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AN EVALUATION OF THE POTENTIAL APPLICATIONS OF NATURE-BASED SOLUTIONS FOR WATER QUALITY PROTECTION: IRELAND AS A CASE STUDY

Elaine Heneghan, Marcus Collier and Mary Kelly-Quinn

ABSTRACT

The nature-based solutions (NBS) approach views nature and natural processes as having a high potential to address societal challenges and sustainable development goals, whilst providing multiple co-benefits. It is an approach that offers a mechanism for mainstreaming climate-related issues into practice and policy. Concurrently, EU member states are struggling to comply with the objectives of the Water Framework Directive (WFD). This paper evaluates the application of NBS in addressing water-quality issues in the EU, using Ireland as a case study through a systematic review of the literature. This study found that there are many anecdotal examples of NBS in Ireland, although they are rarely identified as such in publications and official documents. However, a database was compiled of NBS identified during a systematic review of the literature. Existing research indicates the selected NBS of constructed wetlands (CWs), sustainable drainage systems (Suds) and NBS in the riparian zone can improve water quality, to varying degrees. Limited Irish-based research was available for Suds and NBS in the riparian zone. Reported co-benefits include cost-savings, enhanced biodiversity and ecosystem services such as carbon sequestration and recreation. The potential for further implementation of the selected NBS in Ireland is significant.

INTRODUCTION

The International Union for Conservation of Nature (IUCN) defines nature-based solutions (NBS) as 'actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits' (IUCN 2016). Nature-based solutions is a relatively new and evolving umbrella concept that covers a range of approaches, such as green infrastructure (GI). Examples of NBS include constructed wetlands (CWs), river restoration and urban forestry (Cohen-Shacham *et al.* 2016).

Nature-based solutions can be integrated with and, where feasible, provide a cost-effective alternative to traditional 'hard engineering' solutions. They often provide important co-benefits, including biodiversity habitat provision, climate regulation and socio-economic activities, all of which benefit human well-being; a key advantage of NBS over grey infrastructure (constructed assets, often of concrete, e.g. dams) (EC 2015a; EC 2015b; Wild 2020). In recent years there has been increased investment and interest in NBS as their potential has been recognised (EC 2015; Cohen-Shacham *et al.* 2016; NBS Coalition 2019). The European Union (EU), in its

drive to become a global leader in the field, established a research and innovation agenda on NBS and re-naturing cities under which a number of NBS research projects are being progressed (EC 2015). The most recent implementation report on the Water Framework Directive (WFD) reported that less than half of surface waters had achieved good status and raised concerns about the likelihood of achieving full compliance with the WFD objectives by 2027 (EC 2019a). Hydromorphology (40%), diffuse (38%) and point source (18%) pollution were amongst the most significant pressures on surface water bodies, with nutrient enrichment and chemical pollution among the main resulting impacts (EEA 2018). Drivers of surface water pollution included agriculture, inadequate wastewater treatment, urbanisation and associated run-off and industrial activities.

The European Environment Agency highlighted three areas that offer 'substantial opportunities to improve implementation of, and support for the achievement of, WFD objectives'; of these, two encompassed NBS approaches (EEA 2018). However, the application of NBS in general has been limited (Sarabi *et al.* 2021). This paper evaluates the application of NBS in addressing water-quality issues in the EU, using Ireland as a case study because, like other member states, Ireland is struggling to meet

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the objectives of the WFD. For example, O’Boyle *et al.* (2019) reported that only 53% of surface water bodies were at high or good status and while there were some improvements over the reporting period (2013–18), overall, water quality had declined. Nutrient pollution from nitrogen and phosphorus was the main problem, driven primarily by agriculture and wastewater pressures, with excess sediment another significant issue. Ireland’s second cycle river basin management plan (RBMP) and National Planning Framework recognise the importance of approaches that sit within the NBS framework such as green infrastructure and integrated catchment management (DHPLG 2018; GoI 2018a). However, NBS are apparently not yet widely implemented in Ireland (e.g. Collier and Bourke 2020), and except for a dataset on CWs (Healy 2019), there is no comprehensive national database collating existing NBS or results on their performance in Ireland.

The objective of the study reported here was to compile a database on the application of NBS in Ireland and review the research that assesses the effectiveness of NBS in addressing water quality issues in Ireland, focussing on CWs, sustainable drainage systems (Suds) and NBS in the riparian zone. The effectiveness of the NBS types at addressing water quality issues was assessed based on the reported reduction in nutrient and sediment loads. The associated co-benefits, challenges and the potential for further implementation for each NBS were also considered.

NATURE-BASED SOLUTIONS AS A CONCEPT

The NBS concept has gained momentum in recent years (Faivre *et al.* 2017) via organisations such as the International Union for Conservation of Nature (IUCN) and the EU’s research and innovation agenda on NBS, which saw a move to identify some core principles that set NBS apart (Cohen-Shacham *et al.* 2019). The EU defines NBS as ‘solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions’ (Faivre *et al.* 2017).

Although the concept of NBS was only first mentioned in research articles in the 2000s, many of its approaches have existed for some time. The IUCN grouped these approaches into five categories, outlined in Table 1 with examples (Cohen-Shacham *et al.* 2016), showing that the NBS concept covers a wide range of approaches. This is also evident in the EU’s report on NBS, which includes a preliminary list of 310 possible interventions for NBS (EC 2015). The report identifies 22 water purification interventions (see supplementary material) that cover a broad spectrum of scale and pressures from protecting saltmarshes to intercropping with legumes on farms.

The IUCN also developed eight guiding principles for NBS, which included that they should be implemented at a landscape-scale, alone or with other solutions, to address societal challenges. They should ‘produce societal benefits in a fair and equitable way’ and take account of nature conservation standards and ‘site-specific natural and cultural contexts’ (Cohen-Shacham *et al.* 2016). The societal challenges that NBS can address include climate change, food security, disaster risk, human health, water security, environmental degradation and biodiversity loss, and economic and social development (IUCN 2020). Nature-based solutions can contribute to sustainable development goals (SDG), for example, clean water and sanitation (SDG6), zero hunger (SDG2), and have been shown to accelerate the transition to sustainability by promoting innovative planning, governance and business models (Faivre *et al.* 2017). Given the broad scope of NBS, it can be difficult to determine what does and does not fall under the NBS umbrella. Seddon *et al.* (2020) noted that, for an intervention to qualify as a NBS, it ‘must sustainably provide one or more benefits for people...while causing no loss of biodiversity or ecological integrity (or preferably a gain) compared to the pre-intervention state’. A green roof installed with the sole objective of countering heat stress with little regard to the plants used could qualify as a NBS if it benefitted biodiversity and humans when compared to its pre-intervention state. However, such benefits would be limited and the intervention would not meet the IUCN’s guiding principles for NBS. Conversely, a green roof installed as part of a city-wide planning-led approach with plants appropriate for the surrounding ecosystem addressing

Table 1—NBS categories and examples, adapted from Cohen-Shacham *et al.* (2016).

Category of NBS approaches	Examples
Ecosystem restoration approaches	Ecological restoration
Issue-specific ecosystem-related approaches	Ecosystem-based adaptation
Infrastructure-related approaches	Green infrastructure
Ecosystem-based management approaches	Integrated water resources management
Ecosystem protection approaches	Area-based conservation approaches

multiple objectives such as stormwater attenuation, reduced pollution, and cooling in summer as well as biodiversity and human well-being benefits would easily fit within the NBS framing (Eggermont *et al.* 2015). A broad net has been cast in order to identify NBS and evaluate the extent of and potential for such solutions in Ireland. A natural solution that may not currently maximise potential ecosystem services delivery is considered as a potential NBS, for example, a buffer zone to intercept pollutants but not planted to enhance biodiversity. For this reason, the compiled database considers potential NBS as well as NBS (see supplementary material).

METHODS

A systematic review was performed between March and May 2020 using OneSearch tool, which accesses prominent databases such as Web of Science and Scopus. The keywords used included NBS and approaches or interventions that fall under the NBS umbrella and are known to be applied in Ireland (e.g. Suds). Only studies that were available online and in the English language were included, and those published before 2000 were excluded to limit the volume of data. The geographical reach was limited to Ireland except where insufficient results were returned, in which case this criterion was removed and studies from a similar temperate climate were considered. The full list of search queries and limits applied to the search are included in the supplementary material. The publication selection approach was adapted from the PRISMA statement (Liberati *et al.* 2009). The initial search returned 1,252 results. The titles and abstracts of the search results were screened and studies that were not pertinent to the effectiveness of NBS in addressing water quality issues were excluded. Where a query returned a significant number of results, only the first 100 results were screened. To increase the quality and quantity of data, related websites were searched (e.g. the Irish Department of Agriculture, Food and the Marine (DAFM), and the EU LIFE project database). In order to corroborate data sources and veracity, key actors with expertise in NBS approaches were contacted to locate unpublished data sources.

In June 2020, the project objectives were updated to focus on the following three types of NBS interventions: CWs, Suds and NBS interventions in the riparian margin. This was done in order to focus the scope on NBS types for which the search identified multiple examples extant in Ireland. The manuscripts of the screened publications as well as those identified through searches of relevant websites and engagement with key actors were evaluated and studies were selected for systematic review based on relevance to the project's objectives, for example,

inclusion of nutrient and/or sediment performance results for one or multiple sites, and, where applicable, publication metrics (date and level of citation). Throughout the study, examples of Irish NBS interventions identified were added to the NBS database. Data on the reported reduction in nutrient (nitrogen and phosphorus) and sediment loads were extracted to assess the effectiveness of the selected NBS. The literature search process is illustrated in Figure 1. Of the publications selected, approximately 60% were from Ireland. Further detail on the location of the studies included are available in the supplementary material.

RESULTS

WATER-RELATED NBS IN THE EU

Over 28 projects have been funded under the EU Horizon 2020 research programme, such as Connecting Nature¹, and additional related NBS projects have been progressed through other EU funding streams such as Interreg. Knowledge exchange of NBS evidence from these projects has been facilitated through platforms such as OPPLA (Wild *et al.* 2020). The EU's research efforts on NBS are beginning to bear fruit; a state-of-the-art report on NBS projects published in 2020 summarised project results in relation to efficacy, co-benefits, cost-effectiveness, policy and lessons learned (Wild *et al.* 2020). Wild's (2020) analysis of waterbody conditions found that NBS can improve water quality, be as or more cost-effective than grey infrastructure, reduce combined sewer overflow (CSO) discharges in urban areas, and provide significant co-benefits.

APPLICATION OF NBS IN IRELAND

The systematic review returned a small number of confirmed NBS examples in Ireland. Anecdotally it is clear that NBS are more prevalent but are rarely identified as such, and there is a lack of published material on them (Collier and Bourke 2020). When the broad scope of NBS is considered, there are already a wide range of initiatives ongoing in Ireland that fall under the umbrella of NBS or have the potential to (e.g. Rivers Trust activities). Those identified have been recorded in a database included in the supplementary material; it is not an exhaustive record of NBS in Ireland, rather a starting point that can be added to. The entries in the database mostly fall within the following groupings:

1. www.connectingnature.eu. For a full list and links to project websites visit <https://www.nature4cities.eu/h2020-nbs-projects>.

Fig. 1—The systematic review was carried out between March and May 2020. A sense check conducted in March 2021 did not identify any substantive changes that would alter the findings of the initial systematic review. The publications included in the systematic review were evaluated and relevant data extracted and synthesised qualitatively. This included NBS technology, location, methodology, results, limitations and co-benefits. Details of potential identified NBS in Ireland were included in the database; see supplementary material.

- Utility and developer led projects: these usually address a specific issue (e.g. wastewater treatment). They include CWs and sustainable drainage measures implemented by Irish Water and Transport Infrastructure Ireland (TII).
- Local authority projects: NBS are implemented to address a variety of pressures (e.g. stormwater management, social inclusion, water quality).
- EU schemes: examples of these include European Innovation Partnership (EIP), LIFE and LEADER projects with drivers such as social progress, sustainable agriculture and forestry and climate action.
- Locally led projects: Rivers Trust and other community organisations that have engaged in activities such as tree planting, invasive species control and riverbank restoration.
- Rural Development Programme (RDP) schemes: these are predominantly implemented through the targeted Green Low Carbon

Agri-Environment Scheme (GLAS) (DAFM 2017).

The categories listed above tend to overlap; for example, the local authority-led invasive species control along the River Loobagh was carried out in partnership with Ballyhoura Development CLG and the Heritage Council (LCCC 2021). This demonstrates the collaborative nature of the NBS approach and its role within integrated catchment management. The following sections will evaluate the selected NBS (CWs, Suds and NBS in riparian zones) in further detail.

CONSTRUCTED WETLANDS

CWs are engineered systems that utilise natural processes to treat wastewater. The different types of CWs as outlined by Vymazal (2011) are:

Table 2—Average effluent concentrations (mg l⁻¹) and reductions (%) from selected studies on Irish CWs

Data Source	Application	CW Type	No. CWs	Average CW effluent concentrations (% reductions, where available)			Comment
				P	N	SS	
Hickey <i>et al.</i> (2018)	Municipal	FW/SE, providing secondary treatment	6	Ortho-P 3.5mg l ⁻¹	NH ₃ -N 6.7 mg l ⁻¹ TN 20.5mg l ⁻¹	46.4mg l ⁻¹	Variable results, frequent ELV exceedances.
		HSSE, providing tertiary treatment	35	TP 3.8mg l ⁻¹ Ortho-P 3.7mg l ⁻¹	NH ₃ -N 10.4 mg l ⁻¹ TN 20.3 mg l ⁻¹	19.4mg l ⁻¹	Variable results, frequent ELV exceedances.
		Hybrid	2	TP 4.6mg l ⁻¹ Ortho-P 2.4mg l ⁻¹	NH ₃ -N 7.6mg l ⁻¹ TN 12.5mg l ⁻¹	14 mg l ⁻¹	Variable results with exceedances of typical ELVs but overall, better results than FSFW, HSSE.
		ICW	6	TP 2.8mg l ⁻¹ Ortho-P 1.8mg l ⁻¹	NH ₃ -N 2.4mg l ⁻¹ TN 6.7mg l ⁻¹	5.3 mg l ⁻¹	Less variability, some exceedances for N and P.
		ICW DOE		TP 1.6mg l ⁻¹ Ortho-P 0.2mg l ⁻¹	NH ₃ -N 0.8mg l ⁻¹ TN 2.7mg l ⁻¹	6mg l ⁻¹	Best results of CWs studied. Complied with ELVs monitored except the NH ₃ -N 1mg/l ELV.
Healy and O'Flynn (2011)	Municipal	FW/SE, providing secondary treatment	14	TP 0.3mg l ⁻¹ Variable	NH ₃ -N 11mg l ⁻¹ (77%) NH ₄ -N 6mg l ⁻¹	14 mg l ⁻¹ (96%) 13mg l ⁻¹	Variable nutrient removal.
	Dairy-soiled water	FW/SE, providing tertiary treatment	13	Variable	(37%) NH ₄ -N 6mg l ⁻¹	(82%) 34mg l ⁻¹	Variable nutrient removal.
	Farmyard wastewater	FW/SE	7	Variable	NH ₃ -N (>98%)	(94%) N/A	Variable nutrient removal. Frequent SS ELV exceedances.
Harrington and McInnes (2009)	Various	ICW	12	MRP >90%	NH ₃ -N (>98%)	N/A	Ammonium effluent concentrations generally lower than in adjacent soils.
Babatunde <i>et al.</i> (2008)	Various	Various	13	Inconclusive	NH ₃ -N 0.1-15mg l ⁻¹ (67-99.9%)	20.5mg l ⁻¹ (91%)	Limited assessment. Most CWs performed well; however, results may be biased due to high inlet concentrations. Tolka valley ICW
EC (2013)	Contaminated surface water	ICW	1	N/A	NH ₃ -N (91%) Nitrate (16%) Nitrite (6.5%)	N/A	
TII (2015) (TII, 2015)	Road runoff	N/A	N/A	TP 0.008-0.039 (68%)	N/A	10-32mg l ⁻¹ (88%)	Wetland on M7.

ELV-Emission Limit/Value, OrthoP- Orthophosphate, TP- Total Phosphorus, NH₃-N- ammonium nitrogen, NH₄-N- ammonia nitrogen, TN- Total Nitrogen, MRP-Molybdate Reactive Phosphorus, SS- Suspended Solids.
 Typical ELVs for municipal WWTPs: Ortho-P 2mg l⁻¹, TP 2mg l⁻¹, NH₃-N 1/5mg l⁻¹, TN 15mg l⁻¹, SS 35mg l⁻¹ (Hickey *et al.* 2018).

- Free water surface flow (FWSF) CWs: water flows through areas of shallow open water and floating, submerged and emergent plants. Water level is above the surface.
- Horizontal subsurface flow (HSSF) CWs: water flows slowly under the surface through the porous substrate, which is planted with emergent vegetation.
- Vertical subsurface flow (VSSF) CWs: gravel with macrophytes planted at the top is intermittently flooded with wastewater that trickles down to a drainage network at the bottom.
- Hybrid systems: combination of CW types.

Integrated constructed wetlands (ICWs) are a type of FWSF CW pioneered in Ireland that adopts a holistic approach to water quality management. They comprise a chain of interconnected ponds that largely mimic 'natural shallow emergent-vegetated wetlands'. The three principles of ICWs are effective water resource management, landscape-fit and biodiversity enhancement (Harrington and McInnes 2009).

Extent and Application in Ireland

The compiled NBS database has recorded 105 examples of CWs in Ireland (see supplementary material). These have a range of applications including treatment of sewage, commercial effluents, road runoff, stormwater management, farmyard runoff, landfill leachate and mine tailings (Babatunde *et al.* 2008; Harrington *et al.* 2011; TII 2015). There are 52 CWs in municipal wastewater treatment plants (WWTPs), 35 of which are HSSF CWs used for tertiary treatment (Hickey *et al.* 2018). In Dublin's Tolka Valley, an ICW is used to treat contaminated surface water and plans are progressing for another five across South Dublin (EC 2013a; SDCC 2021). Constructed wetlands and other Suds components are also used to treat motorway runoff (TII 2015) although TII could not advise on the extent (Mills 2020).

Effectiveness

Recent studies on the effectiveness of Irish CWs were reviewed and the results are summarised in Table 2. According to Babatunde *et al.* (2008), wetlands generally have limited capacity for nutrient reduction. This was evident in the performance of municipal HSSF, FWSF and hybrid CWs, where effluent quality was variable and average effluent concentrations for most nitrogenous and phosphorus parameters were above typical emission limit values (ELVs); for example, the average HSSF CW orthophosphate effluent concentration was 3.7 mg l⁻¹, exceeding the commonly applied 2 mg l⁻¹ ELV. However, municipal ICWs, and particularly those constructed in accordance with government guidelines

(ICW DOE), achieved better nutrient reduction results, with average orthophosphate effluent concentrations of 1.8 mg l⁻¹ and 0.2 mg l⁻¹ reported by Hickey *et al.* (2018). Similarly, in ICWs treating farmyard wastewater, high removal efficiencies have been achieved for phosphorus (>90%) and ammonium (88%) (Harrington and McInnes 2009). Hickey *et al.* (2018) noted that the specific area (ratio of CW area (m²) to population equivalent (pe)) of municipal FWSF CWs studied are generally below the national guideline values of 20 and 40 m² pe⁻¹, depending on surface-water input, whereas the average specific area for ICWs, which achieved much lower effluent nutrient concentrations, was 65 m² pe⁻¹. This is consistent with research that suggests larger specific areas (40–70 m² pe⁻¹) are required for adequate nutrient removal (Brix and Schierup 1989). Sediment removal efficiency was generally good with values of up to 96%, although there was variability across effluent concentrations (5.3–46.4 mg l⁻¹). Key factors identified for the successful implementation of CWs are listed below:

- Appropriate sizing. As noted above, CWs with higher specific areas have longer hydraulic residence times providing favourable conditions for nutrient retention (Hickey *et al.* 2018; Scholz *et al.* 2010).
- Effective upstream treatment, for example, in mechanical WWTPs upstream (Hickey *et al.* 2018).
- Separation of stormwater from wastewater appears to improve effluent quality and reduces variability in effluent quality and the land area required (Hickey *et al.* 2018).
- Appropriate design, operation and maintenance to prevent performance issues such as clogging (Babatunde *et al.* 2008).
- Community-based participatory approach to foster understanding and buy-in (Babatunde *et al.* 2008). In the Anne Valley where 16 ICWs have been constructed, using the ecosystem approach and presenting the land and water resource co-benefits such as improved amenities, helped to gain acceptance of the land-take required. Principles of the ecosystem approach employed include decentralised management, decision making at the collective and individual level and intersectoral cooperation (Harrington *et al.* 2011).

Co-benefits and potential

Several studies have assessed the biodiversity potential of CWs. For example, in the Tolka Valley ICW in Dublin, a wide range of species have colonised the site including the reed bunting, banded jewelwing damselfly and the common frog (OPENFIELD 2008). Measures to maximise biodiversity potential include enhancing the range of mesohabitats to create varied habitat mosaics through, for example, provision of a

variety of water depths and vegetation, tree-planting, use of floating islands, and also increasing the overall ICW area and number of ponds (Becerra-Jurado *et al.* 2014; Becerra-Jurado *et al.* 2012). Harrington and McInnes (2009) summarised the range of ecosystem services provided by the Anne Valley ICWs. Those estimated to have the greatest magnitude per unit area include freshwater provision, soil formation, nutrient cycling, climate regulation, water purification, waste treatment, natural hazard regulation and cultural services (spiritual, recreational, aesthetic and educational). Given the challenges in achieving compliance with water quality legislation for small scale WWTPs (Hickey *et al.* 2018), CWs can provide a feasible low-cost alternative to conventional sewage treatment. Furthermore, they can offer significant savings in capital (70–80% less) and management costs (*c.* 90% less) (Harrington *et al.* 2011) in comparison to traditional approaches. They also have the potential to effectively manage stormwater (Lucas *et al.* 2015), remove contaminants of emerging concern and treat wastewater from CSOs (Wild 2020). Accumulated ICW sediment can be used to provide up to 12% of a farm's annual phosphorus requirement (Scholz *et al.* 2007). Other potential co-benefits are being investigated, for example, electrical power generation using microbial fuel cells (Doherty *et al.* 2015).

SUSTAINABLE DRAINAGE SYSTEMS (SUDS)

Sustainable drainage systems utilise natural processes such as evaporation, infiltration and plant transpiration to reduce storm run-off and water pollution, and generally comprise a number of components in a series (EC 2015). They can form part of GI networks, strategic networks of natural and semi-natural areas that provide ecosystem services (EC 2013b). Examples include green roofs, rainwater harvesting, swales, bioretention systems, trees, detention basins and CWs (Fenner 2017; Woods-Ballard *et al.* 2015).

Extent

There are 13 entries for Suds in the NBS database. This includes an entry that refers to a database of 95 sustainable drainage systems installed in developments granted planning between 2005 and 2009 (Dublin City Council 2010). As the implementation of Suds has been included as an objective in local planning policy since 2005, it is likely that there are far more examples of Suds around the country. Nevertheless, studies indicate the implementation of Suds has been slow and fragmented (O'Sullivan *et al.* 2012; Rooney and Gill 2019). Examples of Suds include retention and detention areas in Poppintree Park (Harris 2016) and the use of swales at a housing development in Pelletstown (Connecting Nature 2018). In the Tolka Valley, the ICW was part of a wider Natural Water

Retention Measures (NWRM) project that also included detention ponds, riverbank engineering, tree planting, a greenway and invasive species control (EC 2013a). Sustainable drainage systems such as swales and infiltration basins have also been incorporated into more recent road projects (Mills 2020).

Effectiveness

International studies were relied on for Suds performance data as the literature search returned limited results for Ireland. In a global study, Hager *et al.* (2019) found nutrient removal in Suds to be highly variable due to design, geographic and temporal factors, posing a challenge for decision-makers to promote adoption of Suds (see Table 3). As indicated by the negative treatment efficiency, several components exported nitrogen and phosphorus. Suds can also effectively treat other pollutants, e.g. heavy metals (Woods-Ballard *et al.* 2015) and contaminants of emerging concern (Wild *et al.* 2020) however, this is beyond the scope of this case study.

The Suds manual of Woods-Ballard (2015) provides a summary of outflow concentrations of various Suds components, derived from a database of US performance data. Performance results for total suspended solids (TSS) are shown in Table 4. Of these results, only bioretention and wetland basins yielded outflow results consistently below the allowable EU salmonid regulations (Directive 2006/44/EC) guide value of 25mg l⁻¹ (EC 2006). In general, sediment removal performance improved with increased hydraulic retention times (Woods-Ballard *et al.* 2015).

Sustainable drainage systems also indirectly reduce pressure on waterbodies by diverting stormwater from sewers and reducing water demand via rainwater harvesting. For example, Welsh Water implemented various Suds measures in Llanelli resulting in 4390ML removed from the sewer network, reducing pollution and flood risks (Welsh Water 2020).

Co-benefits, challenges and potential

In addition to water quality and flood control, Suds can provide the following benefits: noise reduction, improved air quality, carbon storage, improved biodiversity, pollination, provision of food and enhanced amenities (Fenner 2017). These benefits have direct economic value, including reduced wastewater treatment costs and increased property value. Capital, energy and maintenance costs are generally much lower for GI than traditional grey infrastructure in stormwater management (Center for Clean Air Policy 2011). Fenner (2017) recommends a proactive approach to multiple benefits through co-design of GI/Suds features to maximise

Table 3—Nutrient removal performance efficiencies of Suds components reported in reduction-specific studies, adapted from Hager *et al.* (2019)

<i>Component</i>	<i>Total Nitrogen % reduction¹ (number of studies)</i>	<i>Total Phosphorus % reduction¹ (number of studies)</i>
Permeable pavement system	15 to 60 (6)	5 to 80 (10)
Infiltration trench	0 to 85 (4)	5 to 70 (4)
Bioswale	5 to 70 (12)	-10 to 80 (17)
Bioretention	-35 to 60 (14)	0 to 70 (18)
Buffer/ filter strip	5 to 60 (10)	-20 to 50 (10)

¹ concentration ranges: 25%–75%. Results are from box plots and are approximate only.

Table 4: TSS outflow concentrations for various (appropriately designed and managed) vegetated/ surface Suds components, adapted from Woods-Ballard *et al.* (2015)

<i>Component</i>	<i>TSS concentration at outflow (mg/l)¹</i>	<i>Treatment efficiency (% reduction)²</i>
Filter strips	10–35	48–95%
Bioretention	5–20	70–93%
Swales	10–43	36–85%
Detention basins	10–47	30–85%
Retention ponds	4–28	58–94%
Wetland basins	4–21	69–94%
Permeable pavements	14–44	34–79%

¹ concentration ranges: 25%–75%

² TSS concentration inflow range: 20–114mg/l. Treatment efficiency based on average inflow concentration of 67 mg/l.

the benefits realised. Rooney and Gill (2019) investigated the barriers to Suds implementation in Ireland and found they largely correlated with those experienced internationally. These included lack of leadership, public awareness, incentives, resources to monitor implementation and regulation on storm-water discharge water quality, and overarching Suds standards. In addition, Suds policy applies to developments that require planning permission and there is a lack of policy and incentives for retrofitting Suds in properties and the urban environment (Rooney and Gill 2019). Potential solutions identified by these authors include public awareness programmes, improved governance at national and local levels, new legislation and regulations, particularly around the water quality of discharges, increased intersectoral cooperation and emphasis on the co-benefits of Suds, financial incentives, demonstration projects and increased training and enforcement resources at local authorities. The leadership needed to implement these solutions and progress Suds in Ireland could come from relevant government departments and the City and County Management Association. Other key actors include state agencies including the Inland Fisheries Ireland (IFI), Office of Public

Works, Environmental Protection Agency (EPA), TII and the National Parks and Wildlife Service, as well as other stakeholder groups including academia, Engineers Ireland, Irish Planning Institute, Construction Industry Federation. The recently established Local Authority Waters Programme (LAWPRO) and Climate Action Regional Offices (CARO) could potentially provide useful vehicles for the inter-sectoral cooperation needed to get projects on the ground and engage local communities. Several funding streams have been established under the Government of Ireland's (GoI) National Development Plan; these present an excellent opportunity to progress Suds in new developments and retrofit them in existing developments (GoI 2018b).

NBS INTERVENTIONS IN THE RIPARIAN ZONE

Nature-based solution interventions in the riparian zone generally involve the establishment of a protected buffer zone in which development is restricted. These riparian buffer zones (also called buffer strips or water setbacks) are ecotones between waterbodies and human-disturbed lands that protect water quality by intercepting sediment, nutrients

and other pollutants from surface runoff, drainage and groundwater (Ma 2016; Stutter *et al.* 2019). NBS interventions in the riparian zone could also include measures to enhance buffer zone function such as invasive species control, bank protection and restoration, tree planting, silt traps and fencing and alternative water source provision for livestock (Duhallow LIFE 2015; DAFM 2017).

Extent

The NBS database recorded 41 entries with measures in the riparian zone. Examples include community- and local authority-led projects such as riparian woodland planting in Riverchapel, Co. Wexford (SRI 2020) and invasive species control along the River Loobagh (LCCC 2021), and EU-funded projects such as riparian and in-stream improvements along the Mulkear river (EC 2014). Buffer zones are required in some land-use plans, for example, the draft Southern Environs Local Area Plan (LAP) in Limerick requires a 20m riparian buffer zone (LCCC 2020). The LAP also requires developers to take cognisance of IFI's recently updated guidance document 'Planning for watercourses in urban environments', which advocates a buffer zone system ranging from 20–60m in width in urban areas (Igoe 2020). In the agriculture sector, buffer zones are mandatory under certain regulations (e.g. Nitrates Directive (DAFM 2018a)). Relevant voluntary measures under GLAS include riparian margins and protection of watercourses from bovines (DAFM 2017). Water setbacks have been implemented in all new forests since 1991 and environmental requirements were updated in 2016 to include additional water quality and biodiversity safeguards (DAFM 2017). DAFM's Woodland for Water measure

promotes the establishment of new native woodland planted under the Native Woodland Scheme and a buffer zone adjacent to a watercourse, with strategic interventions, for example, slow-flow dams, to protect and enhance water quality (DAFM 2018b).

Effectiveness

Due to limited availability of research on the effectiveness of NBS in the riparian zone in Ireland, international studies were also considered (e.g. Stutter *et al.* 2019; Feld *et al.* 2018; Riis *et al.* 2020; Nisbet *et al.* 2011). The synthesis of riparian management studies by Stutter *et al.* (2019) found that the effectiveness of conventional vegetated buffer zones using natural grasses and herbs at improving water quality was variable. In a global review, Feld *et al.* (2018) found the most common buffer vegetation type was trees, followed by grasses and shrubs. The most common plant combinations were single trees and multizone configurations. Their study reported typical phosphorus and nitrate retention efficiencies of 40%–70% (mainly from surface runoff) and 50–75%, respectively. The main removal mechanisms are denitrification and uptake for nitrogen and uptake, adsorption and deposition for phosphorus (Riis *et al.* 2020). Harvesting riparian vegetation is necessary to minimise phosphorus accumulation and leaching risks, thus maintaining the long-term nutrient retention function of buffers, and can also provide (limited) financial returns (Stutter *et al.* 2019). The authors also noted that while narrow buffer widths (<3–4m) appeared to be less effective at enhancing water quality, in general, width was less important than site specific factors (e.g. soil type, topography, vegetation).

Feld *et al.* (2018) found buffer zones had a fine sediment retention capacity ranging from 60 to 100%, with mechanical filtration in grass strips playing a key role for both phosphorus and sediment retention. According to Nisbet *et al.* (2011), tree roots of riparian woodlands strengthen the stability of the riverbank, thus reducing erosion however, there is evidence that tree shading suppresses understory vegetation growth, diminishing the buffers sediment retention efficiencies (Feld *et al.* 2018). Multizone buffers are generally recommended; for example, Nisbet *et al.* (2011) suggest a combination of grassland and woodland buffers, and Feld *et al.* (2018) propose buffer zones at least 20m-wide, including trees, shrubs and grass strips. Control of riparian invasive species is important as they can displace native species, promote soil erosion and reduce light reaching watercourses (Baars *et al.* 2020).

In Ireland, high, good and moderate (with heavy livestock activity) status waterbodies would benefit from cattle exclusion measures (Conroy *et al.* 2016, Madden *et al.* 2019). However, in waterbodies with catchment-wide pressures such as diffuse pollution,

Table 5—Ecosystem services provided by riparian vegetation with the greatest importance, in order of priority, adapted from: Riis *et al.* (2020)

<i>Ecosystem service</i>	<i>Ecosystem Service Importance</i>
Providing habitats
Filtering/ storage of particles	
Fixation storage (carbon sequestration)	
Erosion control	
Providing habitats for native pest control agents	
Flow regulation	
Removal of nutrients in runoff	
Landslide	
Pollination	
	Medium

cattle access may not cause further deterioration and so mitigation measures may not be the most cost-effective measures available (Madden *et al.* 2019).

Co-benefits, challenges and potential

Riis *et al.* (2020) found that riparian vegetation can provide a high amount of ecosystem services relative to their spatial extent. The authors summarised the ecosystem services provided by riparian vegetation, ranking them in order of importance. The services ranked highest are listed in Table 5.

Stutter *et al.* (2019) noted the trend towards designed and targeted buffers with multiple components, and that these tend to perform better at intercepting runoff and enhance the riparian area, thus providing multiple co-benefits. These components could include mini-wetlands, trees or saturated riparian buffers, where a field is drained to a single point and a portion of flow is then diverted to a vegetated buffer. Precisely targeting buffer zones to intercept preferential flow paths, thereby reducing land-take, as well as locating mitigation measures in edge-of-field margins, could help address common barriers to adopting buffer zones such as insufficient economic return, loss of land and interrupted production (Buckley *et al.* 2012; Thomas *et al.* 2016). When compared with blanket implementation of buffer zones, precisely targeted riparian buffers were estimated to reduce buffer zone length by 97%, with an associated cost saving of 90% (over five years) (Thomas *et al.* 2016). Riparian management can provide floodwater regulation co-benefits and form part of wider river restoration or NWRM strategies (DAFM 2018b). Catchment-wide strategies can also have a greater impact on ecology than localised riparian measures (O'Callaghan *et al.* 2019). Stutter *et al.* (2019) highlighted multiple research gaps including utilisation of captured nutrients, greenhouse gas impacts and the potential for pollution swapping, where one form of pollution is reduced but another created such as nitrate uptake in buffer zones leading to emissions of dissolved organic nitrogen and nitrous dioxide. They recommended that researchers coordinate with other disciplines with common interests (e.g. agricultural engineers) to develop appropriate and effective designs and supporting evidence base. Teagasc's ongoing Smarter BufferZ project is currently researching targeted riparian management in Ireland (Connery 2020).

DISCUSSION

EXTENT

The database of Irish NBS compiled during this project has 82 entries. A key issue is that interventions that fall within the definition of NBS are rarely

labelled as such, and it was necessary to search relevant websites and reach out to experts in order to identify NBS projects for the database. Many have water quality improvement as one of the main drivers, in other cases it is a co-benefit. It is likely that there are far more NBS examples in Ireland given the broad scope of the concept. The adoption of the NBS concept may become more common in Ireland through the RBMP, the various ongoing EU and EPA funded NBS projects (Delcroix 2019; Collier and Bourke 2020), media attention (e.g. Carrington 2019) and the promotion of NBS/GI in the National Biodiversity Action Plan 2017–2021 and the National Planning Framework (NPF) (DCHG 2017; GoI 2018a). Indeed, many of the current water-related NBS in Ireland are driven by actions identified in the RBMP. The cross-sectoral approach and joined-up thinking associated with integrated catchment management lends itself to the effective implementation of NBS. Good examples of this are the growth in Rivers Trusts (EPA Catchments Unit 2019) and the Blue Dot Catchments Programme (DHPLG 2018). Although some of the interventions identified in this paper do not necessarily meet all of the NBS principles prescribed by the IUCN (2016), they have the potential to do so with some adjustments, which would in turn maximise the ecosystem services provided. Take, for example, a measure to establish a riparian buffer zone; this could be strategically applied across a catchment and planted by a community group to enhance biodiversity, carbon sequestration and flow regulation, intercept pollutants particularly in areas of preferential flow, provide shading for aquatic biota and food for pollinators. Where appropriate, biomass could be harvested and used as green manure. Thus, one measure to protect water quality can be enhanced to provide multiple co-benefits. This point is reiterated by Riis *et al.* (2020) who noted that most water-related projects focus on habitat or water quality and in doing so, miss out on important ecosystem services.

EFFECTIVENESS

Assessing the effectiveness of the selected NBS at addressing water pollution in Ireland was challenging due to the limited Irish research available for some NBS. A reasonable amount of data were available for CWs although research gaps remain (e.g. on the adsorption capacity of phosphorus (Hickey *et al.* 2018)). Few Irish data were available on the treatment performance of Suds or NBS interventions in the riparian zone and as such, international research was also used. Overall, the effectiveness of the selected NBS at addressing water quality issues was variable, especially for riparian and GI measures. This presents a challenge to decision-makers promoting NBS, and thus, further research and monitoring in Ireland are necessary to develop a reliable evidence base and

inform future projects, policy and schemes. Generally, research indicated that in order to maximise the benefits realised, catchment-wide approaches are favoured over localised measures (Addy *et al.* 2016; O'Callaghan *et al.* 2019). The performance of HSSF, FWSF and hybrid municipal CWs was variable with frequent exceedances of ELVs for nitrogen and phosphorus. Integrated constructed wetlands, especially those designed to comply with government guidelines, had better and more consistent results (Hickey *et al.* 2018). The underlying philosophy for ICWs also means they are more closely aligned with NBS principles than other CW types (Harrington and McInnes 2009; Cohen-Shacham *et al.* 2016). Specific area, storm control and adequate upstream treatment are key factors to consider for effective CW performance (Babatunde *et al.* 2008; Hickey *et al.* 2018). Ongoing research may present additional opportunities to optimise performance (Babatunde *et al.* 2008). The use of CWs to treat surface water in Ireland is increasing (e.g. SDCC 2021), but it is important that long-term monitoring is undertaken for projects like this in order to develop an evidence base for CWs in this context.

Performance efficiencies for individual Suds components are variable, in particular for nutrient reduction, where some components have been recorded exporting nutrients (Woods-Ballard *et al.* 2015; Hewage *et al.* 2019). Correctly designed Suds include multiple components in series where pollutant concentrations can be progressively reduced through a 'management train' (O'Sullivan *et al.* 2012). Thus, the efficiency of a multi-component system may be better than the efficiencies of individual components. The application of the management train approach, however, remains uncommon (Wild 2020). Urban wastewater, including CSO discharges, are a significant pressure on Ireland's waterbodies (DHPLG 2018), with eight Irish wastewater networks recently found non-compliant by the Court of Justice of the European Union in 2019 (EPA 2019). Suds can help address this issue by diverting surface water from sewers to Suds components and so reduce CSO discharge and pollution risks (Woods-Ballard *et al.* 2015). Constructed wetlands have also been used as a point source solution to effectively treat CSO effluent in Italy (Masi *et al.* 2017). The effectiveness of NBS interventions in the riparian zone in addressing water pollution is variable. Feld *et al.* (2018) reported buffer width to be a key controlling factor in nutrient retention although Stutter *et al.* (2019) noted width was less important than site-specific factors such as soil type, vegetation, biogeochemical processes, etc. Riparian vegetation can be effective at retaining sediment (Riis *et al.* 2020). Existing evidence suggests designed and spatially targeted riparian measures with multiple zones and/or components achieve the best results (Feld *et al.* 2018; Stutter *et al.* 2019).

CO-BENEFITS

Each of the three NBS assessed can achieve significant common co-benefits. The magnitude of these co-benefits depends on the spatial extent of implementation of the NBS but also the effort put into realising the co-benefits; a proactive approach is therefore necessary in designing NBS to maximise the potential benefits (Fenner 2017). The ecosystem services that humans can derive from NBS include carbon sequestration, provision of habitats and flood risk mitigation as well as cultural services such as recreation and social cohesion (Harrington *et al.* 2011; Riis *et al.* 2020). These ecosystem services deliver health benefits in the form of improved mental well-being and social interaction, promotion of physical activity and reduction and mitigation of environmental risks (Scott *et al.* 2015). The selected NBS have recorded improved biodiversity at several sites. For example, works in-stream and in the riparian zone in the Mulkear catchment led to an increase in the number of sea lamprey redds and salmon using new sites (EC 2014). In some projects, immediate biodiversity improvements have been less pronounced (e.g. Duhallow LIFE), however, it can take time for ecosystems to recover and therefore, long-term monitoring is essential to fully assess the impact of interventions (Duhallow LIFE 2015). The NBS have also allowed researchers to identify measures to enhance biodiversity that can be applied at other sites, for example, reducing barriers and providing refuges at CWs to enhance habitats for newts (Mulkeen *et al.* 2017). The projected impacts of climate change on water quality include increased flooding and reduced assimilative capacity because of more extreme precipitation, and changes to species distribution and phenology due to higher temperatures (DHPLG 2019). The selected NBS have a role to play in adapting to these increased pressures through, for example, flood attenuation via Suds, using hybrid CW systems to minimise discharge and also in climate change mitigation through carbon sequestration (Woods-Ballard *et al.* 2015; Hickey *et al.* 2018). In terms of costs, numerous studies show there are both direct and indirect financial benefits in terms of reduced capital and maintenance costs and employment, increased resilience to environmental stresses, tourism, harvested biomass and savings associated with improved health; for example, the net benefits of using Suds for stormwater management in Philadelphia were estimated at \$3bn versus \$100mn for a piped system (EC 2015).

POTENTIAL AND CHALLENGES

It is clear from the above that the selected NBS can improve water quality, help meet WFD objectives and provide valuable co-benefits. In Ireland, 1,460 waterbodies are at risk of not meeting their WFD

objectives due to significant pressures from agriculture, wastewater and urban run-off (DHPLG 2018). Taking into consideration the benefits that NBS can offer, the number of possible sites available to implement NBS, as well as the challenges Ireland is facing in terms of declining water quality (O'Boyle *et al.* 2019) and climate and biodiversity emergencies (Sargent 2019), it is clear the potential for further implementation of these NBS in Ireland is significant. Moreover, many of the existing interventions identified in this case study could be enhanced to maximise the benefits generated.

To realise the potential of NBS, common barriers need to be addressed. These include governance, integration of NBS principles at the design stage, balancing trade-offs while delivering multiple goals, citizen involvement, social inclusion, public acceptance, political support, long-term funding, evaluation, mainstreaming, long-term monitoring and knowledge transfer (Finn and Ó hUallacháin 2011; Collier and Bourke 2020; Schmalzbauer *et al.* 2020). Under the NPF, GI and ecosystem services are required to be integrated into land-use plans that will assist in the mainstreaming of NBS (GoI 2018a). However, while incorporating NBS and GI into policy and land-use plans is important, further measures are required to roll these out. Suds has been required in policy since 2005 but its implementation is still fragmented (Rooney and Gill 2019). Furthermore, it only applies to new developments while arguably the greatest potential lies in retrofitting Suds in areas already developed. Additional actions could include financial incentives, leadership, education and legislation (Rooney and Gill, 2019; Schmalzbauer *et al.* 2020).

Various funding initiatives established under the NPF, such as the Urban Regeneration Development Fund and the Land Development Agency will lead to projects in the public realm as well as new mixed-use developments. Such initiatives present significant opportunities to include NBS in urban and rural environments, and many projects awarded to date include GI objectives (e.g. World-class Waterfront in Limerick (GoI 2018b; GoI 2018c)). Nature-based solutions may not always be feasible over traditional measures when addressing a single challenge (e.g. wastewater treatment). However, if the value of the co-benefits were accounted for through natural capital accounting (NCA), NBS could be the best value option and other agencies could potentially contribute to project costs (EC 2015). Natural capital accounting provides a significant opportunity in justifying a NBS over traditional 'grey infrastructure' and has been included as a measure to pursue finance in the European Green Deal (EC 2019b). Various NCA research projects are underway in Ireland, including the EPA's INCASE project, which has

a particular focus on water quality and integrated catchment management (Farrell *et al.* 2020). The advantages of NCA include more informed decision-making and it facilitates shared understanding and cross-sectoral cooperation via a common data platform (Farrell *et al.* 2020). Funding from private sectors can also be leveraged; for example, DAFM established the Woodland Fund which, through a payment for ecosystem services mechanism, enables corporate entities to fund new native woodland establishment to meet corporate social responsibility objectives (DAFM 2018b).

Public participation and citizen science is an important feature of many of the NBS projects underway. The Local Authority Waters and Communities Office (now LAWPRO) and the Community Water Fund were established to promote public participation, and over 69 community groups were awarded funding in 2018 (Walshe and O'Connell 2018). Locally led projects present a valuable opportunity for implementing NBS and have a number of advantages: buy-in from the community, fosters a sense of stewardship, capitalises on local knowledge of waterbodies, generates greater monitoring and data collection, are less costly and more resilient to budget cuts, supports recreation, regeneration and social inclusion (Walshe and O'Connell 2018; Schmalzbauer *et al.* 2020). Such projects can require significant technical and planning supports; LAWPRO can provide technical assistance and facilitate the necessary collaboration between communities and public and private stakeholders to help progress these projects (Walshe and O'Connell 2018; LAWPRO 2021).

Research gaps exist within each of the selected NBS types in relation to both treatment efficiency and how to operationalise the NBS. Addressing the research gaps will provide an evidence base that will assist decision-makers. Of note, there appears to be a lack of water quality performance data for Suds and riparian management NBS projects in Ireland. This, and the limited data available on the extent of the selected NBS in Ireland are considered the main limitations of this case study. Another potential limitation is the list of keywords used. Although this was extensive it may not have identified all applicable publications given the varying terminology used for NBS interventions and approaches. Many of the ongoing NBS projects have a strong focus on knowledge transfer and monitoring, and so, a similar literature search in future may yield more and better results. The knowledge transfer aspect is already being realised for some projects, including the Kerry LIFE project, which has informed the Freshwater Pearl Mussel project (DHPLG 2018). The evidence base generated from the many EU and international NBS projects underway can also be used to inform the operationalisation of NBS in Ireland and elsewhere.

CONCLUSIONS

Member states in the EU are struggling to comply with WFD objectives, with urban wastewater and runoff amongst the most significant pressures on waterbodies. Recent EU analysis found that NBS can help achieve WFD objectives and provide a cost-effective alternative to traditional mitigation measures, whilst also providing multiple benefits and helping achieve SDGs. This case study has found many examples of water-related NBS in Ireland, but they are rarely identified as such. A record has been compiled of the NBS identified that could assist in the establishment of a comprehensive database of NBS in Ireland.

Available research indicates the selected NBS can improve water quality to varying degrees. Measures to improve the treatment performance of each of the selected NBS types have been identified (e.g. management train approach for Suds). The selected NBS can provide human well-being, biodiversity and economic co-benefits as well as form part of climate change mitigation and adaptation strategies. To maximise the benefits generated from NBS, projects should be applied at catchment-scale and co-benefits considered at the design stage. Taking into account the benefits that can be realised from the selected NBS and the challenges Ireland is facing in terms of water quality, climate and biodiversity, it is concluded that the potential for the selected NBS in Ireland is significant. However, challenges exist with regard to treatment performance and the roll-out of NBS. Long-term monitoring and further research on treatment performance is required, particularly for Suds and NBS interventions in the riparian area in an Irish context. Measures to overcome barriers to implementation include cross-sectoral cooperation, legislation and policy, long-term financial support and public participation. Public participation and natural capital accounting are considered key tools in facilitating the mainstreaming of NBS.

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SUPPLEMENTARY MATERIAL

A database of the application of nature-based solutions in Ireland as well as appendices to this article are available online. Visit <https://doi.org/10.3318/BIOE.2021.14> and click on the supplements icon.

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