac{T_i}{5}\right)^{1.514}\right) + 0.49239}$$

.

Monthly PET values computed in this way do not necessarily yield a reliable estimate of PET. Therefore these values are only used to apportion the annual PET to the 12 months. To this end, we rescale them in order to match the annual value of the well-established Penman PET. To this end, we refer to the European scale calculation of PET from recent runs of the LISFLOOD model (Bisselink et al., 2018). In this exercise, we consider as annual PET the projected worst-case annual PET (PET_{worst}) under the regional concentration pathway (RCP) 8.5 regional climate scenarios discussed in Quaranta et al., 2021, also based on Bisselink et al., 2018. The PET of the i-th month is eventually estimated as:

$$PET_i = \frac{PET^*_i}{\sum_1^{12} PET^*_i} PET_{worst}$$

We compute the annual average deficit and surplus, respectively, as:

$$D = \sum_{j=1}^{12} \left(P_j - PET_j\right) \delta\left(P_j \leq PET_j\right)$$

$$S = \sum_{j=1}^{12} \left(P_j - PET_j\right) \delta\left(P_j \geq PET_j\right)$$

Where P_j is total precipitation of the j-th month.

The demand for NBS of type C (suited for water provisioning) is expected to be higher where the deficit (D) is higher, and at the same time there is sufficient surplus to harvest, which may justify investments in water storage, which can be appraised by referring to the distribution of D and of the surplus to deficit ratio (S/D) respectively (**Figure 6**).

[5] https://www.worldclim.org/data/monthlywth.html

Usually Surplus (S) and deficit (D) are inversely related, although in a non-linear way (see **Figure 7**A). Areas where we expect a demand for NBS of type C1 and C2 can be estimated as ~ (D<a)(S/D>b) for appropriate threshold deficit, a, and S/D ratio, b. **Figure 7** shows an example of demand area map with b=0.25 and a set to 350 and 500 mm respectively.

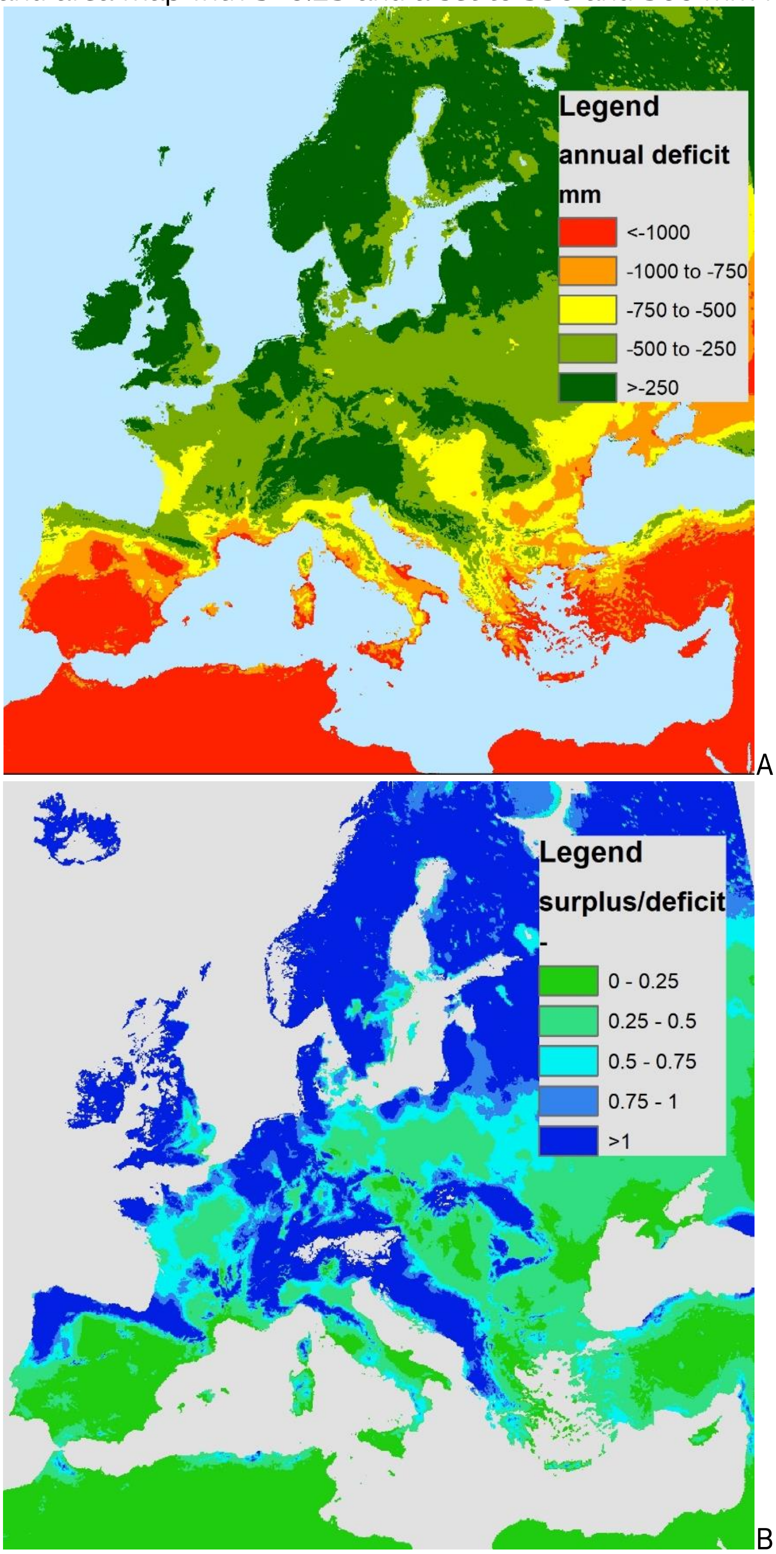
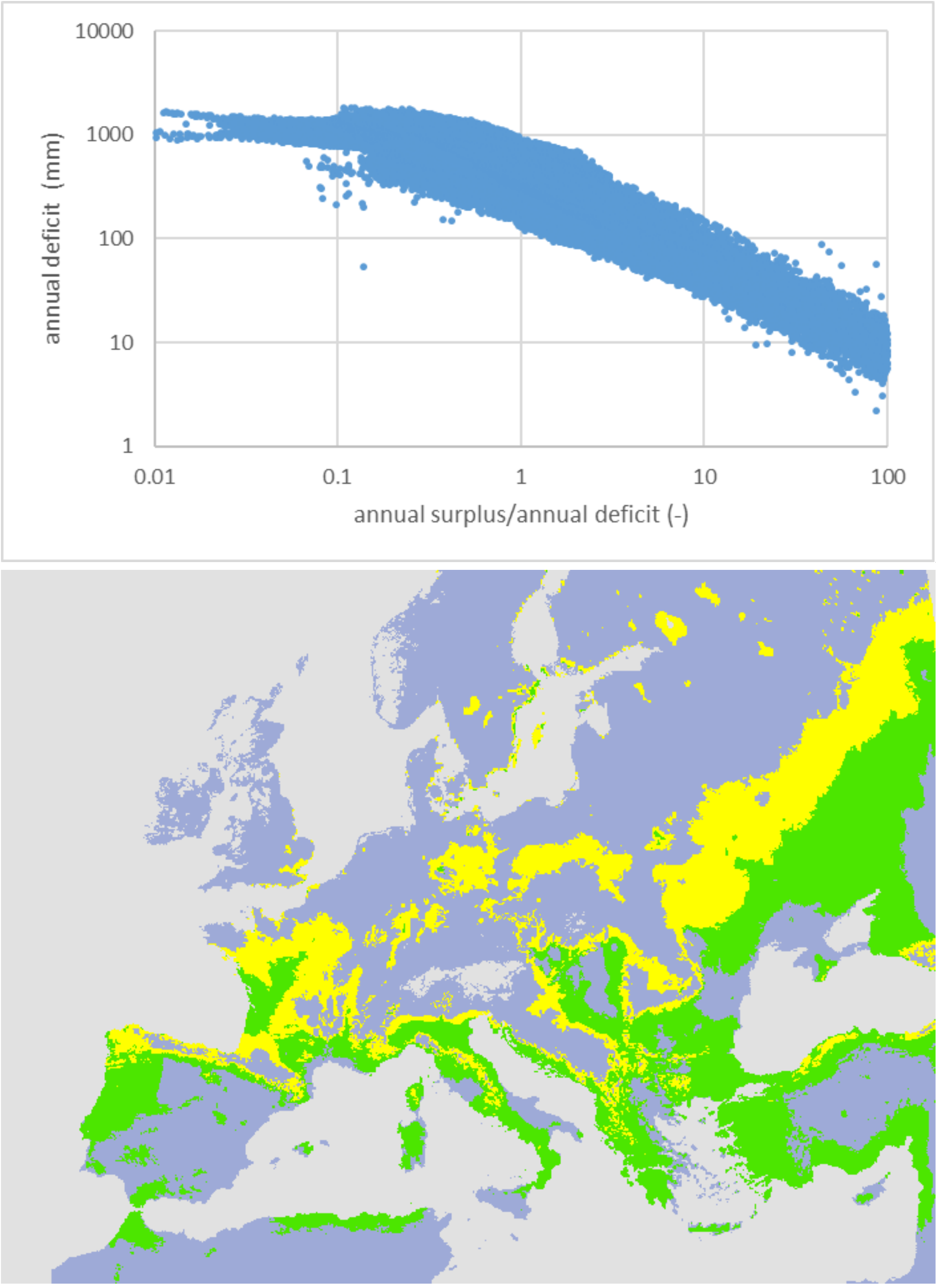


Figure 6. (A)Annual deficit, D. (B) Ratio of annual surplus to annual deficit (S/D).



A
B

Figure 7. (A) Scatter plot of the ratio of surplus to deficit (S/D) vs deficit (D). (B) Example map of areas with high potential demand for irrigation, and sufficient surplus to justify water storage. Green areas have a yearly deficit of 500 mm or more, yellow areas 350 mm or more, and in both cases surplus exceeds 25% of deficit.

Support to biodiversity

The different types of NBS offer an opportunity to create new habitat that can be regarded as either « wetland » or « wood » habitat. We expect a higher demand for support to biodiversity by creating new habitat, where such habitat is less abundant. In order to map the abundance of « wetland » and « wood » habitat, we can refer to the moving sum of extents covered by Corine Land Cover classes with codes 4** (e.g. 411), and 24* (e.g. 241) and 3** (e.g. 311) respectively (**Table 3**), within a given neighbourhood. Example maps of habitat abundance are shown in **Figure 8**.

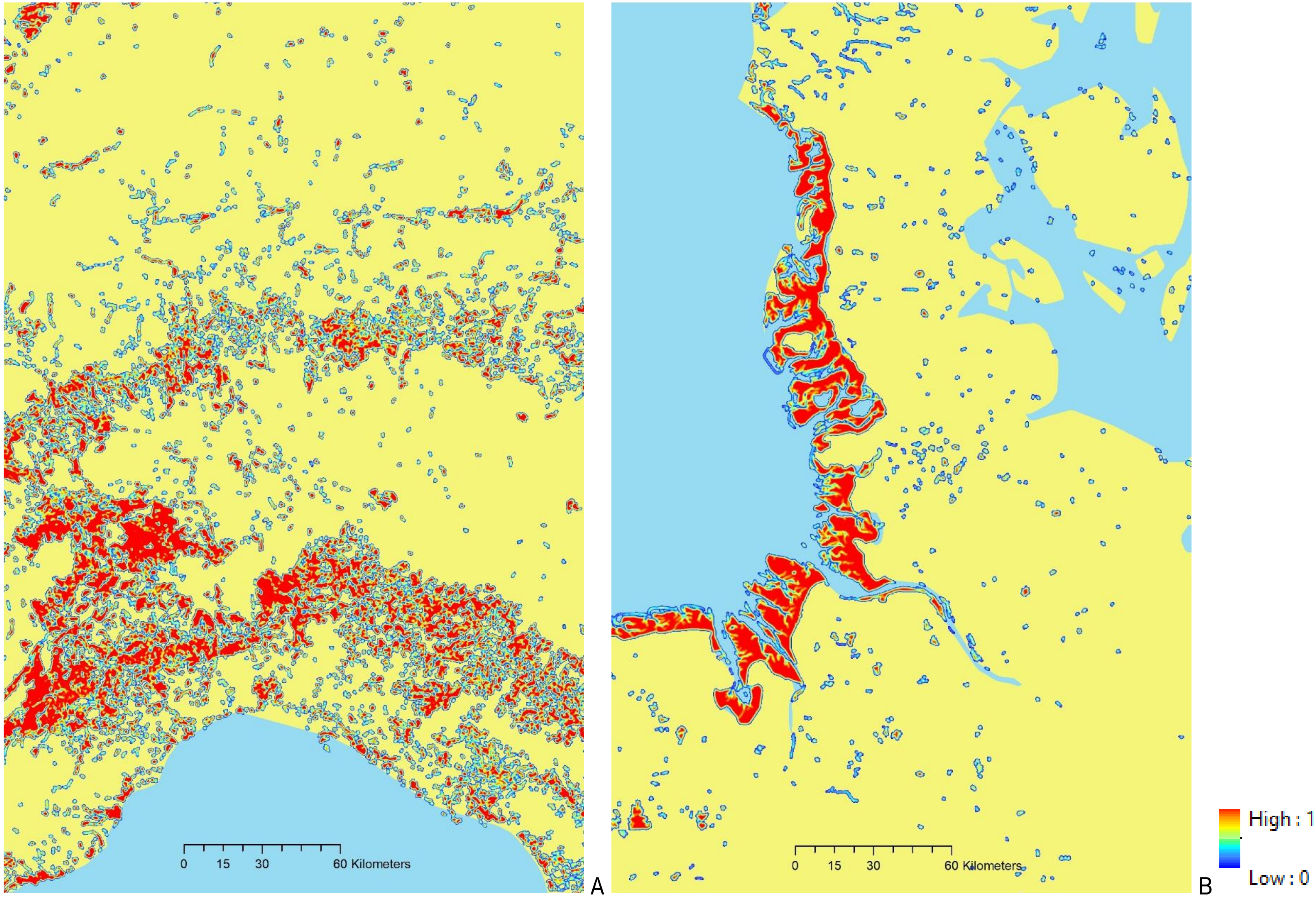


Figure 8. A: moving average fraction of wood-like landscapes. B : moving average fraction of wetland-like landscapes. In both cases, we consider a 500 m radius neighbourhood.

4 Effectiveness

The effectiveness of the various NBS typologies listed in **Table 2** in reducing pollution and regulating the water cycle depends primarily on their design and by the local characteristics of the site. A definition of quantitative relationships between landscape, climate, design parameters and NBS effectiveness for nutrient removal was the subject of an extensive investigation (Rizzo et al., 2022). We have decided to represent effectiveness in terms of the range of performances (mass of contaminant removed per m^2 and year) that one may expect from a given type of NBS if appropriately designed in its context. These ranges are provided in **Table 6**.

It is worth noting that denitrification is sensitive to temperature, and is supposed to be slow or negligible below 6 ⁰C.

Figure 9 shows the fraction of the year when daily temperature falls above this threshold. Denitrification efficiency should scale with this fraction as a first approximation.

For what concerns pesticides, usually we expect a removal efficiency of around 40% for NBS of type A and B, with a higher efficiency for pesticides with a high partition coefficient between organic matter and the dissolved phase (i.e. less hydrophilic), see Annex 1 and Annex 2. However, evidence concerning the performance of NBS is rather limited.

NBS of type A and B may prove rather efficient in retaining also total suspended solids (TSS) and BOD. However, the latter is not expected to represent a key aspect of NBS performance.

For the hydrological regulation functions (drought and flood mitigation), the effectiveness of NBS depends on the available storage volume. We do not consider the performance of NBS of type C for pollution control, although not necessarily negligible, as their primary purpose is water quantity management and, in order to have significant effects on pollution, they require a specific design (e.g. pre-treatment wetlands or additional volumes).

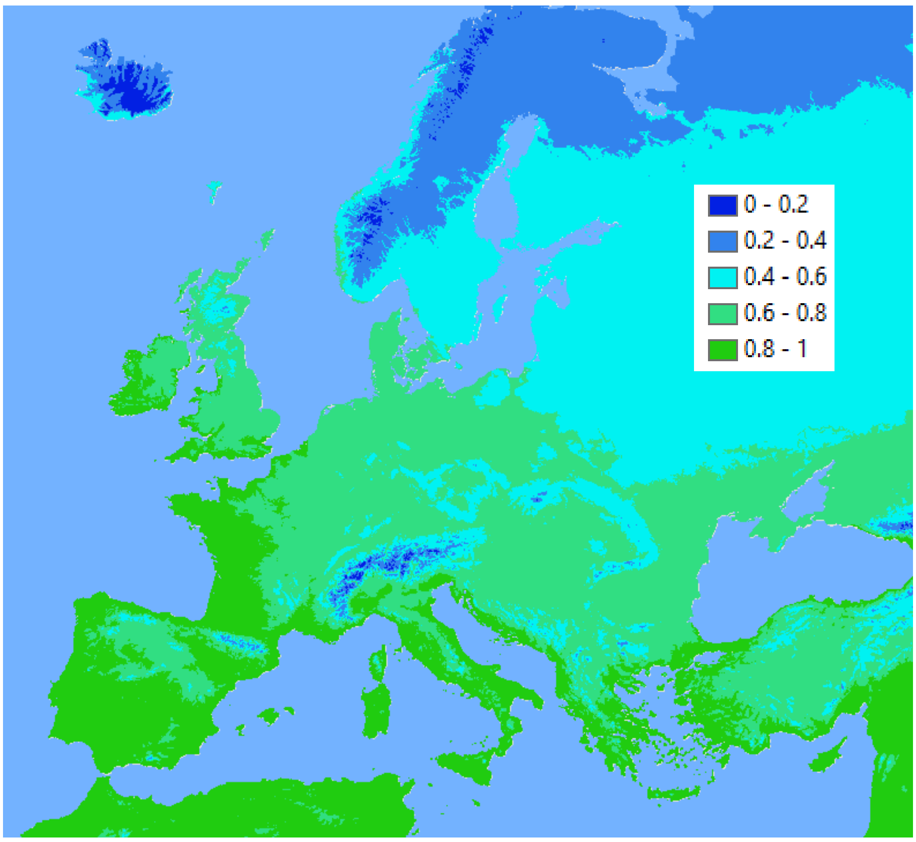


Figure 9. Fraction of the year during which temperature is above 6 ⁰C.

Source: processing of Thiemig et al., 2022 data.

Table 6. Effectiveness of selected NBS in removing pollution. Source: Rizzo et al., 2022.

Objective	*A1: wetlands (typical)*	*A1: wetlands (with surface flow)*	*A1: wetlands (with subsurface flow)*	*B1: free water surface (FWS) wetlands* *B2: vegetated drainage ditches*	*B3.1: buffer strips for runoff*	*B3.2: buffer strips for groundwater*
N	450 g_N m^{-2} y^{-1} (a)	400 g_N m^{-2} y^{-1} (e)	660 g_N m^{-2} y^{-1} (i)	70 g_N m^{-2} y^{-1} (m)	$\eta = 70\%$ (p) C = 25 mg/L (t)	$\eta = 60\%$ (s) as N-NO3 C = 8 mg/L (w)
P	70 g_P m^{-2} y^{-1} (b)	60 g_P m^{-2} y^{-1} (f)	110 g_P m^{-2} y^{-1} (j)	3 g_P m^{-2} y^{-1} (n)	η =70% (q) C =2 mg/L (u)	-
BOD	1400 g_{BOD5} m^{-2} y^{-1} (c)	1160 g_{BOD5} m^{-2} y^{-1} (g)	4900 g_{BOD5} m^{-2} y^{-1} (k)	-	-	-
TSS	1300 g_{TSS} m^{-2} y^{-1} (d)	870 g_{TSS} m^{-2} y^{-1} (h)	7770 g_{TSS} m^{-2} y^{-1} (l)	1950 g_{TSS} m^{-2} y^{-1} (o)	η =90% (r) C =7000 mg/L (v)	-

(a) Median = 467.1 g_N m^{-2} y^{-1}. Interquartile range: 243.1 – 571.0 g_N m^{-2} y^{-1}. (30 CW for manure samples).
(b) Median = 73.0 g_P m^{-2} y^{-1}. Interquartile range: 32.6 – 127.8 g_P m^{-2} y^{-1}. (37 CW for manure samples).
(c) Median = 1407.3 g_{BOD5} m^{-2} y^{-1}. Interquartile range: 483.5 – 3571.7 g_{BOD5} m^{-2} y^{-1}. (26 CW for manure samples).
(d) Median = 1319.6 g_{TSS} m^{-2} y^{-1}. Interquartile range: 364.0 – 3496.7 g_{TSS} m^{-2} y^{-1}. (26 CW for manure samples).
(e) Median = 397.7 g_N m^{-2} y^{-1}. Interquartile range: 185.8 – 753.3 g_n m^{-2} y^{-1}. (24 SF CW for manure samples).
(f) Median = 60.7 g_p m^{-2} y^{-1}. Interquartile range: 28.1 – 112.4 g_p m^{-2} y^{-1}. (31 SF CW for manure samples).
(g) Median = 1159.0 g_{bod5} m^{-2} y^{-1}. Interquartile range: 283.6 – 2519.3 g_{bod5} m^{-2} y^{-1}. (22 SF CW for manure samples).
(h) Median = 866.4 g_{tss} m^{-2} y^{-1}. Interquartile range: 323.4 – 3125.2 g_{tss} m^{-2} y^{-1}. (26 SF CW for manure samples).
(i) Median = 665.0 g_n m^{-2} y^{-1}. Interquartile range: 516.5 – 1977.2 g_n m^{-2} y^{-1}. (6 SSF CW for manure samples).
(j) Median = 116.8 g_p m^{-2} y^{-1}. Interquartile range: 93.1 – 181.2 g_p m^{-2} y^{-1}. (6 SSF CW for manure samples).
(k) Median = 4904.6 g_{bod5} m^{-2} y^{-1}. Interquartile range: 4131.3 – 12349.1 g_{bod5} m^{-2} y^{-1}. (3 SSF CW for manure samples).
(l) Median = 7769.7 g_{tss} m^{-2} y^{-1}. Interquartile range: 4724.3.0 – 8413.6 g_{tss} m^{-2} y^{-1}. (3 SSF CW for manure samples).
(m) Median = 70.8 g_n m^{-2} y^{-1}. Interquartile range: 26.0 – 137.1 g_n m^{-2} y^{-1}. (59 VDD and wetlands samples).
(n) Median = 3.0 g_p m^{-2} y^{-1}. Interquartile range: 0.3 – 20.9 g_p m^{-2} y^{-1}. (32 VDD and wetlands for diffused pollution samples).
(o) Median = 1957.9 g_{tss} m^{-2} y^{-1}. interquartile range: 30.0 – 9708.2 g_{tss} m^{-2} y^{-1}. (21 VDD and wetlands samples).
(p) Median = 72%. Interquartile range: 57 – 83%. (52 BS-R samples).
(q) Median = 74%. Interquartile range: 55 – 85%. (47 BS-R samples).
(r) Median = 89%. Interquartile range: 83 – 95%. (28 BS-R samples).
(s) Median = 58%. Interquartile range: 19 – 93%. (111 BS-G samples).
(t) Median (52 BS-R samples) = 27.2 mg/L
(u) Median (63 BS-R samples) = 2.0 mg/L
(v) Median (28 BS-R samples) = 7199.8 mg/L
(w) Median (110 BS-G samples) = 7.75 mg/L

(*) For NBS of type B3.1 and B3.2 we provide the % reduction (η) of concentration in runoff from upstream to downstream of the buffer strip, along with the upstream concentration, C. For type B3.1 We can estimate the mass of contaminant removed per m2 and year from annual precipitation (R) and catchment area (A) of the NBS, assuming runoff is 10% for precipitation <500 mm/year, 20% between 500 and 1000 mm/year and 30% above 1000 mm/year (FAO, 2014). Under these assumptions, the median mass of contaminant removed per m2 and year in the dataset of Rizzo et al., 2022 is 6.1 g_N/m2/year, 2.0 g_P/m2/year and 3998.5 g_{TSS}/m2/year, respectively (interquartile ranges are 3.2-20.4 (n=38), 0.7-6.9 (n=26) and 17.0-9565.2 (n=17) g/m2/year, respectively,

For what concerns NBS of type C1, the volume of surplus water that can be harvested per unit of NBS volume will depend on the interplay between water demand and availability, which requires an analysis at a more local scale than allowed within the scope of this work.

An indicative calculation for the purposes of investment planning at the broad scale could assume that a NBS is able to harvest a volume of surplus somewhere in between its volume and twice its volume. The first possibility (volume harvested = volume of the NBS) implies that the replenishment and depletion of the storage volume are seasonally separated (e.g. surplus is concentrated from autumn to spring, and deficit is only in summer). The second possibility (volume harvested = 2 x volume of the NBS) is a rough account of the fact that there can be some surplus also during the deficit season (e.g. summer storms). Less uncertain estimates require more sophisticated analyses anyway.
NBS of type C2 (managed aquifer recharge, MAR) use the aquifer as a storage volume for the harvested water. The aquifer can be assumed to be able to store the whole surplus, provided that the managed aquifer recharge infrastructure is sized to enable its infiltration. Usually the hydraulic loading rate (HLR) assumed for MAR is between 30 and 300 m per year (increasing with more sandy soil layers). The area required is therefore calculated as 0.001 times the surplus (S) in mm/year, times the catchment area draining to the NBS, divided by the HLR.

5 Costs

The unit investment cost (euro/m^2 of NBS) is calculated as:

$$CAPEX = (h\,(S + \beta F) + \alpha W + \gamma P)(aA^{-b})$$

Where:
h is the average excavation depth of the NBS
S is the unit cost of excavation and embankment (Euro/m^3)
α is the share of the NBS area that undergoes waterproofing
W is the unit cost of waterproofing (Euro/m^2)
β is the share of the NBS volume that is filled with porous media (sand or gravel)
F is the unit cost of filling (Euro/m^3)
γ is the time required for planting trees
P is the unit cost of planting (Euro/hour)
a is a cost scale coefficient
b is an exponent of the cost function, accounting for the economies of scale
A is the typical area of a single NBS.
The unit cost parameters assumed here are S= 11.50 €/m3, W=11.25 €/m2, F=32.00 €/m3, P=25.00 €/h, an average of typical costs in selected European countries.
The unit operational cost (euro/m^2/y of NBS) is calculated as:

$$OPEX = (\delta + \varepsilon A^{-k})P(a'A^{b'})$$

where ε =Hours of supervision work per m2 of NBS, δ = Hours of vegetation maintenance work per m2 of NBS, k= Exponent accounting for labor economies of scale, a' is a cost scale coefficient, and b' is an exponent of the cost function, accounting for the economies of scale. The values of the parameters are summarized in **Table 7** for the various typologies of NBS. While the extent to which NBS can be deployed on the landscape can vary significant by catchment, we assume that each individual implementation will be local and possibly made by a different actor, therefore we ignore the economies of scale that could be associated with an extensive implementation of NBS. We limit ourselves to define a typical size of each typology of NBS, and we compute a unit cost (Euro/m2) for that typology based on the typical size. The value assumed for the latter (area A) is the median of sizes from the literature, shown in **Table 7** along with its expected variability (interquartile range from the literature). **Figure 10** shows the calculated unit costs of the various types of NBS assuming a discount rate of 4% and a lifetime of 30 years, using the abovementioned parameters.

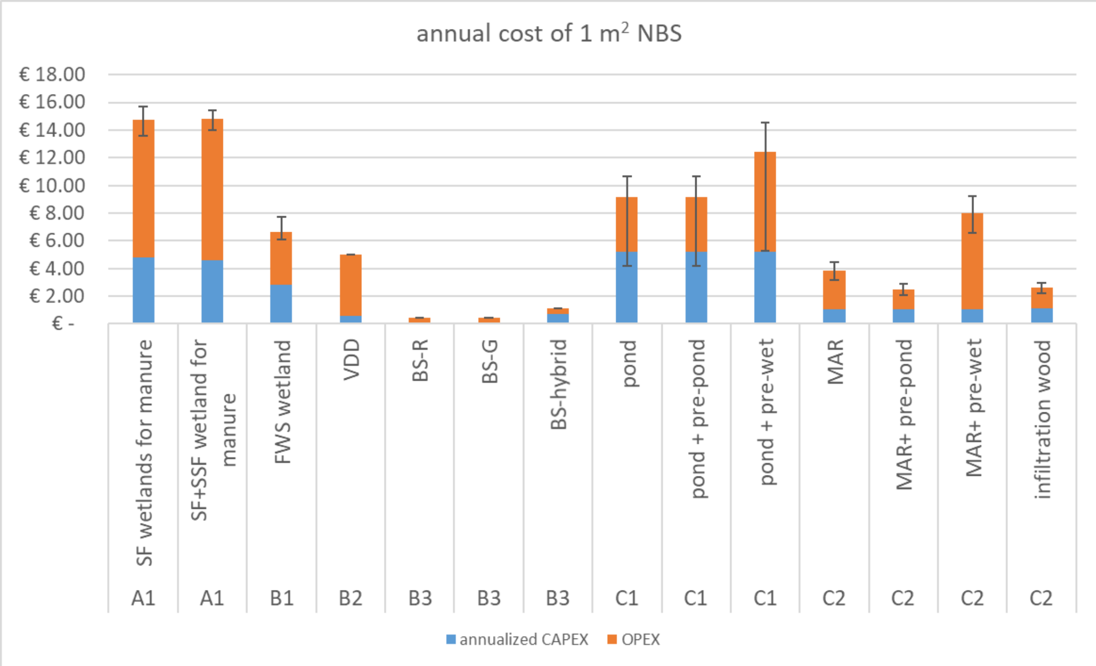


Figure 10. Unit annual costs of selected NBS. The error bars represent the variation of calculated costs within the interquartile range of NBS sizes.

NBS type	NBS category	type	Cost function coeff. for landscaping (a)	Cost function exp. for landscaping (b)	Filling medium (β)	water proofing (α)	Time for planting trees (γ)h/m^2	Excavation depth (h) in m	Hours of vegetation maintenance work per m2 of NBS (δ), h/m2/year	Hours of supervision work (ε), h/m$^{(2+k)}$/year	Exponent accounting for labour economies	Cost scale coefficient (a')	exponent of the cost function (b')	A in m2 (median)	A in m2 (interquartile range)
A1	A1.1	SF wetlands for manure	1.5 x 7.46	0.102	0	1	0	0.3	0.07	12.016	0.758	1.06 x 1.9	0.046	800 (a)	300 – 2600 (a)
A1	A1.2	SF+SSF wetland for manure	1.4 x 3.71	0.088	0.5	1	0	0.6	0.09	12.016	0.758	1.17 x 1.8	0.024	800 (a)	300 – 2600 (a)
B1	all	FWS wetland	7.46	0.102	0	1	0	0.3	0.07	12.016	0.758	1.06	0.046	2800 (b)	200 – 8000 (b)
B2	all	VDD	1.7	0	0	0	0	0.5	0.01	12.016	0.758	1.5	0	500 (c)	300 – 1900 (c)
B3	B3.1	BS-R	1	0	0	0	0.04	0	0	0.01	0	1.6	0	N/A	N/A
B3	B3.2	BS-G	1	0	0	0	0.04	0	0	0.01	0.758	1.6	0	N/A	N/A
B3	B3.3	BS-hybrid	1	0	0	0	0.04	0	0	0.01	0.758	1.6	0	N/A	N/A
C1	C1.1	pond	7.819	0.189	0	1	0	2.5	0	12.016	0.758	0.332	0.2637	700 (d)	310 – 4875 (d)
C1	C1.2	pond + pre-pond	7.819	0.189	0	1	0	2.5	0	12.016	0.758	0.332	0.2637	700 (d)	310 – 4875 (d)
C1	C1.3	pond + pre-wet	7.819	0.189	0	1	0	2.5	0.07	12.016	0.758	0.332	0.2637	700 (d)	310 – 4875 (d)
C2	C2.1	MAR	7.819	0.189	0	0	0	1	0	12.016	0.758	0.332 x 1.9	0.2637	5000 (e)	2558 – 9550 (e)
C2	C2.2	MAR+ pre-pond	7.819	0.189	0	0	0	1	0	12.016	0.758	0.332	0.2637	5000 (e)	2558 – 9550 (e)
C2	C2.3	MAR+ pre-wet	7.819	0.189	0	0	0	1	0.07	12.016	0.758	0.332	0.2637	5000 (e)	2558 – 9550 (e)
C2	C2.4	infiltration wood	7.819	0.189	0	0	0.04	1	0	12.016	0.758	0.332	0.2637	5000 (e)	2558 – 9550 (e)

Table 7 – Parameters of the CAPEX and OPEX cost functions. Notes: Value from the dataset (a) (CW for manure, 113 samples); (b) (wetland for diffuse pollution, 73 samples); (c) (wetland for diffuse pollution, 27 samples); (d) (wetland for diffuse pollution, 61 samples); (e) (wetland for diffuse pollution, 7 samples).

6 Integrated analysis and conclusions

In the previous sections we have illustrated a set of maps prepared in order to support the identification of the most suitable areas for implementation of various types of NBS, depending on multiple criteria. For application at the European scale, we refer to the mapping units of the Catchment Characterization and Mapping 2 (CCM2) dataset (Vogt et al., 2007), used within the JRC as the support for the GREEN model of nutrients (Grizzetti et al., 2021) and other modelling exercises (e.g. Vigiak et al., 2022).
To this end, the following information layers are made available at the resolution of the CCM2 sub-basins:

- Available area
    - Agricultural area of the catchment (A), ha
    - Total area suitable for NBS of type A1 (cstr_A1), ha
    - Total area suitable for NBS of type B1 (cstr_B1), ha
    - Total area suitable for NBS of type B2 (cstr_B2), ha
    - Total area suitable for NBS of type B3.1 (cstr_B31), ha
    - Total area suitable for NBS of type B3.2 (cstr_B32), ha
    - Total area suitable for NBS of type C1 (cstr_C1), ha
    - Total area suitable for NBS of type C2 (cstr_C2), ha
- Demand for primary services from NBS
    - Diffuse emissions of nitrogen (DeN), tonnes/year
    - Diffuse emissions of phosphorus (DeP) , tonnes/year
    - Diffuse emissions of pesticides(Pest) , conventional grams (g*)/year
    - Application of N with manure fertilizer (ManN) , tonnes/year
    - Application of P with manure fertilizer (ManP) , tonnes/year
    - Potential application rate of sludge on land (S), tonnes/year
    - Extent of area potentially requiring irrigation and enabling rain harvesting, based on water surplus and deficit
- Demand for secondary services from NBS
    - Erosion of agricultural soils, tonnes/ year
    - Average daily precipitation with return period of 10 years, mm
    - Average moving sum of wood-like habitat extent (WoH)
    - Average moving sum of wetland-like habitat extent (WeH).

A scenario of NBS implementation can be defined once we provide criteria for the selection of priority sub-basins (where the demand for NBS is high and there is area for their implementation), and criteria for the maximum acceptable cost and/or acceptable percentage of agricultural land that can be set aside for NBS.
Moreover, it is necessary to define a share of agricultural land in each catchment that can be accepted for NBS. The minimum between this and the extent of NBS defined by the demand provides the basis to compute costs and expected reduction of demand.

We can use the information on demand to select priority sub-basins for implementation. A sub-basin could be selected because of its high primary demand, or because of a combination of multiple significant demands for primary and secondary services.
Once priority sub-basins are selected, we can calculate the required extent of a given type of NBS as the demand divided by the performance of the unit area of NBS. For instance, if the demand is to control diffuse source emissions of nitrogen, we can use the removal rates per m^2 of wetland shown in **Table 6** to calculate the corresponding extent of NBS required. For other primary demands we can refer to the first approximation criteria in section 4.

Once we have estimated the extent of NBS required to meet the demand, we can compare the latter with the available land, in terms of suitability and as a percentage of the total agricultural land, and carry on with the minimum between demand and availability of land for NBS.

On the basis of the costs per m^2 of NBS, we can estimate the overall cost of investment and compare it with the expected effect (cost-effectiveness analysis) using the cost parameters of **Table 7**.

The analysis can be performed at European scale with reference to the control of nutrients (including from manure and sludge) and erosion. For pesticides, the removal efficiency is less well documented. Using a reference value of 40% allows only a first indicative assessment. For NBS of types C1 and C2, section 4 provides criteria for a similarly indicative first appraisal.

The approach discussed here can be applied at a regional scale within the EU by making use of more specific information. In particular, the distribution of demands and some landscape parameters affecting the assessment (such as the water table depth, soil texture and erosion) are expected to be significantly better represented by local/regional datasets in comparison to those used here. When possible, a more specific hydrological analysis should also be performed in order to better identify the surplus harvesting and flood buffering potentials of NBS.

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Annexes

Reports supporting the work presented here, prepared by IRIDRA srl, are provided as separate annexes.

1) Annex 1: Riccardo Bresciani, Giulio Conte, Nicola Martinuzzi, Fabio Masi, Andrea Nardini, Anacleto Rizzo. Nature-based solutions for climate change adaptation and water pollution in agricultural regions: services supporting the synthesis and dissemination of results. Final report (deliverable D2), 21 may 2021.
2) Annex 2: Riccardo Bresciani, Giulio Conte, Nicola Martinuzzi, Fabio Masi, Andrea Nardini, Anacleto Rizzo. Nature-based solutions for climate change adaptation and water pollution in agricultural regions: services supporting the synthesis and dissemination of results. Internal report on D4.1 activities. May 2021.

The annexes are available on the web site https://water.jrc.ec.europa.eu.

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