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Integrated Strategies to Improve Drinking Water Quality: A Comparative Assessment of Source Protection and Drinking Water Treatment

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Lead organisation: Ryan Hanley

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Government of Ireland

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5. Office of Communications and Corporate Services

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What did this research aim to address?

This research addresses the challenge of ensuring safe, sustainable drinking water by investigating how integrating source protection (SP) measures with advanced drinking water treatment (DWT) technologies can potentially improve water quality across diverse Irish catchments. SP measures (e.g. riparian buffers, artificial wetlands) offer environmental benefits like biodiversity protection and flood resilience, but their effectiveness varies due to maintenance, site suitability and community engagement challenges. In contrast, DWT technologies provide centralised control over water quality, but often incur higher financial and environmental costs.

Based on six Irish case studies representing a variety of hydrological and geological contexts, catchment attributes, local pressures, water quality and socio-economic factors are evaluated in terms of their influence on the effectiveness of SP measures and DWT technologies, supported by a review of national and international best practices.

The most suitable DWT technologies and SP measures were selected using multi-criteria analysis (MCA) (focusing on technical, economic, social and environmental criteria) combined with a cost assessment to ensure feasibility.

By combining expert insights with real-world case studies, this research supports integrated strategies, balancing immediate water quality needs with long-term sustainability, and aligning research findings with practical treatment conditions.

What did this research find?

The research suggests that integrating SP measures with advanced DWT technologies can improve water quality by bridging technological and environmental gaps. Cost estimations show that while DWT technologies require high capital and operational investments, combining them with effective SP measures can reduce long-term costs and environmental impacts.

Key findings highlight critical trade-offs:

- SP measures rely on community buy-in and adaptive governance, with success varying due to social and maintenance challenges.
- DWT technologies ensure regulatory compliance, but involve high costs and energy use, affecting sustainability.

The six case studies demonstrated that site-specific hydrological and socio-economic factors influence the effectiveness of these measures. Tailored solutions proved most effective in meeting water quality regulations. SP measures were more sensitive to the social context than DWT technologies. Public awareness initiatives were identified as essential for driving behavioural change and sustaining water protection efforts.

The study's MCA framework offers policymakers a tool to balance technical, economic and social criteria. However, quantitative validation is needed to strengthen recommendations, emphasising the need for integrated, sustainable approaches.

How can the research findings be used?

This research offers evidence-based insights for investors, policymakers and water resource managers on strategies to improve water quality. The methodology integrates economic, technical, social and environmental considerations to support balanced, long-term decision-making for SP measures and DWT technologies.

By incorporating industry experience from case studies, this study highlights site-specific challenges, empowering stakeholders to implement solutions that protect public health, preserve ecosystems and secure long-term water resource viability. A phased approach is recommended to balance urgent needs with sustainability goals. Integrating research-based and real-life scenarios enables practical, data-driven water quality strategies.

The effectiveness of the selection framework relies on robust raw water monitoring to assess contaminant risks and overall water quality, aligning with the Water Framework Directive and Drinking Water Regulations. Further refinement of cost data and investigation into SP–DWT interactions, such as cost savings, are recommended to enhance decision-making.

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This report is based on research carried out/data from March 2024 to February 2025. More recent data may have become available since the research was completed.

The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Executive Summary

Ensuring the safety and sustainability of drinking water sources is a critical component of modern water resource management. This research project aims to address these challenges by evaluating drinking water source protection (SP) measures (e.g. installing buffer strips, providing additional storage for slurry) and advanced drinking water treatment (DWT) technologies (e.g. adsorption using powdered activated carbon, advanced oxidative processes) through an integrated approach.

While SP measures extend beyond purely technical solutions and can subsequently provide multiple environmental benefits, their effectiveness may vary due to maintenance, siting and continuity challenges. DWT technologies, however, typically offer greater control and reliability, but with more limited benefits. This project aims to bridge this gap by offering a holistic approach to tackling water quality issues, with a focus on emerging contaminants on the European Union (EU) Watch List and in Ireland's 2023 Drinking Water Regulations. Combining a review of national and international practices with robust analytical methodologies, this project seeks to support sustainable decision-making on investments in SP and/or DWT technologies.

Six case studies representing a variety of hydrological and geological contexts in Ireland formed the basis of the analysis. The study examined how site-specific catchment attributes, e.g. local pressures, water quality characteristics and socio-economic factors, influence the effectiveness of SP and DWT strategies. A cornerstone of the project is the application of multi-criteria analysis (MCA) to determine, independently, the most suitable SP and DWT strategies. MCA is a systematic method for comparing measures and technologies against technical, economic, social and environmental criteria. MCA ensures that an objective methodology is utilised to identify the most effective and sustainable solutions, which are tailored to address the challenges posed by the presence of site-specific raw water quality parameters. This approach highlights the strengths and limitations of different measures and provides actionable insights for policymakers, water managers and stakeholders. Multiple benefits, provided in particular by SP measures, are acknowledged and taken into account indirectly, as they are incorporated into the scoring system.

The most suitable SP and DWT strategies were then assessed to determine whether each was either necessary or recommended, supported by a cost assessment and taking into account environmental and social conditions. These assessments evaluate capital and operational expenses, ensuring that selected solutions are financially feasible and environmentally sustainable.

The effectiveness of the proposed selection framework is highly dependent on the implementation of a robust raw water monitoring programme to assess contaminant risks and overall water quality. This aligns with the Water Framework Directive (2000/60/EC) and the Drinking Water Directive (EU 2020/2184), which require Member States to regularly monitor water intended for human consumption to ensure that it is wholesome and clean, and ensures that DWT and SP measures are applied where necessary. Collecting more refined cost data and further investigation into SP and DWT interactions, e.g. potential cost savings, are recommended.

This research project also incorporates a comprehensive review of practices from national and international contexts. By examining case studies and best practices from around the world, it provides a rich repository of knowledge and insights. This global perspective helps identify innovative and proven solutions that can be adapted to local contexts, enhancing the effectiveness of water quality management strategies.

The research suggests that integrating SP measures with advanced DWT technologies may help address the challenge of improving water quality by bridging both technological and environmental gaps. Cost estimations revealed that while advanced treatment technologies often require high capital and operational investments, combining them with effective SP measures can reduce long-term expenses and environmental impacts. Through its dual focus on SP measures and advanced treatment technologies, this project offers a unique contribution to water resource management.

From a practical perspective, this project supports informed decision-making, including actionable recommendations for raw water monitoring and treatment practices, empowering stakeholders to implement solutions that protect public health, preserve ecosystems and ensure the long-term viability of water resources. The research offers insights from Ryan Hanley's in-house industry experts, who have first-hand experience of drinking water treatment at some of the case study sites, offering a balanced perspective and highlighting the specific challenges of each site. By systematically addressing the technical, economic, social and environmental dimensions of water quality challenges, the study provides a roadmap for ensuring safe, sustainable and high-quality drinking water.

1 Introduction

1.1 Project Overview

This research project evaluates drinking water source protection (SP) measures and drinking water treatment (DWT) technologies using an innovative approach through the application of multi-criteria analysis (MCA) as a systematic methodology to compare various strategies against technical, economic, social and environmental criteria in order to select the most suitable SP measure and/or DWT technology to address site-specific source water challenges. The evaluation includes cost assessments of both SP measures and available advanced DWT technologies, ensuring a balanced and pragmatic basis for sustainable and informed decision-making. It not only assesses these technologies, but also conducts a comprehensive review of national and international practices in SP and advanced water treatment. By bridging the gap between the efficacy of SP measures and applicability of DWT technologies, using six case studies, the project offers a holistic approach for addressing source water quality challenges, with a focus on emerging contaminants, in accordance with the European Union (EU) Watch List, and newly regulated contaminants, as part of the EU 2023 Drinking Water Regulations (S.I. No. 99/2023) (Government of Ireland, 2023).

1.1.1 Structure of the report

The structure of this report is designed to provide a clear, logical flow, from the introduction through to the methodology, results and discussion. Chapter 1 sets the scope, objectives and legislative context of the research. The methodology is detailed in Chapter 2, and includes data collection methods, case study selection criteria and a breakdown of evaluation techniques for SP measures and DWT technologies. Chapter 3 presents the findings from the comparative analysis, including insights on SP and DWT costs. Finally, Chapter 4 discusses the results and provides actionable recommendations for integrating SP measures with advanced DWT technologies. A comprehensive literature review covering both SP measures and DWT technologies is available on request to the EPA.

1.1.2 Scope and key limitations

This research utilises six case studies to explore specific local challenges and applies comparative analysis to identify optimal solutions to improving raw water quality, with a focus on drinking water sources. Although the study acknowledges key limitations, it is not strictly bound by them.

The case studies comprise source waters with different chemical characterisation and contaminant levels from varied geographical, hydrological and subsurface geological contexts; however, the limited scopes of the case studies restrict the generalisation of findings to broader settings, as follows:

- This research is based on six case studies that were selected to represent Ireland's diverse hydrological, geological and socio-economic contexts. While this enables focused analysis of site-specific challenges, the limited number of cases may constrain the broader applicability of specific findings to other regions or settings with different conditions. However, the methodology and overall approach employed are broadly applicable and can be adapted to different contexts beyond the current study.
- This research focuses on river and lake waterbodies, as well as groundwater. Marine (coastal and transitional) waterbodies are not included in the scope of this assessment.
- Evaluations assume that conventional treatment systems are operating under ideal conditions, offering limited consideration of existing site-specific operational deficiencies.
- Data pertaining to the case studies were obtained from open sources that are publicly available.
- It is noted that data for some parameters specified in the 2023 Drinking Water Regulations and for Water Framework Directive (WFD) compliance are not currently in the public realm, potentially limiting the comprehensiveness of contaminant assessments.
- Treatment technologies are evaluated as stand-alone processes or combined sequential process elements, but recommendations depend on site-specific adaptability, which may limit scalability.

- For the MCA scoring stage, the level of uncertainty regarding the performance of a specific SP measure or DWT technology for a given criterion at a particular site was not considered in detail, and thus there are potential variability and limitations in that assessment. It is acknowledged, however, that the performance of DWT technologies is generally less uncertain than the efficiency of SP measures, which tend to be more variable.
- Stakeholder behaviour regarding SP measures and the socio-economic impacts of both SP measures and DWT technologies, although considered, are not fully quantified in the analysis.
- Cost assessments are based on generalised scenarios, recognising that specific variables (e.g. catchment size, waterbody type and upstream catchment land use) can influence scalability and feasibility.
- SP measures and DWT technologies are assumed to provide the same levels of certainty of compliance with the requirements of the 2023 Drinking Water Regulations.
- The effect of raw water improvement techniques in avoiding costs in existing water treatment expenditures is not particularly explored in the present study, although it is acknowledged as an important benefit.
- A departure from "good" WFD status does not necessarily reflect a decline in drinking water quality (e.g. due to factors such as fish status). This distinction has been simplified in the context of this research.

1.2 Objectives of the Study

The primary goal of this research project is to provide evidence-based recommendations to support informed decision-making for future investments in SP measures and DWT technologies. Additionally, the research aims to assess current raw water monitoring practices and offer actionable recommendations for their improvement.

The present study aimed to employ actual case studies entailing various raw water configurations. The specific focus was on assessing the overall implications of three independent conditions:

1. implementation of SP measures while assuming conventional treatment is in place;
2. incorporation of supplementary advanced DWT technologies into existing treatment plants assumed to be employing conventional treatment;
3. integration between SP measures and incorporation of supplementary advanced DWT technology into existing treatment plants assumed to be employing conventional treatment.

1.3 Legislative Context (Water Framework Directive and National Regulations)

The legislative framework governing drinking water SP in Ireland is grounded in the EU (Drinking Water) Regulations 2023 (S.I. No. 99 of 2023) (Government of Ireland, 2023), which transposes the recast Drinking Water Directive (EU 2020/2184) into national law. These regulations aim to ensure the delivery of safe drinking water by strengthening protections along the entire supply chain, from source to tap, adopting a risk-based approach to water safety, as recommended by the World Health Organization (WHO, 2023).

To safeguard drinking water sources, the EU has established a comprehensive set of water-related directives, guidelines and policies over the years. The Drinking Water Directive sets minimum quality standards for drinking water in the EU. Additionally, the WFD, the Groundwater Directive, the Nitrates Directive and the Sustainable Use of Pesticides Directive mandates Member States to protect drinking water resources from pollution, ensuring the provision of safe drinking water (Hansen *et al*., 2017; Glavan *et al*., 2019).

Regulation 10 of the 2023 Drinking Water Regulations (S.I. No. 99 of 2023) emphasises the need for comprehensive risk assessment and risk management in drinking water catchments identified by the EPA in each river basin district throughout Ireland.

In this context, water suppliers in Ireland – Uisce Éireann, as the public water supplier, and group water schemes (GWSs) and small private supplies, as private water suppliers – are required to ensure that, under the water treatment regime applied, the treated water will meet the requirements of these regulations.

Water suppliers are required to liaise with the following SP agencies named in Schedule 6 of the 2023 Drinking Water Regulations: Uisce Éireann, the EPA and Geological Survey Ireland (GSI) in respect of groundwater sources, and local authorities, in accordance with their roles and responsibilities under the WFD and the Water Pollution Act. The responsibility of these SP agencies is to delineate and manage drinking water catchments using risk assessment and risk management under Regulation 10(4), for all drinking water abstraction points by 12 July 2027.

Historically, Ireland has been proactive in implementing groundwater protection schemes (DoELG *et al*., 1999), and this experience can help achieve the requirements of S.I. No. 99 of 2023, as derived from the Drinking Water Directive. Additionally, drinking water safety plans and integrated SP plans have been developed by water suppliers such as Uisce Éireann and the National Federation of Group Water Schemes (NFGWS). These plans promote achievable mitigation strategies that are aligned with Ireland's broader catchment management plans under the WFD, addressing risks to both surface and groundwater sources.

The implementation of these legislative requirements is critical for advancing public health protection, ensuring that water suppliers maintain robust monitoring systems and that communities engaged in water catchments contribute to the sustainable management of local water resources. The inclusion of emerging substances in the 2023 Drinking Water Regulations and on the first EU Watch List reflects the evolving nature of water safety management in response to raw water contaminants and emerging environmental pressures.

The WFD requires Member States to establish registers of all areas lying within each river basin district that have been designated as requiring special protection under specific community legislation for the protection of their surface water and groundwater or for the conservation of habitats and species directly depending on water. The WFD also requires that a river basin management plan be established and used to protect and, where necessary, restore waterbodies in order to reach good status and prevent deterioration (Government of Ireland, 2024). In Ireland, this is reflected more recently in the development and implementation of the Water Action Plan 2024. The plan follows an "integrated catchment management" approach and will be further strengthened through the development and use of 46 catchment management work plans in order to locate measures within each catchment.

2 Methodology

To assess the trade-offs between improving raw water quality through SP measures and the additional costs of DWT, a flexible and robust methodology is essential. This study employed a comprehensive methodology to guide decision-makers across six case studies. The case studies were carefully selected to represent diverse water sources and real-world conditions commonly experienced in the region. Selection criteria included source type (surface or groundwater), relative location (upland, lowland, upstream, downstream) and exposure to various pressures such as forestry, agriculture and hydro-morphology. Further details on the selection process are provided in section 2.2.

The analysis comprised a four-stage process conducted for each case study, using an optioneering process involving three levels of screening (1 – pre-screening, 2 – coarse screening, 3 – fine screening) to derive, independently, the most suitable SP and DWT interventions. This optioneering stage was then followed by a fourth stage where a final comparative analysis was undertaken of the best SP and best DWT solutions resulting from the optioneering stage. Moreover, the study considered significant pressures under the WFD, including agriculture, forestry, industry and hydro-morphology, as well as other relevant local pressures on the raw water source.

SP measures and DWT technologies were grouped based on the specific goals identified for each case. This approach was applied independently for SP measures and DWT technologies. Following a coarse and fine screening process, the most promising SP measures and DWT technologies were selected. Finally, a comparative analysis was conducted to identify the optimal solution for each case study.

The methodological steps for comparative analysis are discussed in sections 2.1–2.5.

2.1 Data Collection

The data collected for this study were utilised to support a targeted analysis of SP measures and DWT technologies. Given the research's focus on case study-specific assessments, the reliance on open-access data was strategic and selective, and supports wider replicability. Moreover, it is pertinent to highlight that the nature of this research heavily emphasised a literature-based approach to understand existing pressures and management practices, while using data selectively to fill gaps in case-specific contexts.

Information sources such as EPA Maps, CORINE and GSI provided critical inputs, including catchment characteristics, raw water quality parameters and significant pressure assessments. These datasets were supplemented by findings from existing reports and studies, as well as expert knowledge from in-house specialists, in order to ensure that the analysis was both robust and tailored to the unique needs of each case study. This approach allowed for a balanced combination of theoretical insights and practical data applications, focusing resources on actionable outcomes for each catchment. Catchment size and WFD names and codes were obtained from EPA Maps (https://gis.epa.ie/EPAMaps/). Land use data were obtained from CORINE (https://land.copernicus.eu/en/products/corine-land-cover/clc2018), and are also available online from EPA Maps. Details on the production capacity of the water treatment plants (WTPs) were collected from audit reports available on the EPA website (https://www.epa.ie/) and other publicly available sources. The data regarding SP measures and DWT technologies were developed based on the literature review. Details on the additional data obtained for other stages of the methodology (MCA, costs, etc.) are provided in each specific section, where applicable.

2.1.1 Raw water monitoring

Collecting and analysing raw water data is key to the comparative assessment in this research. This data collection process serves as the cornerstone for informed decision-making. For instance, alkalinity is one of the key parameters monitored in raw water sources, as it has a significant influence on the design and operation of DWT processes. In particular, high alkalinity can pose challenges for membrane-based treatments due to increased scaling potential. It also affects pH stability, which is critical for optimising coagulation, disinfection and other chemical processes.

By systematically gathering and examining open-source data from various sources, the aim was to identify gaps, trends, indicators, significant issues and pressures, thereby enhancing understanding of the available information at hand. Furthermore, this scrutiny of data also pinpoints areas where additional data are needed.

Existing data with regard to raw water monitoring, including open-access data from the EPA, Uisce Éireann and GSI, were gathered from all available sources, as follows:

- EPA Maps (https://gis.epa.ie/EPAMaps/)
- EPA Geoportal (https://gis.epa.ie/GetData/Download)
- EPA Catchments (https://www.catchments.ie/data/)
- GSI Spatial Resources (https://dcenr.maps.arcgis.com/apps/MapSeries/index.html?appid=a30af518e87a4c0ab2fbde2aaac3c228)
- up-to-date WFD chemistry monitoring data at the sub-catchment level (https://www.catchments.ie/catchments-ie-changes-chemistry-data-downloads/)
- EPA Remedial Action List (https://www.epa.ie/our-services/compliance--enforcement/drinking-water/remedial-action-list/).

Details of each open-source data provider are presented in the supplementary material, which is available upon request from the EPA. Geological data pertaining to the catchment area were secured from GSI (https://www.gsi.ie/en-ie/data-and-maps/Pages/default.aspx). Various geological formations, including limestone, sandstone and basalt, were identified within these catchment areas. Furthermore, water chemistry data for the rivers were acquired from the EPA (https://www.catchments.ie/catchments-ie-changes-chemistry-data-downloads/) and other relevant sources.

2.2 Case Studies Selection

The methodology presented in this section was applied to six WTP sites, which were selected due to their representativeness of varied hydrological and geological contexts in Ireland, as well as the familiarity of the specific plants to the project team (see Table 2.1 for a summary description of each case study). The location of all case studies is illustrated in the map in Figure 2.1.

The lake case studies presented sources with very different chemical characterisations, as follows:

- Case study 1. Ballymacravan WTP in West County Clare abstracts water from a small upland lake situated in a rural setting where water has a very low alkalinity characterisation due to the underlying sandstone geology and a high total organic carbon (TOC) level, which varies seasonally. The WTP has undergone a major process upgrade recently; however, sub-optimal treatment of water treatment sludge and liquid residuals persists.
- Case study 2. Luimnagh WTP in County Galway, which abstracts raw water from Ireland's largest lowland lake, namely Lough Corrib, has moderate to high alkalinity raw water, with a consistent, moderate background raw water TOC range. It is situated in a mixed landscape, combining a major downstream urban-influenced tributary entering the source at the base of the lake, with minor upstream urban, but primarily rural, elements. The existing treatment process comprises coagulation, flocculation and clarification (CFC) and filtration, followed by ultraviolet (UV) and chlorination disinfection.

The river systems presented contrasting contexts:

- Case study 3. Liscarton WTP in County Meath abstracts water from the Kells Blackwater river, which has moderate to high alkalinity raw water with a high variability in TOC contaminant load, and is classified as urban due to nearby development.
- Case study 4. Mogeely WTP in East County Cork is positioned north of Mogeely village and abstracts low alkalinity raw water from an infiltration gallery adjacent to the Kiltha river in an agricultural area of northeast Cork. It retains a rural classification, highlighting its natural and less developed surroundings. The Mogeely public water supply (PWS) was included in the EPA's Remedial Action List in July 2018 due to inadequate treatment for *Cryptosporidium*. The pre-existing chlorination disinfection treatment,

Table 2.1. Summary description of the case studies

Case study no.	Source type	Source detail	WFD source name	WFD waterbody code	Approximate catchment size (km^2)	Prominent land use upstream of the abstraction point	WTP	Approximate WTP production capacity (MLD)	Approximate population served	Water supplier
1	Surface water	Upland lake	Lickeen lake	IE_SH_28_85	9	Rural	Ballymacravan WTP	5	14,000	Uisce Éireann
2	Surface water	Lowland lake	Lough Corrib	IE_WE_30_666a	3000	Mixed	Luimnagh WTP	50	40,632	Uisce Éireann
3	Surface water	Low in catchment	Kells Blackwater river	IE_EA_07B011800	690	Urban	Liscarton WTP	15	37,979	Uisce Éireann
4	Surface water	High in catchment	Womanagh/Kiltha river	IE_SW_19W011000	20	Rural	Mogeely WTP	1	2609	Uisce Éireann
5	Groundwater	Karst aquifer	Cong–Robe/Cregduff springs	IE_WE_G_0019	32	Rural	Cregduff GWS	0.7	300	GWS
6	Groundwater	Gravel aquifer	Carndonagh Gravels/ Tirnaleague	IE_NW_G_078	1	Mixed	Carndonagh PWS	1.5	6114	Uisce Éireann

MLD, megalitres per day.

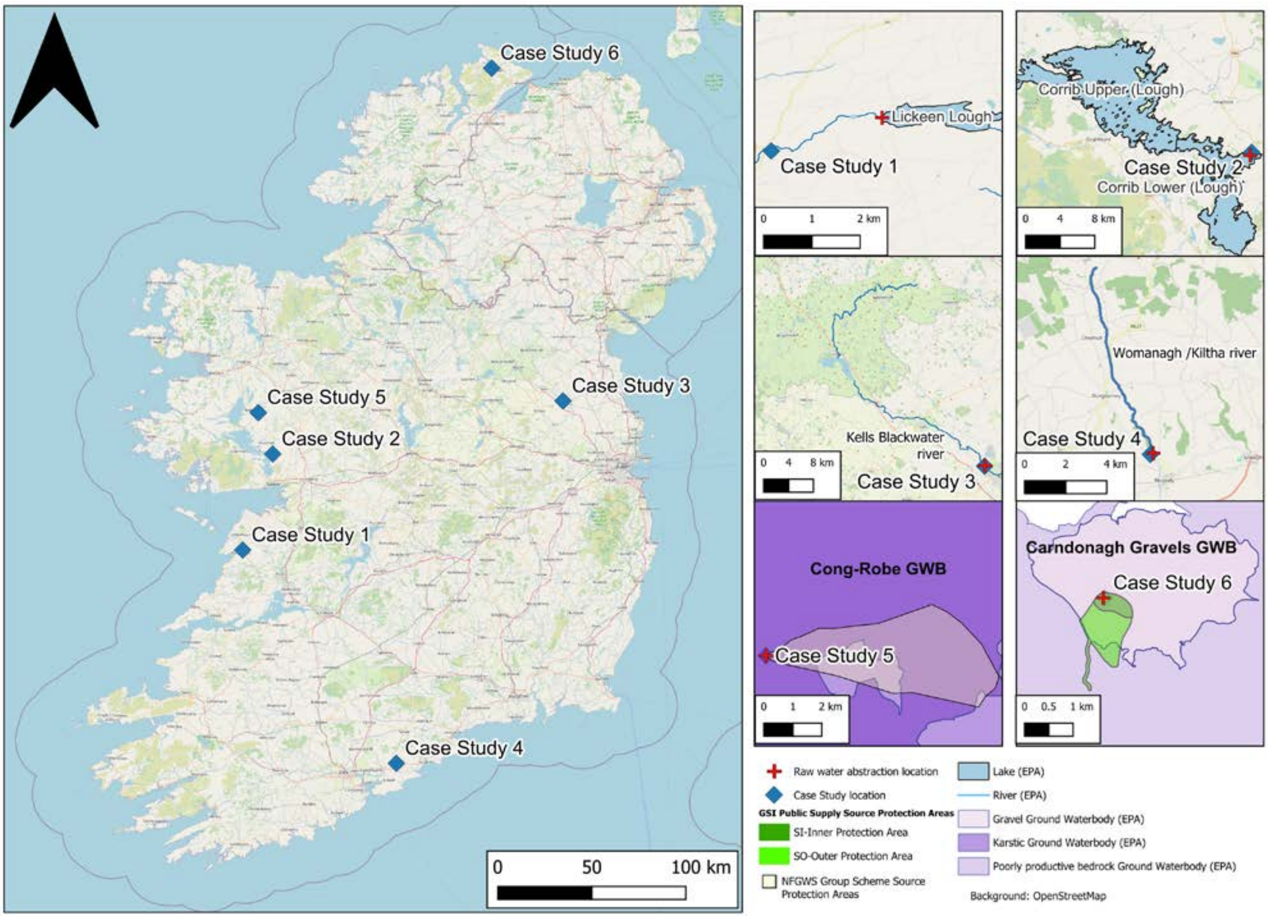

Figure 2.1. Map of the locations of the six case studies. Source: Background map from OpenStreetMap, made available under the Open Database License (https://opendatacommons.org/licenses/odbl/1.0/).

upgraded in 2019 by the addition of dual media pressure filters and a UV disinfection system, validated to the U.S. Environmental Protection Agency dosing protocols, resulted in its removal from the EPA's Remedial Action List.

The groundwater studies explored two aquifer types:

- Case study 5. Cregduff GWS, near Ballinrobe, County Mayo, abstracts high alkalinity raw water from Cregduff spring, which sits in an extremely vulnerable, rural, karstic aquifer with underlying complex, fractured limestone formations, resulting in episodic variations in raw water quality due to surface contamination, which have resulted in periodic treated water quality incidents.
- Case study 6. Carndonagh WTP is supplied by low alkalinity water from a mixed sand and gravel aquifer (Carndonagh Gravels GWB), and is influenced by both rural and urban landscapes. The intake comprises two infiltration galleries, supplemented by two boreholes located 500 m east of the well field. GSI maps the groundwater vulnerability as "extreme" over much of the zone of contribution (ZOC) delineated for Carndonagh PWS due to the thin layer of overlying, unsaturated material. On-site wastewater treatment systems, leaky underground sewers, spreading of fertilisers and diesel/oil spillages contribute to urban risks. The supply was subject to a Boil Water Notice in 2023 due to operational issues with the existing CFC treatment process.

These varied environments underscore the importance of tailoring SP measures and DWT technologies to address the different site-specific treatment challenges posed at each location.

2.3 Methodology Workflow

The comparative evaluation is summarised in Figure 2.2. Details are discussed in sections 2.3–2.5.

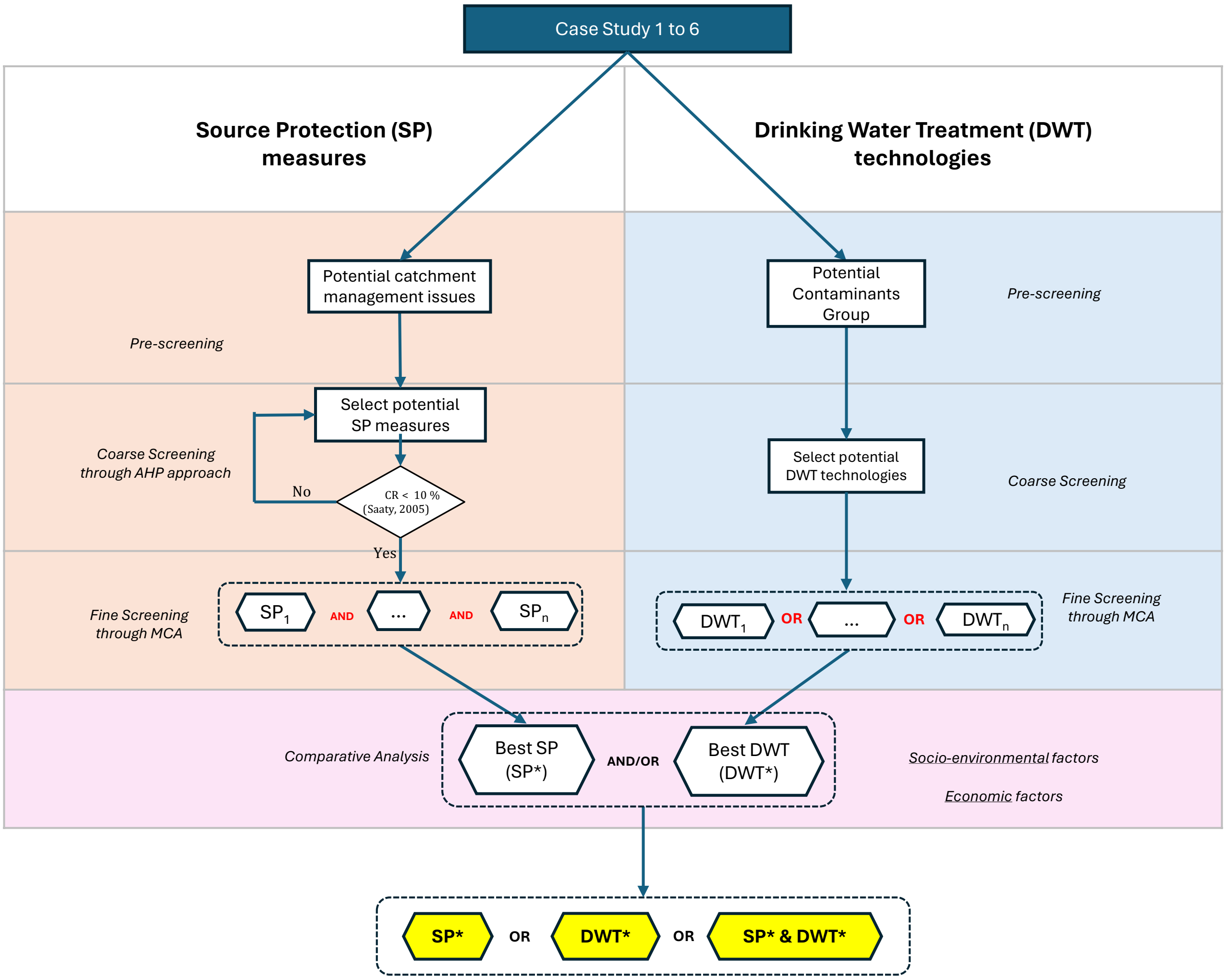

Figure 2.2. Schematic of the comparative analysis for selection of the most suitable SP measure (SP*) and/or most suitable DWT technology (DWT*). AHP, analytic hierarchy process.

2.4 Materials and Methods for Selection of the Most Suitable Source Protection Measures and Drinking Water Treatment Technologies

The optioneering process for the selection of the most suitable SP measures and DWT technologies involves three stages: pre-screening, coarse screening and fine screening. Details of each are provided in the sections that follow.

2.4.1 Pre-screening

2.4.1.1 Source protection – grouping measures

The initial stage is pre-screening, during which relevant SP measures are identified and assigned to each case study based on site-specific pressures and available land use information. This process involves selecting measures from a comprehensive list of SP measures derived from threats identified to the drinking water source within the Irish context, as per NFGWS guidelines (NFGWS, 2012, 2019, 2020) and aligned with the projects mentioned in the literature review, as described in the supplementary material to this research (available upon request from the EPA). Systematically evaluating these measures ensures that the most applicable and effective measures are selected for each case study. See Table 2.2 for the list of SP measures considered in this research.

2.4.1.2 Drinking water treatment technologies – grouping potential contaminants

The DWT technology proposed for the comparative analysis was assumed to be an advanced DWT technology that would be combined with an existing, optimised conventional treatment considered to be already in place at each case study's WTP.

Table 2.2. List of SP measures derived from the literature review

Group code and source water issue	Objective/goal	Code	Measure description
(A) Excessive pathogens and nutrient levels in source water	Implement sustainable nutrient management	A1	Delineate and/or install buffer strips (grass and forest) or create riparian zones in catchment areas upstream or adjacent to source water abstraction for exclusion of slurry or chemical fertilisers
		A2	Construct artificial wetlands, giving multiple ecosystem benefits (i.e. to store floodwaters and maintain surface water flow during dry periods and to provide fish and wildlife habitat)
		A3	Implement riverbank or lake shoreline protection measures
		A4	Provide additional storage for slurry on farmyards
		A5	Encourage crop rotation, rotating crops according to seasonal and soil conditions, and inter-cropping (planting two or more crops in the same field, e.g. combining one crop with nitrogen fixing plants)
		A6	Encourage sustainable land use practices
		A7	Implement regulatory measures (setting standards, technology requirements, pollution caps)
		A8	Identify proximity and connectivity of nutrient sources to hydrological pathways
		A9	Improve knowledge about soils and plants related to factors affecting nutrient delivery rates from land surfaces
(B) Livestock grazing adjacent to source water	Exclude grazing animals from waterbodies	B1	Fence the borehole to exclude farm animals and install stock watering points away from the borehole
		B2	Ensure drinking water borehole abstraction points are constructed to standards, including casing and grouting of sections of the borehole depth where ingress surface contaminated water is identified
		B3	Create off-stream watering points, away from surface waterbodies, to reduce the risk of faecal contamination and to enhance biodiversity. Provide troughs or tanks near animal watering points that are regularly cleaned and refilled
		B4	Use covered facilities for storing waste, feed or fertiliser
		B5	Reduce cattle stock near hillslopes, riverbanks and gully drainage point areas to reduce faecal contamination of downstream abstraction points
		B6	Consider changes in animal feeds to low-phosphorous feeds (e.g. rbST use in lactating dairy cows) to reduce nitrogen and phosphorus excretion
		B7	Restrict access of animals to old, shallow and abandoned spring well heads
		B8	Raise public awareness and provide education/training to farm staff
(C) Forestry plantation impacting water quality	Implement sustainable forest management	C1	Apply fertiliser or manure as per soil requirement at the right time
		C2	Encourage sustainable logging methods to minimise nutrient loading and changes in source water pH levels
		C3	Reforestation along riverbanks and lake shorelines to stabilise soil
		C4	Avoid frequent ground disturbances near source water lakes or rivers
(D) Commercial activity impacting water quality	Promote responsible commercial practices	D2	Incorporate or review land use planning at abstraction catchments
		D3	Ban PBDEs and PFAS in consumer products
		D4	Raise awareness about PFAS sources, exposure routes and potential health impacts to empower consumers to make informed decisions
(E) Poor land management practices	Improve land management practices	E2	Consider range structures (e.g. access roads, fencing, grade stabilisation)
		E3	Precision fertiliser application, irrigation efficiency, contour farming and agroforestry
		E4	Active or passive forest restoration on grazing lands
		E5	Apply land treatments (e.g. brush management, range seeding, edge-of-field treatments)
		E6	Educate farmers on the better use of MCPA to limit formation of rushes in marginal lands adjacent to surface water sources, and to incentivise farmers not to use MCPA to avoid reduction of their annual Single Farm Payment and avoid the yearly spike in pesticide occurrences in abstracted water nationally

Table 2.2. Continued

Group code and source water issue	Objective/goal	Code	Measure description
(F) Run-off issue from artificial surfaces	Prevent run-off from contaminating waterbodies	F1	Review maintenance practices for road and other drainage surfaces and develop a plan to minimise risk of microplastics, metals and polycyclic aromatic hydrocarbons entering source waters
		F2	Construct buffer strips or vegetated swales alongside roadways
		F3	Regularly inspect road signs and maintain impermeable surfaces to minimise erosion and run-off
		F4	Ensure that upgrades of road and other impermeable surfaces follow alignments and incorporate measures to avoid or minimise water source contamination risks (e.g. minimising the scale and size of new road works, including signage with emergency contact number)
		F5	Educate population about the importance of preventing run-off entering source waterbodies
		F6	Implement sustainable infrastructure for stormwater management (e.g. rainwater harvesting, green roofs, green walls, pervious pavements) in large-scale urban environments such as apartment, commercial or industrial buildings, and buildings for institutional use (e.g. schools or hospitals)
(G) Internal farm roadways as part of the nutrient transfer continuum issue	Manage internal farm roadways to minimise nutrient transfer	G1	Adjust roadway slopes to prevent excessive run-off. Contouring roadways can slow down water flow and reduce erosion
		G2	Regularly clean and clear ditches alongside roadways to ensure proper water flow and prevent clogs
		G3	Target areas around the farmyard (100-m radius)
		G4	Address underpasses and waiting areas associated with underpasses
		G5	Address roadway junctions or any location impeding animal movement
		G6	Use gravel or concrete for high-traffic areas to minimise soil erosion and run-off
(H) Groundwater contamination	Reduce nutrients load into groundwater	H1	Increase plant uptake of nutrients to reduce nutrient movement to groundwater
		H2	Grow legumes and other crops in a rotation to reduce the need for fertiliser inputs
		H3	Encourage vegetated cover crops to take up nutrients that would otherwise be lost through surface or drainage water
		H4	Protect areas around sinkholes, which are a common feature in karst areas and allow surface contaminants to flow directly into groundwater
		H5	Seal and permanently close inactive, abandoned or unusable water wells

MCPA, 2-methyl-4-chlorophenoxyacetic acid; PBDEs, polybrominated diphenyl ethers; PFAS, perfluoroalkyl and polyfluoroalkyl substances; rbST, recombinant bovine somatotropin.

The assumption on the configuration of such optimised conventional treatment for each case study was based on the water source type, as follows:

- surface water (case studies 1, 2, 3 and 4): optimised CFC plus filtration followed by chlorination disinfection for bacterial and viral inactivation;
- groundwater (case studies 5 and 6): optimised disinfection.

The selection of the DWT options for each case study was based on the grouping of the most common target contaminants in raw water, considering conventional and emerging contaminants based on (i) the parameters depicted in Tables A to C of Schedule 1 for the 2023 Drinking Water Regulations and (ii) the compounds and substances from the first Watch List, issued by the European Commission in January 2022. This resulted in nine groups of target contaminants (see Table 2.3). The listing for effective treatment technologies that can be used for each group of the nine target contaminants was reviewed and is also presented in Table 2.3.

2.4.2 Coarse screening

2.4.2.1 Source protection – analytic hierarchy process

Following the pre-screening phase, to remove the subjectivity of the decision analysis, the analytic

Table 2.3. Groups of target contaminants considered for the screening of DWT technologies and effective treatment technologies

Group no.	Group of target contaminants	2023 Drinking Water Regulations parameters and 2022 EU Watch List compounds	Treatment technology
1	Low molecular weight synthetic organic carbons and cyanobacterial toxins released by algal blooms	Pesticides, pesticides – total, microcystin-LR, taste and odour	**PAC**, **GAC**, **NF**, **RO**, **AOP**
2	Natural organic matter in source waters comprising suspended solids, colloidal solids as colour and turbidity dissolved organic carbon	Colour, turbidity, TOC (precursors of disinfection by-products: total trihalomethanes and haloacetic acids)	**PAC**, **GAC**, **NF**, BAC, eCFC
3	Heavy metals and metalloids (inorganic)	Antimony, arsenic, boron, cadmium, chromium, copper, lead, mercury, nickel, selenium, uranium	**NF**, **RO**, IXsp_c
4	Industrial chemicals	Polycyclic aromatic, acrylamide, epichlorohydrin, bisphenol A, cyanide	**PAC**, **GAC**, **NF**, **RO**, **AOP**, IRB, SCOx
5	Volatile organic compounds	Benzene, 1,2-dichloroethane, tetrachloroethene, trichloroethene, vinyl chloride, polycyclic aromatic	**GAC**, AS
6	PFAS	PFAS total, sum of PFAS	**GAC**, **NF**, **RO**, IXsp_a
7	Endocrine disrupting compounds	Bisphenol-A, nonylphenol	**GAC**, **NF**, **RO**, **AOP**
8	Pharmaceuticals and personal care products	17-beta-estradiol	**PAC**, **GAC**, **NF**, **RO**, **AOP**
9	Pathogenic protozoa	*Cryptosporidium* or *Giardia*	**UV dose as per specific UV reactor validation certification**

Most frequent technologies used in the subsequent fine screening optioneering stage are marked in bold.
AOP, advanced oxidation process; AS, air stripping; BAC, biological activated carbon pre-ozonation; eCFC, enhanced coagulation CFC process for optimal TOC removal; GAC, granular activated carbon; IRB, ionisation radiation beam; IXsp_a, ion exchange using expensive single-use specialist anionic synthetic resins; IXsp_c, ion exchange process using cationic synthetic resins; NF, nanofiltration; PAC, powdered activated carbon; PFAS, perfluoroalkyl and polyfluoroalkyl substances; RO, reverse osmosis; SCOx, supercritical water oxidation.

hierarchy process was employed in the coarse screening stage to evaluate the suitability of each SP measure. This structured approach not only enhances transparency, but also ensures that decisions are data driven and systematically ranked based on weighted criteria.

The approach was further strengthened by checking the consistency of the SP measures for each case study, fostering a robust evaluation process. The coarse screening was initiated by evaluating the suitability of each measure, considering four key criteria – catchment size, waterbody type, WTP production (design) capacity, and overall landscape upstream of the abstraction point (visual assessment of CORINE (2018) mapping) – allowing for a comprehensive assessment tailored to diverse environmental contexts. The coarse screening process helps distinguish the most suitable and effective solutions at the outset and filters out non-essential details.

The criteria were defined as follows:

- catchment size: small (0–10 km²), medium (10–100 km²), large (> 100 km²);
- waterbody type: river, lake, groundwater;
- overall landscape: urban, rural, mixed;
- WTP production (design) capacity: small (< 1 megalitres per day (MLD)), medium (1–20 MLD), large (> 20 MLD).

The four criteria were applied to the different case studies, where key attributes helped contextualise the analysis. Measures were evaluated only within their own thematic areas (see Table 2.2). Each SP measure was ranked based on its relevance and effectiveness, with the top three measures advancing to the next stage of MCA (fine screening). This structured approach ensures that only the most effective SP measures are considered for further evaluation, enhancing the decision-making process. More details on this approach are presented in the supplementary material, available upon request from the EPA.

2.4.2.2 Drinking water treatment – technologies targeting contaminant groups

A "basket" or "catch-all" approach was employed to ensure that a single treatment technology could effectively address a broad spectrum of contaminants. Following this concept, the coarse screening process for DWT technologies was based on a preference for those technologies that are cited most frequently in Table 2.3, as opposed to single target technologies. This resulted in shortlisting four advanced DWT technologies, as follows: (i) adsorption of organic matter or low molecular weight contaminants, using granular activated carbon (GAC), (ii) adsorption of organic matter or low molecular weight contaminants, using powdered activated carbon (PAC), (iii) contaminant removal using membranes filtration of varying pore size, involving nanofiltration (NF) or reverse osmosis (RO), and (iv) advanced oxidation processes (AOPs).

2.4.3 Fine screening

In the present analysis, MCA was used to evaluate each measure based on four weighted evaluation dimensions: technical, economic, social and environmental. The same weight was assigned to each of the four dimensions (25%). The evaluation dimensions, criteria and the adopted weight for each evaluation dimension are presented in Table 2.4.

Table 2.4. Description of MCA criteria for fine screening of SP measures and DWT technologies

	SP measures selection		DWT technology selection	
Dimension (weight)	**Code**	**Criterion**	**Code**	**Criterion**
Technical (25%)	T1	Design expertise required for implementation	T1	Design expertise required for implementation
	T2	Implementation time	T2	Operational skill level required
	T3	Operational simplicity	T3	Design efficacy regarding case-specific target contaminants
	T4	Technical feasibility	T4	Implementation time
	–	–	T5	Scalability considering existing WTP capacity
Economic (25%)	EC1	Impact on current DWT costs	EC1	Impact on residuals management costs
	EC2	Economic impact on land use agreements and compensation	EC2	Indicative capital expenditures
	EC3	Resilience in relation to economic variations	EC3	Indicative operational expenditure
	EC4	Community economic benefits	EC4	Community economic benefits
Social (25%)	S1	Impact on amenity areas (parks, sport clubs, etc.)	S1	Noise/disturbance due to operation
	S2	Land acquisition	S2	Public health
	S3	Impact on agricultural land use (socially acceptable)	S3	Social perception of drinking water quality improvement
	S4	Improvement of human health and life quality	S4	Contribution towards achieving SDG 6, Target 6.b: "Support and strengthen the participation of local communities in improving water and sanitation management"
	S5	Public awareness, outreach and education for resilient SP	–	–
Environmental (25%)	EN1	Conservation of EU habitats and national natural heritage sites	EN1	Fossil fuel emissions due to transport during operational phase (transport of chemicals or other products)
	EN2	Boosts ecological status	EN2	Risk due to storage of chemicals
	EN3	Fluvial flood mitigation	EN3	Indicative carbon footprint (at WTP implementation phase)
	EN4	Carbon sink management	EN4	Waste management, including opportunities for circularity (operational phase)
	–	–	EN5	Effect on water quality of waters receiving WTP discharges

–, not applicable; SDG, Sustainable Development Goal.

Table 2.5. Scoring system of MCA – fine screening

	Description		
	Favourable	Neutral	Unfavourable
Score	1	0	–1

Each criterion then received a score based on a three-option system, as presented in Table 2.5.

2.4.3.1 Source protection

Following the coarse screening process presented in section 2.4.2, three measures emerged as the top candidates for further scrutiny in the MCA process. The subjectivity usually associated with the MCA process was deemed to have been already addressed in the previous step (coarse screening).

The final selection was based on average weighted total score in all four dimensions. The weighted average total score for each SP measure was then normalised according to all other measures within each respective group, and the highest scoring alternatives were selected.

In the case of SP measures, the best-scoring measure in each group of measures was selected and was brought forward to the comparative analysis step (see section 2.5) as a combined solution.

2.4.3.2 Drinking water treatment

The fine screening for DWT technologies followed a similar approach to that presented in section 2.4.3.1 for SP measures, the difference being that for DWT technologies only the best-scoring technology was chosen. This is due to the fact that implementing an advanced DWT solution in general entails higher costs than combining SP measures. See Table 2.4 for the criteria considered. The criteria were scored according to the particularities of each case study.

Constraints

In this research, cost and operation were considered key elements when assessing the efficacy and suitability of advanced DWT technologies to be integrated into an existing WTP. Consequently, the final selection was based on the final MCA score of each DWT option combined with the application of operational and financial constraints associated with the technologies and the case studies where they were considered. An internal consultation stage was conducted involving two industry experts from Ryan Hanley, selected for their significant knowledge of and experience in DWT, as well as their familiarity with several of the case study sites. Specifically, Maebh Grace and Michael Joyce provided expert insights regarding the practical application of treatment technologies. While this consultation provided valuable input, it is acknowledged that relying on only two experts may limit the diversity and representativeness of perspectives, which is a constraint of the study. To address this limitation, validation through the comprehensive literature review undertaken for this study was utilised. The consultation indicated that some of the treatment technologies may not be appropriate for specific water source types and production capacities, as follows:

- **Technical and financial constraints for treatment using GAC.** May not be appropriate for plant capacities > 1 MLD due to financial implications (high capital and replacement costs) or for treatment of raw water with frequent organic contamination events, e.g. some karstic aquifers (high replacement costs).
  - Case studies where treatment using GAC may not be appropriate: 1, 2, 3, 5 and 6.
- **Operational and financial constraints for treatment using PAC.** May not be appropriate for treatment of groundwater, as groundwater abstraction tends to involve smaller volumes (< 1.5 MLD) due to operational constraints, such as handling and precise dosing difficulties, risks of PAC mixing systems clogging due to the hydrophilic nature of PAC, and increased maintenance requirements yielding higher capital and operational costs.
  - Case studies where treatment using PAC may not be suitable: 5 and 6.
- **Financial constraints for treatment using membrane filtration such as NF or RO.** Not appropriate for WTP capacities > 2.5 MLD due to financial implications (capital, operational and replacement costs), particularly when treating high alkalinity raw waters.
  - Case studies where treatment using membrane filtration such as NF or RO may not be suitable: 1, 2, 3 and 5.

The above constraints were considered during the final stage of the screening process, only after the MCA scoring was conducted, to allow scoring across a larger range of treatments.

In conclusion, the most suitable DWT (DWT*) selected for the comparative analysis stage was the one with the highest MCA score, chosen from options that had no significant financial or operational constraints, such as those considered above.

2.5 Comparative Analysis

In order to compare raw water quality improvement linked to the implementation of SP measures and/or DWT technologies, a decision flow chart was proposed, as presented in Figure 2.3.

The final choice was based upon defining circumstances in which each raw water improvement strategy (DWT* and most suitable SP measure (SP*)) was either (i) a necessary intervention or (ii) a recommended intervention. The socio-environmental and economic circumstances considered for each of these two instances are further outlined in sections 2.5.1 and 2.5.2. The conditions for integrating both approaches (DWT* and SP*) are further discussed in section 2.5.3.

Insights on co-benefits and risks are further discussed in Chapter 4.

2.5.1 Necessary intervention (first instance)

In the first instance, the circumstances where DWT* and/or SP* are deemed to be absolutely necessary are evaluated. This is considered to be the case in two situations, as follows:

- Where there is a risk of failure in regulatory compliance, DWT* is deemed an absolute necessity. From a broader perspective, the risk of regulatory non-compliance is considered as a consequence of the land use setting and the presence of anthropogenic impact over the catchment for the source water abstraction point.
- Where there is an overarching goal of achieving a higher WFD status for the waterbody under consideration, SP* is deemed an absolute necessity. For this purpose, data on the status assigned to the source waterbody were collected from the latest WFD cycle (2016–2021). Other prominent information for the case study may also be used if it indicates an environmental gap to be addressed in the catchment.

2.5.2 Recommended intervention (second instance)

In the second instance of the evaluation, SP* or DWT* has already been tested for the "necessity" decision and the remaining raw water improvement strategy/strategies can be tested for a "recommendation" decision. Essentially, where there is significant social resistance to the implementation and/or operation of the proposed SP*, then SP* is not recommended and DWT* is otherwise suggested. The identification of such social aspects was based on a qualitative analysis and insights from the MCA scores for SP, namely criteria S1 (impact on amenity areas), S2 (land acquisition) and S3 (impact on agricultural land use). Although these scores do not provide an exact quantification of social resistance towards an SP measure, they are considered a relevant indicator, which is deemed sufficient for the proposed analysis. Where available, stakeholder engagement activities, for instance workshops and surveys with residents in the catchment area of application, are encouraged to provide more refined results.

As well as socio-environmental factors, economic attributes were used in the second instance of the evaluation, i.e. for testing when SP* and DWT* are "recommended". For comparative purposes, costs were estimated as indicative total expenditures (TOTEX) for both the implementation (indicative capital expenditures) and operation (indicative operational expenditures) of the strategy (SP* and DWT*).

Several institutions were contacted regarding costs for the SP measures (NFGWS, Uisce Éireann, the Agricultural Sustainability Support and Advisory Programme). Costs for the DWT technologies were obtained through market research of suppliers in Ireland and the UK. An amortisation based on a 20-year lifespan and 5% compound interest was utilised to determine total expenditures of the DWT technology based on a 20-year lifespan ($TOTEX_{DWT,20}$) and total expenditures of the SP measure water treatment based on a 20-year lifespan ($TOTEX_{SP,20}$). Replacement costs were estimated as a percentage of the indicative capital expenditures applied at specific intervals (every 3 years for DWT* and on a

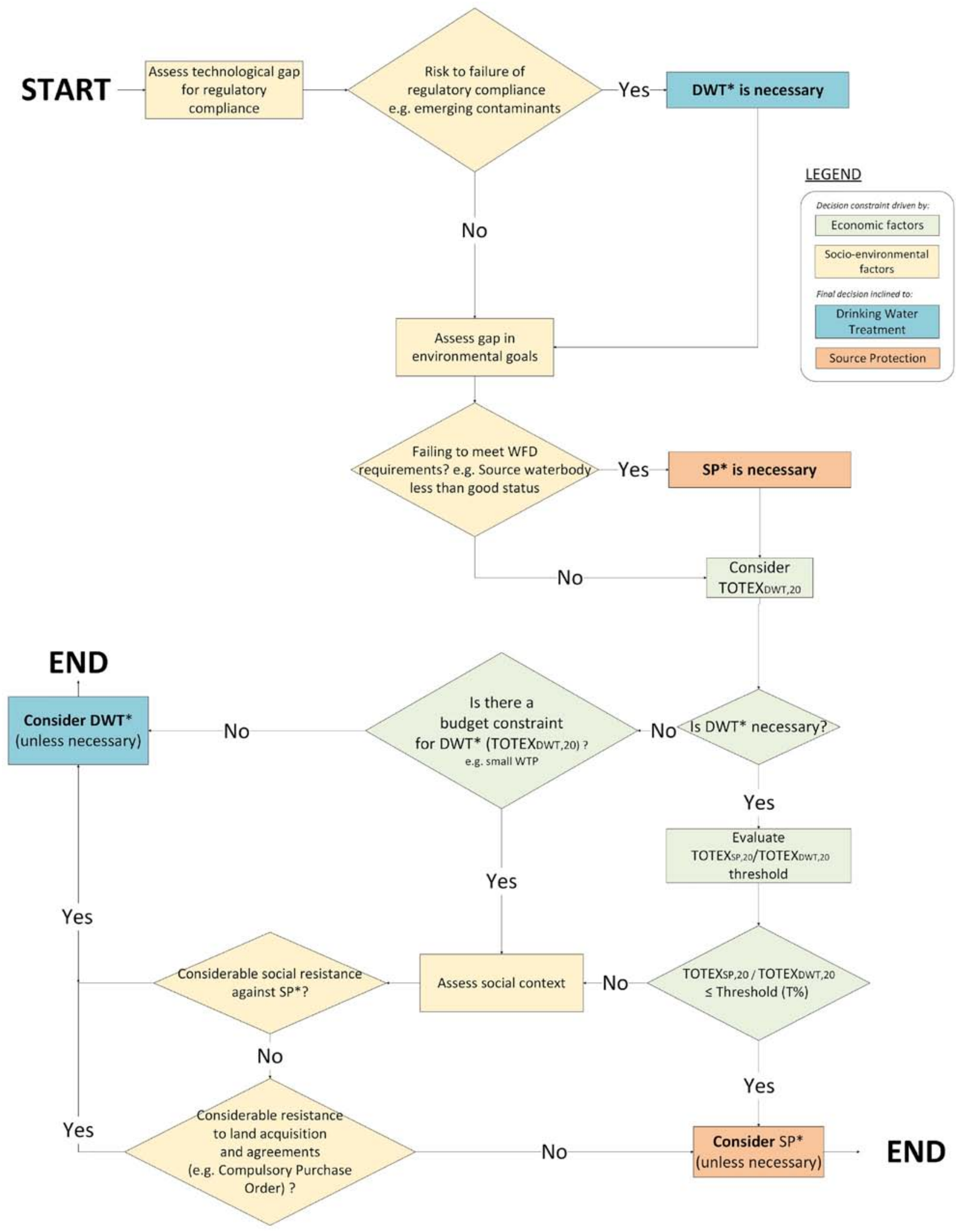

Figure 2.3. Decision flow chart for selecting water quality improvement strategy under comparative analysis. $TOTEX_{DWT,20}$, total expenditures of the DWT technology based on a 20-year lifespan; $TOTEX_{SP,20}$ – total expenditures of the SP measure water treatment based on a 20-year lifespan.

case-by-case basis for SP*). The information collected accounted for catchment size, WTP production capacity and associated elements of each specific proposed strategy (fencing costs per metre for SP A1, chemical costs for PAC, etc.). Indirect costs, e.g. costs for sludge treatment in the case of DWT, were not considered due to data and time constraints inherent to the research project.

2.5.3 Integrated approach

Where financial capability is available, integrating both DWT* and SP* strategies is recommended, given their combined benefits. This study found that integration of strategies should be considered when any of the following three conditions apply:

- **$TOTEX_{SP,20}/TOTEX_{DWT,20} \leq$ threshold (T%).** In this case, when the investments in SP* are equal or less than "T%" of the investment in DWT*, then SP* could be integrated into the selected DWT*. The threshold for consideration of $TOTEX_{SP,20}$ in relation to $TOTEX_{DWT,20}$ (T%) is a dummy variable. Framing it as a flexible parameter ("T%") enhances the framework's adaptability for future applications, as it may be reconsidered depending on the decision-maker's preferences and based on financial capabilities, incentives and subsidies, etc. In the case of the present study, a T% value of 20% was initially selected as a pragmatic threshold to enable comparative analysis and decision-making within the constraints of this project. It also served as a starting point to standardise comparisons between SP* and DWT* costs.
- **Budget availability.** Where the WTP has a significantly large capacity, budget constraints are usually minimal. Thus, the selected DWT (DWT*) could be combined with the selected SP (SP*).
- **Social acceptance.** In this case, DWT* is recommended as an additional intervention to ensure that drinking water quality meets the required standards.

3 Results

The screening results of DWT* and SP* are presented in section 3.1. Further discussion on the strategy selection derived from the comparative analysis of DWT* and SP* is presented in section 3.2.

3.1 DWT* and SP* Screening Results

This study sought to provide evidence-based recommendations for prioritising investments in drinking water SP measures and DWT technologies in the Irish context. Over the course of this research project, a comprehensive analysis was conducted using the MCA framework based on extensive national and international literature and open-source data.

Particularly for the selection of DWT*, practical insights from Ryan Hanley in-house experts revealed site-specific challenges and constraints that warranted a complementary approach. To ensure decision-makers have a balanced perspective, two scenarios (Sc1 and Sc2) have been developed for the selection of DWT*:

- **Sc1 – research-based scenario (MCA approach).** This scenario reflects the outcomes of a systematic MCA process, i.e. fine screening, as discussed in section 2.4.3, which prioritises SP measures and DWT technologies based on theoretical evaluations of environmental, technical, economic and social considerations. The results for Sc1 are presented in section 3.1.1.
- **Sc2 – practical/real-life scenario.** This scenario integrates field-specific expertise and acknowledges the operational realities and constraints observed in the case study sites. It provides pragmatic adjustments to the research-based recommendations, ensuring feasibility and effectiveness in practice. The outcomes from the analysis of Sc2 are presented in section 3.1.2.

3.1.1 Sc1: research-based scenario

Based on the methodology presented in Chapter 2, the most adequate strategies for improving drinking water quality based on SP measures (SP*) and DWT technologies (DWT* – research scenario) were obtained for each case study, as presented in Table 3.1, using the SP measures listed in Table 2.2 and the DWT options listed in section 2.4.2.2.

3.1.2 Sc2: practical/real-life scenario

The results for DWT and the respective recommendations ("recommended", "necessary", etc.) at each case study are presented in the last column of Table 3.1. The differences between the results shown in the last two columns of Table 3.1 highlight the need to evaluate solutions in the short term versus the long term. It is noted that the real-life scenario addresses immediate issues and challenges, whereas the research-based scenario provides a long-term strategic investment approach, allowing for potential future pressures on the WTP (e.g. increase in water demand, emerging contaminants load) to be taken into consideration. Decision-makers should adopt a phased approach, balancing urgent needs with the goal of achieving sustainable water quality in Ireland. In addition, extended periods are usually required to implement SP measures, and measuring their effectiveness may be challenging.

3.2 Comparative Analysis of SP* and DWT* for the Research-based Scenario (Sc1)

The assessment shown in Table 3.2 is the result of the decision flow chart illustrated in Figure 2.3 applied to the strategies presented in Table 3.1.

In the case of catchments for water sources that are an upland lake (case study 1), upstream settlements (case study 4) or a large lowland lake with upstream rural settings (case study 2), the risk of the presence of a significant concentration of emerging contaminants is considered low, and thus a technological gap in water treatment is unlikely. In this sense, prioritising investments in SP would be a more cost-efficient option than upgrading or expanding WTP infrastructure, i.e. SP* is recommended only. Conversely, in cases where the drinking water source catchment is downstream or there are nearby settlements (case study 3), there is potential for

Table 3.1. Screening results of most suitable raw water improvement using SP measures (SP*) and DWT technologies (DWT*) applied to case studies 1–6

Case study	Source type	Potential issues identified in raw water quality[a]	Source detail	SP*	DWT* – Sc1	DWT* – Sc2
1	Surface water	C, E	Upland lake	C4: Avoid ground disturbance near source E6: Educate farmers on the better use of MCPA in marginal land within the source catchment	PAC	Use of PAC and sludge/liquid residual treatment recommended
2	Surface water	A, B, D	Lowland lake	A4: Provide additional storage for slurry on farmyards close to source B8: Raise public awareness and provide education/training on exclusion of farm animals near source waters E6: Educate farmers on the better use of MCPA in marginal land within the source catchment	PAC	No major additional treatment deemed necessary
3	Surface water	A, D, F	River, low in catchment	A4: Provide additional storage for slurry on farmyards D4: Raise awareness about PFAS discharges within catchment F5: Educate population about run-off prevention	PAC	No major additional treatment necessary subsequent to recent upgrade
4	Surface water	A, C	River, high in catchment	A1: Install buffer strips with fencing C4: Avoid frequent ground disturbances near source within the upstream catchment	PAC	Validated UV disinfection. May not be necessary due to recent process upgrade
5	Groundwater	A, E, H	Spring, karst aquifer	A4: Provide additional storage for slurry on farmyards within the ZOC E6: Improve land management practices within the ZOC H4: Protect areas around sinkholes and karst features in the ZOC	AOP	Upgraded CFC plus validated UV disinfection necessary; alternatively, connection to nearby PWS, as proposed
6	Groundwater	A, D, H	Borehole and infiltration gallery, gravel aquifer	A4: Provide additional storage for slurry on farmyards within the ZOC D4: Raise awareness about PFAS discharges within the ZOC H3: Encourage vegetated catch/cover crops in the ZOC	AOP	Upgraded CFC and consider membrane filtration if low molecular weight contaminants exist: necessary

[a]A, excessive pathogens and nutrient levels in source water; B, livestock grazing adjacent to source water; C, forestry plantation impacting water quality; D, commercial activity impacting water quality; E, poor agriculture/land management; F, run-off issue from artificial surfaces; H, groundwater contamination.
MCPA, 2-methyl-4-chlorophenoxyacetic acid; PFAS, perfluoroalkyl and polyfluoroalkyl substances.

Table 3.2. Integration of water quality improvement strategies applied across case studies 1–6

Case study	Waterbody status gap	Technological gap	$TOTEX_{SP,20}$/ $TOTEX_{DWT,20}$	Budget constraint	SP*	DWT*
1 Ballymacraven	Yes ("bad")	No	15%	–	Necessary	Recommended
2 Luimnagh	No	No (lowland rural setting, upgradient to the lake abstraction point)	2%	Minimal (large WTP)	Recommended	Recommended
3 Liscarton	Yes ("poor")	Yes (urban setting)	25%	–	Necessary	Necessary
4 Mogeely	Yes ("moderate")	No	38%	Likely (small WTP)	Necessary	Conditional – if resistance to SP arises, DWT* is recommended
5 Cregduff GWS	Yes, indirectly (susceptible to seasonally frequent raw water quality variations of long duration)	Yes (inadequate treatment technology to address raw water quality events)	21%	Likely (small WTP)	Necessary within the ZOC	Necessary
6 Carndonagh	No	Yes (mixed setting)	11%	–	Recommended within the ZOC	Necessary

significant nutrient run-off (nitrates and phosphates) and risk of presence of emerging contaminants due to urban run-off and industrial and domestic discharges. This can lead to algal blooms, degraded water quality and increased operational costs at the WTP to meet drinking water quality standards. In these scenarios, the comparative assessment suggests that investments in upgrading WTP infrastructure to advanced treatment technology (DWT*) would be necessary.

An environmental gap linked to the WFD river waterbody status has been identified for case studies 1 and 4, given the raw water source's status being mapped as less than "good" during the most recent assessment period (2016–2021). This prompts concerns with regard to the WFD and indicates that improvements in waterbody quality should be taken as priority, i.e. SP* would be necessary. For case study 3 specifically, the river waterbody is mapped as "poor" status, and thus investing in both DWT* and SP* measures should take priority in this instance. However, it is acknowledged that this is a simplification considered in this research, since a departure from "good" WFD waterbody status may not necessarily be directly correlated to drinking water quality (e.g. "poor" WFD status may be related to fish status).

In the case of groundwater sources, the level of interaction between the groundwater system and surface water system is critical for strategy selection. Where water was sourced from a karstic aquifer in a rural setting, such as in case study 5, a likely technological gap was identified. This is due to the porous limestone formation in karstic aquifers being highly vulnerable to contamination due to rapid water flow into the karst fissures carrying surface contamination into the groundwater, with minimal natural filtration through the shallow depth of topsoil and subsoil depths in such areas. Similarly, an environmental gap was also identified for case study 5 due to the karstic nature of the aquifer of the raw water source. Even though the underlying groundwater body is mapped as "good" status (2016–2021), it is "at risk" (third cycle) of not achieving WFD objectives, and the aquifer is susceptible to seasonally frequent raw water quality variations of long duration. In that case, the combination of both SP* and DWT* should be implemented. Note that this evaluation does not factor in aspects such as borehole construction and contaminant travel times, which may be derived from GSI SP zones, and consideration should be given to these aspects where applicable.

Sources based on mixed gravel aquifers with rural and urban influences, such as in case study 6, are susceptible to diffuse pollution from agricultural activities in rural areas and point-source pollution from urban areas. In these cases, treatment technologies are essential to ensure safe drinking water, and therefore the implementation of DWT* is considered a necessary intervention. Due to the absence of environmental gaps in that case, SP* within the ZOC is recommended.

The results shown in Table 3.2 and the arising discussions can be extended to other case studies with similar raw water configurations.

4 Outcomes and Recommendations

This study sought to provide evidence-based recommendations for prioritising investments in drinking water SP measures and DWT technologies in the Irish context and with a focus on emerging contaminants, as per the EU Watch List, and the newly regulated contaminants, as part of the Irish Drinking Water Regulations. The evaluation of SP measures and DWT technologies identified critical interdependencies between source management and treatment processes. Key outcomes emphasise the importance of targeted, site-specific interventions for surface and groundwater sources to enhance water quality, meet regulatory standards and promote sustainability. The recommendations offer a roadmap for implementing context-specific measures and technologies to achieve these goals.

Comprehensive analysis was conducted using an MCA framework based on extensive national and international literature and open-source data. However, practical insights from Ryan Hanley in-house experts revealed site-specific challenges and constraints that warranted a complementary approach. To ensure decision-makers have a balanced perspective, two scenarios were developed: Sc1, a research-based scenario (MCA approach), and Sc2, a practical/real-life scenario.

While a real-life scenario can address immediate issues and challenges, the research-based scenario provides a long-term strategic investment approach, allowing for potential future pressures on the WTP (e.g. increase in water demand, emerging contaminants load) to be acknowledged. Decision-makers should adopt a phased approach, balancing urgent needs with the goal of achieving sustainable water quality in Ireland. The integration of these two scenarios can enable actionable strategies for stakeholders through more realistic calibration of the tool upon considering key operational conditions of the WTP under consideration, as well as recent and/or planned upgrades.

The six case studies analysed in this research provide valuable insights into the applicability of the proposed comparative methodology across different catchments in Ireland. While these case studies represent diverse hydrological, geological and socio-economic conditions, their replicability depends on the similarity of environmental and policy contexts in other regions. The selected locations reflect key characteristics of Irish catchments, allowing for broader generalisation, but site-specific variations must be considered when extending findings to other areas. Future applications should assess local watershed conditions, governance frameworks and stakeholder engagement to ensure that the approach remains adaptable and effective.

The performance of the strategy selection approach proposed in this research is highly dependent on the implementation of a robust raw water monitoring programme for the waterbody under consideration. Specifically, monitoring raw water is crucial for assessing the risk of emerging contaminants and also for establishing the overall quality of the water source. This aligns with the objectives of the WFD and the Drinking Water Directive, while being critical for identifying conditions where DWT technologies and SP measures are strictly necessary.

More refined data relating to the capital and operational costs of SP measures and DWT technologies are required to improve the reliability of the results. Further investigations on the co-interactions between SP measures and DWT technologies (e.g. treatment costs reduction) are recommended.

The following items highlight the key outcomes identified in the study.

Key contaminant groups identified

- **Surface water sources.** Vulnerable to agricultural run-off, including seasonal application of pesticides such as MCPA (2-methyl-4-chlorophenoxyacetic acid) and persistent emerging anthropogenic organic contaminants such as perfluoroalkyl and polyfluoroalkyl substances (PFAS), where there is a risk of municipal or industrial wastewater discharges entering the source catchment upstream of abstraction. Compliance with PFAS parametric values – and corresponding monitoring – will become mandatory for all water supplies from 11 January 2026.

- **Groundwater sources.** Primarily impacted by poor well/well head construction and poor land management practices within zones of contribution, especially in areas underlaid by karstified limestone, including improper slurry storage and slurry spreading near sinkholes or other infiltration areas, leading to contamination risks.

Source protection measures selection

- **Surface water.** Focused on reducing agricultural run-off through the implementation of buffer strips, riparian fencing and public education. Mitigation measures aim to prevent erosion, reduce direct animal access to water sources and limit nutrient and pesticide inflow.
- **Groundwater.** Targeted at improving land management practices, including protecting sensitive groundwater zones of contribution and adjacent to high vulnerability areas, such as sinkholes and high infiltration karstified zones. Emphasis should be placed on reducing contamination risks from agrochemicals and slurry spreading through farmer education and enhanced regulatory oversight.

DWT technology selection

- **PAC.** Selected for its ability, using the adsorptive properties of activated carbon, to remove small molecular weight contaminants such as (i) pesticides, algal toxins and taste and odour compounds, and (ii) chemically persistent PFAS from surface waters. The dosing of PAC in response to identified seasonal risks such as pesticide spreading and algal blooms makes it suitable for use on lake sources, where such risks are identified seasonally, and different PACs have been trialled to identify the grade to effect optimal removal of the contaminant in question.
- **GAC.** Treatment with GAC filtration is not recommended for variable quality sources, such as raw water abstracted from karst groundwater sources, as GAC is readily exhausted while adsorbing moderate TOC levels. Unless the adsorption capacity of GAC filters is constantly monitored to ensure the availability of its residual capacity, it may not be able to deal with the amplitude or duration of the frequent organic contamination events that commonly occur in karst limestone sources due to water table level variation. However, a successful application of GAC was demonstrated in one project, which involved treatment of small sources on remote islands off the coast of Ireland to reduce high TOC levels where conventional CFC chemical dosing and treatment was difficult to maintain. In this case, GAC filtration containers were employed on a plug and play basis, with spare available containers when the previous one was exhausted.
- **AOP.** May be suitable for water abstracted from surface water gravel aquifers, where the risk of emerging persistent bioaccumulating organic pollutants such as PBDEs is identified and requires advanced oxidative degradation. As PFAS compounds are persistent because of the very strong carbon–fluor bonds in their chemical structure, more information would be needed before recommending AOP use. Additionally, more information should be sought in relation to the transform compound(s) formed after use of AOP methods as a treatment stage.
- **Treatment using UV disinfection.** While this specific treatment was not evaluated in the research, it is worth noting that the availability of different-sized UV reactors with validation certification makes it an appropriate supplementary process where source water testing establishes the risk of protozoal pathogens.

Measures effectiveness

- The four-stage analysis process (pre-screening, coarse screening, fine screening and comparative analysis) identified site-specific SP measures and appropriate DWT technologies for six case studies.
- The integration of MCA and an analytic hierarchy process revealed how factors such as catchment size, waterbody type, overall land use and WTP production design capacity influenced the potential effectiveness of specific SP measures.
- Measures like buffer strips, reforestation along riverbanks and sustainable nutrient management practices were assessed as suitable within specific catchments.

- For DWT, advanced technologies such as AOP and PAC were identified as being critical in addressing, over a short period, critical raw water quality issues and emerging contaminants like pesticides, PFAS and trihalomethanes.

Economic and social implications

- SP measures are usually more sensitive to the social context of where it is proposed that they be implemented. Public awareness initiatives can lead to benefits by encouraging behavioural changes to support water protection, enhancing public participation and acceptance. However, as reflected in some of the criteria under the social dimension for the SP MCA, the implementation of certain SP measures is subject to the acceptance of the community in the catchment under consideration. This is significantly different in the case of DWT technologies, which, given their localised application, are, in general, less susceptible to social acceptance than SP measures.
- The evaluation of indicative capital and operational costs for each strategy highlighted the importance of ensuring compatibility with the investor's financial capability. It is also recommended that the influence of political and economic circumstances is considered.

Environmental and technical benefits

- Environmental evaluations underscored the value of SP measures in enhancing ecological status, conserving habitats and contributing to carbon sink management. For instance, measures like reforestation along riverbanks and sustainable logging practices positively impacted biodiversity and reduced sedimentation.
- Technical evaluations highlighted the importance of simplicity and feasibility in the implementation of measures. Measures requiring advanced design expertise or long implementation timelines, such as large-scale wetland construction, were less favoured for plants in smaller catchment/ ZOC areas and their relative proportion of the restoration areas.

General observations

- **Surface water sources.** Across upland and lowland areas, SP measures such as public education and land management improvements consistently proved to be potentially suitable.
- **Groundwater sources.** Required more customised solutions tailored to local risks (e.g. sinkhole protection, aquifer-specific regulations). This study demonstrates that integrating SP measures with DWT technologies offers a robust framework for improving water quality and achieving sustainability goals. Tailored interventions, informed by catchment characteristics and contaminant profiles, are critical for addressing diverse water challenges while balancing economic, social and environmental priorities.

Taking a broader perspective, SP measures should not be viewed in isolation but rather considered within the broader context of measures outlined in local sub-basin management plans. Their effectiveness and adoption are significantly enhanced when aligned with complementary actions at the local level. It should also be acknowledged that, in addition to multiple ecological benefits, SP measures may contribute to meeting other statutory objectives under the wider WFD umbrella. Importantly, the enforcement of existing legislation – such as land use regulations or discharge controls – also constitutes a critical measure that can support and enhance the impact of SP efforts. As a result, framing SP measures in an integrated manner with DWT technologies can act as a strong force multiplier, reinforcing both local and national water quality goals.

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Abbreviations

AOP	Advanced oxidation process
CFC	Coagulation, flocculation and clarification
DWT	Drinking water treatment
DWT*	Most suitable drinking water treatment
EU	European Union
GAC	Granular activated carbon
GSI	Geological Survey Ireland
GWS	Group water scheme
MCA	Multi-criteria analysis
MLD	Megalitres per day
NF	Nanofiltration
NFGWS	National Federation of Group Water Schemes
PAC	Powdered activated carbon
PFAS	Perfluoroalkyl and polyfluoroalkyl substances
PWS	Public water supply
RO	Reverse osmosis
Sc1	Scenario 1
Sc2	Scenario 2
SP	Source protection
SP*	Most suitable source protection measure
TOC	Total organic carbon
TOTEX	Total expenditures
$\mathbf{TOTEX_{DWT,20}}$	Total expenditures of the drinking water treatment technology based on a 20-year lifespan
$\mathbf{TOTEX_{SP,20}}$	Total expenditures of the source protection measure water treatment based on a 20-year lifespan
UV	Ultraviolet
WFD	Water Framework Directive
WTP	Water treatment plant
ZOC	Zone of contribution

An Ghníomhaireacht Um Chaomhnú Comhshaoil

Tá an GCC freagrach as an gcomhshaol a chosaint agus a fheabhsú, mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ar thionchar díobhálach na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialáil: Rialáil agus córais chomhlíonta comhshaoil éifeachtacha a chur i bhfeidhm, chun dea-thorthaí comhshaoil a bhaint amach agus díriú orthu siúd nach mbíonn ag cloí leo.

Eolas: Sonraí, eolas agus measúnú ardchaighdeáin, spriocdhírithe agus tráthúil a chur ar fáil i leith an chomhshaoil chun bonn eolais a chur faoin gcinnteoireacht.

Abhcóideacht: Ag obair le daoine eile ar son timpeallachta glaine, táirgiúla agus dea-chosanta agus ar son cleachtas inbhuanaithe i dtaobh an chomhshaoil.

I measc ár gcuid freagrachtaí tá:

Ceadúnú

> Gníomhaíochtaí tionscail, dramhaíola agus stórála peitril ar scála mór;
> Sceitheadh fuíolluisce uirbigh;
> Úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe;
> Foinsí radaíochta ianúcháin;
> Astaíochtaí gás ceaptha teasa ó thionscal agus ón eitlíocht trí Scéim an AE um Thrádáil Astaíochtaí.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

> Iniúchadh agus cigireacht ar shaoráidí a bhfuil ceadúnas acu ón GCC;
> Cur i bhfeidhm an dea-chleachtais a stiúradh i ngníomhaíochtaí agus i saoráidí rialáilte;
> Maoirseacht a dhéanamh ar fhreagrachtaí an údaráis áitiúil as cosaint an chomhshaoil;
> Caighdeán an uisce óil phoiblí a rialáil agus údaruithe um sceitheadh fuíolluisce uirbigh a fhorfheidhmiú
> Caighdeán an uisce óil phoiblí agus phríobháidigh a mheasúnú agus tuairisciú air;
> Comhordú a dhéanamh ar líonra d'eagraíochtaí seirbhíse poiblí chun tacú le gníomhú i gcoinne coireachta comhshaoil;
> An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Dramhaíola agus Ceimiceáin sa Chomhshaol

> Rialacháin dramhaíola a chur i bhfeidhm agus a fhorfheidhmiú lena n-áirítear saincheisteanna forfheidhmithe náisiúnta;
> Staitisticí dramhaíola náisiúnta a ullmhú agus a fhoilsiú chomh maith leis an bPlean Náisiúnta um Bainistíocht Dramhaíola Guaisí;
> An Clár Náisiúnta um Chosc Dramhaíola a fhorbairt agus a chur i bhfeidhm;
> Reachtaíocht ar rialú ceimiceán sa timpeallacht a chur i bhfeidhm agus tuairisciú ar an reachtaíocht sin.

Bainistíocht Uisce

> Plé le struchtúir náisiúnta agus réigiúnacha rialachais agus oibriúcháin chun an Chreat-treoir Uisce a chur i bhfeidhm;
> Monatóireacht, measúnú agus tuairisciú a dhéanamh ar chaighdeán aibhneacha, lochanna, uiscí idirchreasa agus cósta, uiscí snámha agus screamhuisce chomh maith le tomhas ar leibhéil uisce agus sreabhadh abhann.

Eolaíocht Aeráide & Athrú Aeráide

> Fardail agus réamh-mheastacháin a fhoilsiú um astaíochtaí gás ceaptha teasa na hÉireann;
> Rúnaíocht a chur ar fáil don Chomhairle Chomhairleach ar Athrú Aeráide agus tacaíocht a thabhairt don Idirphlé Náisiúnta ar Ghníomhú ar son na hAeráide;
> Tacú le gníomhaíochtaí forbartha Náisiúnta, AE agus NA um Eolaíocht agus Beartas Aeráide.

Monatóireacht & Measúnú ar an gComhshaol

> Córais náisiúnta um monatóireacht an chomhshaoil a cheapadh agus a chur i bhfeidhm: teicneolaíocht, bainistíocht sonraí, anailís agus réamhaisnéisiú;
> Tuairiscí ar Staid Thimpeallacht na hÉireann agus ar Tháscairí a chur ar fáil;
> Monatóireacht a dhéanamh ar chaighdeán an aeir agus Treoir an AE i leith Aeir Ghlain don Eoraip a chur i bhfeidhm chomh maith leis an gCoinbhinsiún ar Aerthruailliú Fadraoin Trasteorann, agus an Treoir i leith na Teorann Náisiúnta Astaíochtaí;
> Maoirseacht a dhéanamh ar chur i bhfeidhm na Treorach i leith Torainn Timpeallachta;
> Measúnú a dhéanamh ar thionchar pleananna agus clár beartaithe ar chomhshaol na hÉireann.

Taighde agus Forbairt Comhshaoil

> Comhordú a dhéanamh ar ghníomhaíochtaí taighde comhshaoil agus iad a mhaoiniú chun brú a aithint, bonn eolais a chur faoin mbeartas agus réitigh a chur ar fáil;
> Comhoibriú le gníomhaíocht náisiúnta agus AE um thaighde comhshaoil.

Cosaint Raideolaíoch

> Monatóireacht a dhéanamh ar leibhéil radaíochta agus nochtadh an phobail do radaíocht ianúcháin agus do réimsí leictreamaighnéadacha a mheas;
> Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha;
> Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta;
> Sainseirbhísí um chosaint ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Ardú Feasachta agus Faisnéis Inrochtana

> Tuairisciú, comhairle agus treoir neamhspleách, fianaise-bhunaithe a chur ar fáil don Rialtas, don tionscal agus don phobal ar ábhair maidir le cosaint comhshaoil agus raideolaíoch;
> An nasc idir sláinte agus folláine, an geilleagar agus timpeallacht ghlan a chur chun cinn;
> Feasacht comhshaoil a chur chun cinn lena n-áirítear tacú le hiompraíocht um éifeachtúlacht acmhainní agus aistriú aeráide;
> Tástáil radóin a chur chun cinn i dtithe agus in ionaid oibre agus feabhsúchán a mholadh áit is gá.

Comhpháirtíocht agus Líonrú

> Oibriú le gníomhaireachtaí idirnáisiúnta agus náisiúnta, údaráis réigiúnacha agus áitiúla, eagraíochtaí neamhrialtais, comhlachtaí ionadaíocha agus ranna rialtais chun cosaint chomhshaoil agus raideolaíoch a chur ar fáil, chomh maith le taighde, comhordú agus cinnteoireacht bunaithe ar an eolaíocht.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

Tá an GCC á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóir. Déantar an obair ar fud cúig cinn d'Oifigí:

1. An Oifig um Inbhunaitheacht i leith Cúrsaí Comhshaoil
2. An Oifig Forfheidhmithe i leith Cúrsaí Comhshaoil
3. An Oifig um Fhianaise agus Measúnú
4. An Oifig um Chosaint ar Radaíocht agus Monatóireacht Comhshaoil
5. An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tugann coistí comhairleacha cabhair don Ghníomhaireacht agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

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