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ABSTRACT	This deliverable provides a review of literature and real-world practice in relation to source water protection and Dissolved Organic Matter. It reviews potential source water protection measures specifically for the mitigation of organic matter based on its pathway and process of contamination. It uses input from water managers, group water scheme members in Ireland, Spain and Cyprus through a combination of a focus group and survey and interviews to evaluate the success and community buy-in of these selected measures.		

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ABBREVIATIONS

Abbreviations	Description
ACRES	Agri-Climate Rural Environment Scheme
BMP	Best management practice
C	Carbon
CAP	Common Agricultural Policy
C-DBPs	Carbonaceous DBPs
CDOM	chromophoric dissolved organic matter
DBO	Design, Build, Operate
DBP	Disinfectant By Product
DCAN	Dichloroacetonitrile
DOC	Dissolved Organic Carbon
DOM	Dissolved organic matter
DON	Dissolved Organic Nitrogen
EPI	Environmental Performance Index
GAC	Granular Activated Carbon
GWS	Group Water Schemes
HAAs	Haloacetic acids
HALs	Haloacetaldehydes
HAN	Haloacetonitriles
HBQs	Halobenzoquinones
HKs	Haloketones
LAWPRO	Local Authority Waters Programme
MARWP	Multi-Annual Rural Water Programme
NAs	Nitrosamines
N-DBPs	Nitrogenous DBPs
NDMA	Nitrosamines
NFGW	National Federation of Group Water Schemes
OM	Organic Matter
P	Photosynthesis
PAR	Participatory Action Research (PAR)
POC	Particulate organic carbon
R	Respiration
RAL	Remedial action list
R-DBPs	Regulated DBPs
SLM	Sustainable land management
SMZs	Streamside management zones
SWP	source water protection
THMs	Trihalomethanes
UR-DBPs	Unregulated DBPs
UV	ultraviolet
WHO	World Health Organisation

EXECUTIVE SUMMARY

Dissolved organic matter (DOM) is found across all freshwater systems and originates from soils, leaf litter and leachate from plant material and the decomposition processes. However, as a consequence of a combination of changes in both land use practices and climate change there has been a recorded increase in DOM export in freshwater systems over the last number of years. High concentrations of DOM in aquatic resources can cause issues for drinking water treatment, as disinfection by-products (DBP) such as trihalomethanes (THMs) and chloroform can be produced as a consequence of the reactions between chlorine and naturally occurring DOM in water. Evolving research has found that DBPs pose a threat to human health and are associated with certain cancers as well reproductive and developmental problems.

There are numerous options available to mitigate and treat disinfection byproducts as part of the water treatment process, including a range of technologies and management procedures which aim to reduce contact between DOM precursors and disinfectants. Nevertheless, protection of the water at source represents an alternative and likely additional activity which could act to reduce DBP formation in drinking water in a more cost effective and efficient way. Source Water Protection (SWP) has been widely implemented in many regions of the world to improve raw water quality. However, to date much work relating to SWP has focused on pollutants such as microbial pathogens, nutrients such as nitrate and phosphorus and chemicals such as herbicides and pesticides, with less work focusing specifically at reducing DOM input to water treatment plants. This report will, therefore, examine the potential effectiveness of these measures in reducing organic matter with the aim of minimising human exposure to DBPs in drinking water.

A desk-based review of the literature is provided, which describes the role of DOM in freshwater ecosystems, examining its principal sources and drivers, the main biogeochemical processes governing its transformation in natural environments and the impact of human activities on these processes. A range of SWP measures are reviewed, including a summary of the principal legislative basis for SWP in Europe. This information was then evaluated in order to identify SWP measures most likely to mitigate against DOM. Forestry, peatland, agriculture, lakes/reservoirs and wastewater treatment were identified as the five main land use categories linked to DOM loading. Each collated mitigation measure was assessed firstly on the evidence, where available, of its likely effectiveness at reducing DOM concentration in source water and where this was not available other relevant pollutants such as nutrients and sediments were considered. While considering the particular characteristics that influence DOM movement and attenuation, the most suitable SWP measures were selected to mitigate against each of the driving processes and activities previously identified. For most measures, despite the availability of evidence on their effectiveness in reducing other important aquatic pollutants, evidence for their effectiveness

against DOM were rare, absent and in some cases contradictory.

To evaluate the potential and usefulness of implementing these selected measures at a catchment scale input was sought from a range of individuals working in the water sector. A particular focus was placed on Ireland which has a track record of SWP implementation for protection of drinking water sources, particularly within the Group Water Schemes sector which are community led co-operatives which source and supply water to local communities and, therefore, have a direct link with local farmers and landowners. Through a combination of research forums, surveys and semi-structured interviews it was found that the Irish participants were initially most concerned with issues relating to effective treatment plant infrastructure and operation with little evidence that SWP had been a consideration for DBP management in drinking water. However, through knowledge exchange and discussion, there was a realisation of the important role of SWP as a potential additional solution to the management of water resources acting in combination with improved water treatment for effective mitigation against DBP formation. However, barriers identified by the participants were lack of consistent government policy compounded by issues related to climate change and lack of knowledge amongst the public as well as landowners, creating a feeling of frustration and helplessness among the participants. In addition, information was collated on SWP in Spain and Cyprus (both case study sites in the intoDBP project) in order to gain insight in the wider implementation of SWP measures for DOM mitigation in Europe, taking account of different water quality, quantity and governance issues. In both these countries, water quantity issues represented a significant issue and in the case of Cyprus is particularly critical. For example, in Cyprus implementation of SWP measures are largely delivered from the perspective of water retention and includes measures which will improve moisture retention, soil health and increasing forestry cover. Key difference in management and governance structures between the three countries impacted the implementation and co-ordination of SWP measures, but as with Ireland there is a recognition that climate change is likely to place increasing pressure on water resources and will likely impact SWP implementation, increasing the complexity of their implementation and likely effectiveness while also potentially diverting attention away from long-term planning around SWP to more short-term mitigation measures in response to increasing extreme weather events and drought conditions.

Overall, the work presented here indicates that there is a potential role for SWP for the mitigation of DOM in source water leading to improved DBP management in conjunction with treatment improvements and upgrades. However, currently, there is still a larger focus on treatment plant solutions with less direct and coherent mechanisms in place to drive SWP in many countries. In addition, the lack of evidence-based research demonstrating the effectiveness of SWP measures in mitigating against DOM and DBP formation is a significant

barrier to the uptake and implementation of such measures. Active and participatory approaches to education and support in this area will encourage stakeholders to shift their perception from an end of pipe only solution to a multi-barrier approach to reduce the overall risk of DBP contamination of drinking water. Effective monitoring and data collection is required in order to ensure the successful long-term sustainability of such measures.



1.0 INTRODUCTION

Disinfection by-products (DBP) such as trihalomethanes (THMs) and chloroform are produced as a consequence of the reactions between chlorine and naturally occurring dissolved organic matter (DOM) in water. Evolving research has found that DBPs pose a threat to human health, with many DBPs being considered carcinogenic, mutagenic and associated with problems with the reproductive system. A person can be exposed to DBPs principally through consumption of drinking water containing high concentrations of DBP, although exposure through inhalation or skin contact is also possible. While drinking water plants use various disinfectants including chlorine dioxide, chloramine, ultraviolet light and ozone (Saqib Ishaq et al., 2019), chlorine has several advantages including the fact that it eliminates most microorganisms, can oxidize iron and manganese to avoid unpleasant tastes in water, is comparatively cost effective and most importantly maintains residual chlorine content in drinking water distribution systems. For these reasons chlorine remains the most commonly used disinfectant for drinking water worldwide (Donald et al., 2025a). Currently there are over 700 DBPs reported in drinking water, with new DBPs continuing to be discovered, such as Halo benzoquinones (HBQs) whose toxicity has been reported to be higher than that of THMs and haloacetic acids (HAAs). Water treatment plants, therefore, face significant challenges in the balance between preventing harmful bacteria entering the drinking water supply and reducing the spread of harmful DBPs to drinking water.

When source water quality is poor, effective water treatment often becomes prohibitively expensive. Investing in mitigation measures at source is relatively affordable and can lead to not only a reduction in operational costs for drinking water treatment utilities, but also lower microbial regrowth and a reduction in harmful DBPs in the distribution networks. These measures, often variably referred to as source water protection measures (SWP), best management practices (BMPs), Streamside management zones (SMZs), sustainable land management (SLM) or watershed management are actions and strategies implemented to prevent or minimise the pollution and degradation of surface and groundwater sources currently used or intended to be used in the future as public drinking water supplies (O'Connor, 2002; Krewski et al., 2004).

There are a range of harmful activities within a catchment that can affect the quality of the surface water. Point sources of pollution is pollution which arises from identifiable sources such as nearby factories and sewage or wastewater treatment plants, and diffuse or nonpoint pollution is any pollution which arises on account of dispersed sources where the origin is not easily identifiable such as pasture runoff of animal wastes, fertiliser and sediments. The main function of SWP measures implemented in a catchment is to maintain or improve raw water quality by protecting source waters from nonpoint pollutants in a cost-effective manner. However, to date much work relating to source protection measure implementation have

focused on solutions primarily to mitigate against microbial pathogens, nutrients such as nitrate and phosphorus and chemicals such as herbicides and pesticides with little to no work focusing on organic matter as a potential issue for drinking water quality which could be mitigated at source. This report will address this gap by specifically looking at the potential effectiveness of these measures in reducing dissolved organic matter (DOM) with the result of minimising human exposure to DBPs in drinking water.

The work presented focuses on three European Case Study sites in Spain, Cyprus and Ireland. In Spain, two drinking water treatment plants were involved directly in the intoDBP project, the Ter Drinking Water Treatment Plant in Barcelona and the Val mayor Drinking Water Treatment Plant in Madrid. The case study site in Cyprus consists of the Water Distribution Network of Limassol and Limassol Drinking Water Plant. Finally, the case study in Ireland includes a cluster of three small Group Water Schemes (GWS) located in County Mayo, supplying rural communities. The utilities are co-operative schemes which are privately managed and are represented by the National Federation of Group Water Schemes (NFGWS). Each of the three GWSs involved in the project are located within 15 Km of each other and are located within catchments which experience high prevalence of peatland.

1.1 Objectives

The information gathered from this report will meet the overall objective of Work Package 5 of the intoDBP project which is focused on "Adaptation options and source protection" by meeting Deliverable 5.3 which aims to present a review of potential mitigation measures for reducing DOM in raw water sources and report on real-world source protection measures. In order to meet this deliverable, a desk-based review process was undertaken to identify source protection measures most likely to mitigate against DOM. Through this extensive literature review the five main categories of DOM sources within catchment were identified. The main biogeochemical processes or land use activities associated with these sources leading to increased DOM concentrations were then determined and potential measures to mitigate DOM production were then considered. Using peer-reviewed published papers, each collated mitigation measure was reviewed firstly on the evidence, where available, of its likely effectiveness at reducing DOM concentration in source water and where this was not available other relevant pollutants like nitrogen, phosphorus and sediments. While taking into account the particular characteristics that influence DOM movement and attenuation, the most suitable SWP measures were selected to mitigate against each of the driving processes and activities previously identified.

To evaluate the success of these selected measures, input was sought from people working in the water sector in Ireland, farmers and landowners particularly those who are involved with the Group Water Schemes sector which form part of the Irish intoDBP Case Study sites. In addition,

input from stakeholders from Spain and Cyprus working in catchment management was sought through various forms of engagement including semi-structured interviews.

1.2 Report Structure

This report will be broken up into six sections (Fig.1). The first section provides background information describing DOM in freshwater habitats, examining its role in the ecosystem, its sources and drivers and what impact it has on human health via the water treatment process. This section will also provide an introduction to SWP, its implementation historically from a global and European perspective and a general overview of SWP measures. Section 3 reviews potential SWP measures specifically for the mitigation of DOM based on its pathway and process of contamination. Section 4 introduces valuable input from water managers and group water scheme members in Ireland based on both data collected at the stakeholder forum/focus group and the survey distributed to GWS members, respectively. Section 5 will give the European in relation to the case study sites in Spain and Cyprus. Section 6 concludes the report by summarising key findings and providing recommendations and future outlook for research related to DOM mitigation in source waters.

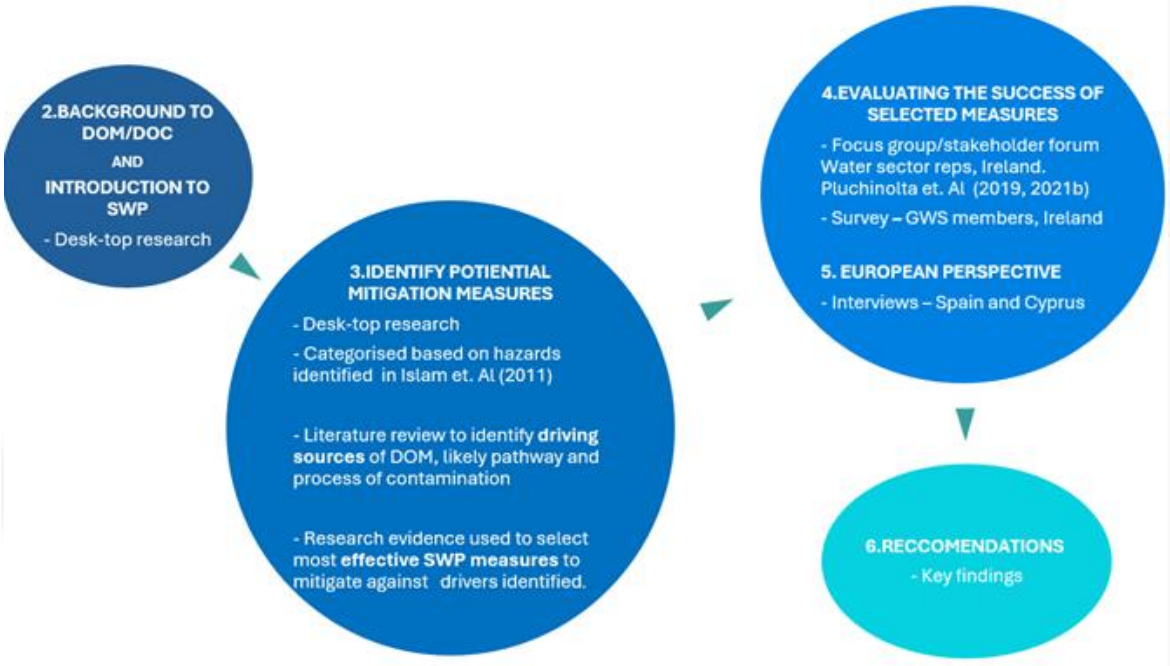


Figure 1. Overview of the structure of the report and approaches taken for each section.

2.0 Background to Dissolved Organic Matter in freshwater systems and Introduction to Source Water Protection: A literature review.

2.1 Background to Dissolved Organic Matter in freshwater systems

There are two forms of aquatic carbon, inorganic and organic carbon (Fig. 2). Inorganic carbon can come from mineral weathering of rocks and sediments (particulate inorganic carbon) or, from the atmosphere as dissolved carbon dioxide (CO_2) and biological processes such as respiration and decomposition of organic matter (OM) within soils and water bodies (dissolved inorganic carbon). Organic carbon is a mixture of organic compounds originating from detritus or primary producers released during and after their life. Particulate organic carbon (POC) is OM that is suspended or settles in water bodies and can be filtered out and can be degraded to form dissolved organic carbon (DOC). Inorganic and organic carbon are linked through aquatic organisms. CO_2 is used by aquatic organisms in photosynthesis (P) and produced by respiration (R) and exchanged with the atmosphere (Fig.2).

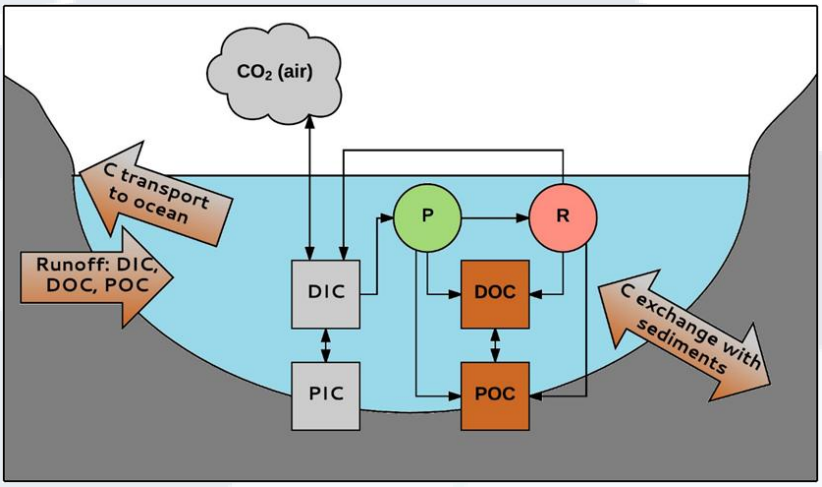


Figure 2. *A summary of autochthonous DOC processes in freshwater sources (Reitsema et al., 2018).*

Dissolved organic matter is found across all freshwater systems and originates from the decomposition of plants including algae and soils. Consequently, DOM is involved in many physical and biological processes in freshwater systems which are responsible for changing both the chemical structure as well as the concentration of the different fractions present (Tranvik et al., 2009). For the purposes of identification and quantification following laboratory analyses, it is defined as comprising any organic compound which can pass through a 0.45 µm filter (Evans et al., 2005). Organic matter is difficult to quantify because it refers to the entire organic molecule. Measuring the concentration of carbon (C) as DOC is one of the most common methods used to measure DOM in aquatic ecosystems, however DOM also contains other

elements such as phosphorus, hydrogen, sulfer, oxygen and nitrogen (Xenopoulos et al., 2021). Reflecting this in literature, the terms DOM and DOC (Table 1) are variously used depending on the study and the focus of analyses, and both terms have also been used interchangeably. Consequently, although this review will generally use the term DOM, considered to be the more inclusive term which better reflects the range of organic components which enter source water, the use of both the terms DOM and DOC will be used as necessitated to reflect the individual studies under consideration.

The mixture of compounds found in DOM varies depending on the source and the biogeochemical processes it has undergone. In aquatic systems there are two main categories of organic matter, autochthonous DOM, produced within the aquatic water body itself as a consequences of processes such as photosynthesis, microbial production, degradation or photochemical reactions and allochthonous DOM which is any external terrestrially derived organic matter, such as leaf litter, leachate from plant debris, soils, or sediments (Herzsprung et al., 2020). Dissolved organic matter is chemically complex and can vary in terms of its age, colour, molecular weight and composition of biochemicals such as sugars and amino acids (Xenopoulos et al., 2021). Allochthonous DOM usually passes through several degradation stages on its way to freshwater and as a result it consists of mostly refractory, high-molecular weight compounds (Tulonen, 2004), as opposed to the lower-molecular weight and more aliphatic compounds found in autochthonous DOM (Evans et al., 2005; Liu et al., 2019).

Allochthonous DOM can be divided into two broad categories, non-humic and humic organic matter (Wetzel, 2001). The non-humic fraction is composed of low molecular weight carbohydrates, amino acids, fats, peptides and pigments (Hayes & Clapp, 2001). These substances are considered to be generally labile and easily degraded and incorporated into microbial processes. The humic components, however, have a higher molecular weight and are relatively resistant to biological degradation and can, therefore, be stored in the soil and sediments for extended periods of time (e.g. peat soils; Hudson et al., 2007). These humic compounds can be further categorised as either humic acids, fulvic acids and humins and differ in their solubility and pH. Humic compounds in DOM are also described collectively as coloured, or chromophoric dissolved organic matter (CDOM), and absorb light in the ultraviolet and in the short wavelengths of visible light and range from dark brown to almost black colours depending on their concentration and relative proportions (Williamson et al., 1999). The types and ratios of these compounds depend on the source and types of degradation processes to which they have been exposed. Increases in human disturbance has led to notable and extensive changes to the quantity and type of DOM transported through freshwater systems, with for example agriculture linked in some cases to increases in the proportion of microbial humic like DOM (Shang et al., 2018), and in other cases to increases in protein-like DOM (Lu et al., 2014). Increases in the more

humic-like compounds, which are associated with brown colour in DOM-rich waters (Evans et al., 2005), is otherwise known as brownification.

Table 1. *Relevant terminology and their meaning*

Term	Explanation
Allochthonous / terrestrial	DOM derived externally from outside the aquatic ecosystem e.g soils or humified plant material.
Autochthonous	DOM that is derived within the aquatic ecosystem produced by microbes, algae or aquatic macrophytes
Aliphatic	Compounds resistant to rapid microbial degradation
Aromatic	Unsaturated compounds having one or more planar rings of atoms with alternate single and double bonds, resulting in a unique stability known as aromaticity.
Bioavailable / biolabial	Parts of DOM that are useable by microbial organisms
Dissolved Organic Carbon (DOC)	Mass of Carbon found in DOM that is able to pass through a filter with a pore size typically between 0.2 and 0.45-µm.
Dissolved Organic Matter (DOM)	Diverse mixture of soluble organic material that passes through a 0.45-µm filter pore
Fulvic	Compounds characterized by relatively lower aromaticity and molecular weight, mostly found in autochthonous DOM
Humic	Compounds characterized by relatively high aromaticity and molecular weight, mostly found in allochthonous DOM
Hydrophilic	A molecule that can mix and interact with water.
Labile	Easily degraded through abiotic and or biotic transformations.
Oligotrophic	A deficiency of plant nutrients that is usually accompanied by an abundance of dissolved oxygen.
Recalcitrant	Not easily degraded

2.1.1 Role DOM/DOC plays in the ecosystem

Concentrations of DOM in water bodies has implications for carbon cycling both on a local as well as a global scale (Battin et al., 2009). Inland waters act like a 'pipe' transporting C from land to the ocean. Dissolved free amino acids and carbohydrates are the main energy and carbon sources for microbial metabolism and growth in freshwater ecosystems (Azam & Ammerman, 1984; Wright, 1984). The consumption of DOC by bacteria, producing bacterial biomass influences the flow of C through the microbial food web and represents one of the major sinks of DOC in the biosphere (Raymond and Bauer, 2000; Cole et al., 2007). However, bacterial consumption of DOC is influenced by a number of environmental factors, including temperature, nutrient availability, and ultraviolet (UV) radiation (Zweifel et al., 1993; Marschner and Kalbitz, 2003; Anesio et al., 2005). DOC is an important regulator of ecosystem production, since its absorptive properties hinder photosynthesis (Jones, 1998), while simultaneously, it serves as a substrate for heterotrophic bacteria (Tranvik, 1988). This results in many lakes being considered net heterotrophic ecosystems that respire more carbon dioxide (CO_2) than is fixed by photosynthesis, leading to net CO_2 export to the atmosphere (Sobek et al., 2005).

For many freshwater ecosystems, allochthonous carbon inputs, particularly via leaf litter, is a principal source of organic carbon for trophic food webs, particularly in forested catchments (Bogatov et al., 2024). DOC is channelled via the 'microbial loop' between primary producers such as phytoplankton and macrophytes and higher trophic levels (Pome-roy, 1974; Sorokin, 1977; Azam, 1986). However, only a small fraction of the total DOC pool is easily bioavailable for

bacterioplankton. In a cross-system analysis performed by Søndergaard & Middelboe (1995) using data collected from lakes, rivers and seawater, 75% of total organic carbon (TOC) was found to be refractory DOC meaning it is not degradable (Tulonen, 2004). Humic substances account for about 50% of the DOC pool in most surface waters (Kronberg, 1999). While autochthonous C is higher in clearwater oligotrophic lakes and preferentially utilised by bacteria over DOC of terrestrial origin (Kritzberg et al., 2004). In humic systems, the input of allochthonous C always exceeds the input of autochthonous C. This results in increased growth of bacterioplankton affecting the overall C flow from the base to the top of the food chain (Tulonen, 2004).

2.1.2 Natural sources of DOM/DOC

Allochthonous inputs of DOM to freshwater systems is determined by a range of catchment and environmental characteristics such as catchment area, vegetation land use, geology and soil type (Sepp et al., 2019). High concentrations of DOC are often associated with areas which are rich in peat soils, swamps or bogs (Satoh and Abe, 1987; Moran and Hodson, 1990). For example, Mattsson et al.(2009) examined data from 745 lakes in Europe and found that the proportion of wetlands in the catchment was an important predictor of DOC in lakes across diverse geographical regions. Riverine DOC concentrations and fluxes were found to be significantly correlated with the percentage of wetland area, peat cover, and stream channel slope (Mulholland, 2003). In this study streams draining areas dominated by water flow paths in contact with organic-rich soil had higher DOC concentrations than those receiving drainage along deeper flow paths (Mulholland, 2003). In addition, areas with thick soils and high runoff have been found to have lower DOC concentrations when compared to areas with thicker soils containing more peatland despite lower runoff (Mattsson et al., 2009). Significant associations between the percentage of peat cover in a catchment and DOC export to surface water has also been recorded in a number of studies (Laudon et al., 2011; Odefeddt et al., 2013). Higher catchment elevation has also been found to be linked to lower DOC, likely a consequence of lower wetland extent on steep slopes and reduced accumulation of OM in soils (Mattsson et al., 2009). Consequently, the highest DOC concentrations globally are generally found in humic, brown-coloured lakes that are commonly found in temperate and cold regions of the Boreal Zone associated with bogs and organic rich soils and litterfall or root leachate with associated mycorrhiza (Cole et al., 2007). On a global scale, peatlands are an important source of DOM export, with boreal peatlands accounting for 58% of these exports (Rosset et al., 2022). Nevertheless, increased DOM levels can also be associated with catchments dominated with agriculture and forestry, particularly coniferous or mixed woodlands (Sepp et al., 2019; Mattsson et al., 2005; Hongve, 1999). Higher DOM export has been recorded in catchments with larger drainage areas (Sepp et al., 2019). In this study it was also noted that the type of soil found in a catchment was much more important than land cover and hydrogeological factors in influencing

DOC properties in Estonian lakes (Sepp et al., 2019), with soil organic carbon values having the strongest relationship with DOC concentrations in lakes (Sepp et al., 2019; Billett et al., 2006).

Since aquatic systems receive a significant proportion of DOM from terrestrial sources, climate and hydrological conditions are important factors contributing to the leaching of organic matter from catchments (Tulonen, 2024). Pulses of DOC have been linked to flood events which are considered to be a consequence of the succession of hydrological connection and disconnection between aquatic drainage areas and water bodies. DOM export has been found to be determined by the water table depth in which DOC produced as a consequence of soil microbial degradation during drier periods is hydrologically reconnected and flushed out into aquatic pathways leading to greater exports during flood events (Rosset et al., 2020; Prijac et al., 2023). In peatland soils, DOC export in flood events was found to be composed largely of recently produced C (Antonin Prijacet al. 2023). The type of DOC which is exported during flood events will be variable and dependent on a number of factors such as the magnitude of rainfall, seasonality, porewater temperature, the frequency of rainfall events and the rainfall free period (Rosset et al., 2020; Blaurock et al., 2021). Soil temperature can also have an important role to play, since soil microbial processes are temperature dependent and the DOC concentrations in the pore water of peat have been found to be associated with peat temperature (Buzek et al., 2019). Additionally, in Boreal regions for example, freezing and snowmelt can impact DOC export from peatland leading to delays in DOC export (Laudon et al., 2012), and as such, seasonal cycles have been found to be important in determining DOC movement and concentration in aquatic systems, and are dependent on regional precipitation and temperature patterns (Jennings et al., 2020). In agricultural landscapes, DOC composition has also been found to be influenced by flood events in which increased export of proteinaceous compounds have been recorded following flood events relative to more natural land cover types in the region (Fasching et al., 2019). Therefore, the composition as well as the concentration of DOM is also affected by hydrological conditions. During extended periods of drought with low flow conditions, DOM inputs were found to be derived primarily from groundwater and therefore had a more protein-like biolabile composition (Inamdar et al., 2011). In addition, summer periods with low flow can also be linked to increased production of in-stream or autochthons sources of DOM from primary production (Hosen et al., 2020), and in areas with low DOM production or where overland flow dominates, increased rainfall can act to dilute DOM and also reduce contact time between mineral soils, reducing microbiological processes and increasing the mobility of hydrophilic fractions of DOM to waterbodies (Worrall et al., 2002; Kaiser and Zech, 1998).

Lower residence times in lakes are also associated with higher DOC values (Jussi Vuorenmaa, 2006), owing to a reduction of within lake removal processes such as sedimentation and decomposition. The steepness of slopes within catchments can also determine DOC generation,

as it affects rainwater infiltration and transport of mobile constituents such as DOC (Xenopoulos et al., 2003). Catchments with steep topography and non-porous bedrock will tend to have more rapid flow, delivering precipitation faster and more directly to water bodies (Frost et al., 2006). Lakes with deeper mean depth have also been found to have a negative association with DOC (Pace and Cole, 2002).

Autochthonous DOC originates from within the body of water i.e. in-lake production. It is produced from metabolic activities and the breakdown of microbes (heterotrophic bacteria, cyanobacteria, fungi, and algae), macrophytes (aquatic plants) and some soil processes. It consists mainly of non humic substances (e.g., monomeric sugars, carboxylic acids, amino acids, and alditols) (Bertilsson and Jones, 2003) that are labile and easily utilized or degraded by microorganisms (Thurman, 2012). This provides essential energy and nutrients for aquatic organisms and drives biogeochemical processes within the freshwater ecosystem (Rolf David Vogt et al., 2023). It also plays a significant role in the aquatic carbon cycle with inland aquatic systems forming the second largest carbon sink (Luyssaert et al., 2012). Eutrophication and land use changes can increase the availability of autochthonous OM during algal bloom periods and this can affect the composition and environmental behaviours of DOM (Wilkinson et al. 2013; Jonsson and Stenroth 2016)

2.1.3 Anthropogenic and Climatic drivers of DOM/DOC

Through a combination of changes in both land use practices and weather patterns owing to climate change there has been a recorded increase in DOC export in freshwater systems over the last number of years. According to a study conducted by Evans et al (2005), DOC concentrations have increased on average by 91% relative to the period between 1988 and 1993. The term browning is used to describe this increase in DOC concentrations which has been reported across a large number of freshwater systems in the northern hemisphere in recent decades (de Wit et al., 2016; Kritzberg et al., 2019).

Land cover and land-use changes are one of the main drivers of brownification (Fig. 3). Sixty percent of land-use changes are associated with direct human activities (Fig. 3; Blanchet et al., 2022). Clearcutting, agriculture, afforestation and peatland drainage are all examples of anthropogenic activities that modify DOM cycling and have led to brownification. Clearcutting involves topsoil disturbance, increased soil temperature and a rise in groundwater level, all of which result in increased DOM leaching into freshwater sources. Agriculture results in soil degradation and water flow modification which releases microbial-derived DOM in addition to excess nutrients such as dissolved organic nitrogen and pesticides into freshwater (Karlen et al., 1997; Ogle et al., 2005; Graeber et al., 2012). Afforestation, especially coniferous trees, leads to excess soil organic carbon exportation to surrounding surface waters (Meyer Jacobs et al., 2015;

Kritzberg, 2017; Skerlep et al., 2020). Peatland drainage increases the decomposition of surface peat and results in an increase of DOM, usually more recalcitrant DOM from deeper parts of the soil, consequently increasing its export to surface waters (Hulett et al., 2014a, 2014b; Martilla et al., 2018; Finear et al., 2021; Neminen et al., 2021).

Urbanisation typically affects the composition of DOM resulting in the production of DOM with lower molecular weight and aromaticity. The removal of natural structures, the increase in impervious surfaces and sewers, and by-passing of surface flow with subsurface artificial drainage result in DOM that is more hydrophobic than other types of land cover (McElmurry, Long and Voice, 2014). Decreased residence times behind dams and river straightening reduce the opportunity for within system DOM degradation via microbial processing (Griffiths et al., 2012). The burial of streams, where streams are directed into culverts, pipes, concrete-lined ditches, or simply paved over, has also been linked to lower levels of humic DOM as well as a reduction in DOM complexity and lability (Pennino et al., 2014; Arango et al., 2017). DOM in urbanised rivers is strongly affected and can increase in concentration as a result of inputs of treated and/or untreated wastewater (Greenwood et al., 2012; Kalscheur et al., 2012). Wastewater derived DOM has been shown to exhibit a greater organic nitrogen content and was more aliphatic than the DOM in natural waters (Chen et al., 2011; Czerwionka et al., 2012; Mesfioui et al., 2012; Sirivedhin and Gray, 2005). Another symptom of urbanisation and industrialisation are the emissions of sulfur and nitrogen oxides that form acid rain. Acid rain (pH < 5.6) reduces the solubility of OM by increasing intermolecular and intramolecular bonding (Tipping and Woof, 1991; Lumsdon et al., 2005), leading to surface water dominated by hydrophilic compounds (David et al., 1989; Ekström et al., 2011), and hence lower DOC levels. With the introduction of strict legislation acid rain has reduced by approximately 80% from its peak in the late 1960s (Likens, 2021). Laboratory experiments on organic soils suggest that reduced acidity increases the electrical charge thereby increasing the solubility and mobility of DOM (Tipping and Hurley, 1988; Kennedy et al., 1996). Therefore, the increase in pH levels from the reduction of acidification may be considered one of the driving factors for the increases in DOC levels over recent decades.

The ability of natural wetlands to remove streamside pollutants (denitrification) has also been hindered by the availability of bioavailable DOM as a result of anthropogenic activities (Wiegner and Seitzinger, 2004). DOM originating from agricultural inputs is mainly of a low aromaticity and molecular weight increasing the growth of aquatic plants, which in turn increases the amount of decaying plant matter in lakes and therefore the amount of buried carbon. Carbon burial in lakes can be thought as offsetting the effects of anthropogenic CO_2 release. However, this human derived DOM cocktail directly affects freshwater DOM quality, metabolism and food web dynamics.

These human activities are additionally affected by climate change (Fig. 3) and climate change is predicted to bring more intense precipitation events and associated flooding in many temperate regions, as well as more intense drought and wildfires. These climate changes will affect DOC concentration in freshwater sources, which will in turn affect their ecosystem structure and function.

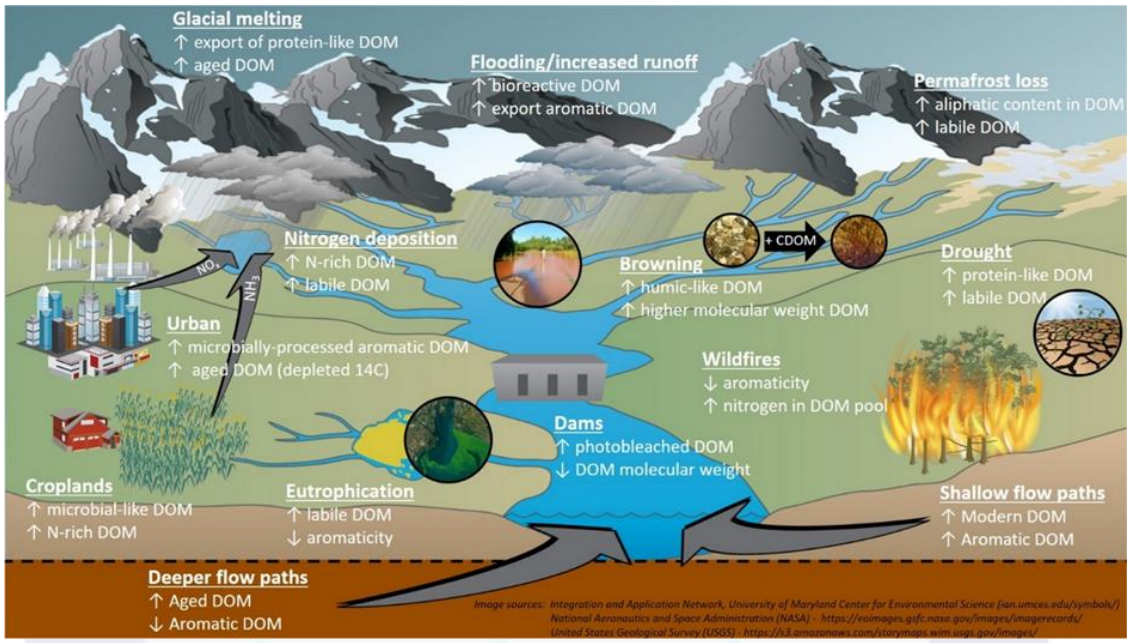


Figure 3. A summary of human and climatic influences on the composition of DOM (Source: Xenopoulos et al. 2021).

Increased extreme precipitation events will lead to faster degradation rates and therefore an increase of terrestrially derived aromatic DOM into surface waters (Ren et al., 2016). Several studies have linked an increase of terrestrial, aromatic DOM with greater CO_2 and methane production in freshwaters (D'Amario and Xenopoulos, 2015; West et al., 2012; Zhou et al., 2018). DOM from flooding events in agricultural catchments has been shown to have higher levels of protein (Fasching et al., 2019) compared with natural/forested catchments. In this case DOM showed a higher molecular weight, aromaticity and carbon content (Fasching and Battin, 2012; Hood et al., 2006; Nguyen et al., 2010; Vidon et al., 2008; Wilson and Xenopoulos, 2008; Wilson et al., 2016). This disruption of biogeochemical fluxes may increase CO_2 emissions from lakes (Sobek et al., 2005), creating a feedback loop and amplifying global warming. In addition, further warming will increase the rate of glacier and permafrost melting which is also linked to increased DOM export.

Permafrost soils cover approximately a quarter of the land in the Northern Hemisphere and contains frozen organic C stored underground for millennia. It is predicted that continued permafrost melting will release between 41 and 288 Pg-C (1 PgC is equal to 1 Gigatonne of carbon) by 2100, and up to 616 Pg-C by 2300 (Schaefer et al., 2011; Schuur et al., 2013; Zimov et al., 2006). A further consequence of permafrost thaw is the drainage of the wetlands that cover 25% of land in the Arctic region, most of which are peatlands (Kåresdotter et al., 2021). These degraded wetlands facilitate the export of aromatic, high molecular weight DOM (Frey and Smith, 2005; Minayeva et al., 2016). In addition, DOM release from melting glaciers may initially increase bioavailable DOM to downstream surface water and will moreover lead to the release of ancient, stored stocks of carbon.

While the loss of permafrost, and areas of increased precipitation receive more terrestrially derived DOM, warmer and drier areas may become hydrologically disconnected and eventually be characterized by an increase in microbial-like DOM (Xenopoulos et al., 2021). An experimental study by Tang et al, (2013) found that DOM produced in surface water during droughts is more hydrophilic and harder to remove by coagulation. This suggests that future short-term drought events could have a greater impact than increased temperature on DOC processing. Droughts also increase the chance of wildfires occurring. Changes in vegetative cover and soil properties following fire, lead to increases in surface runoff (Hallema et al., 2017). The DOC exported by burned watersheds is a product of C stock combustion during fire and a large fraction of black carbon (charcoal) leaching from soils into the surrounding surface water bodies (Rhoades et al., 2019). A study by Qi et al. (2020) suggests that dissolved black carbon released from charcoal was labile and could be degraded by bacteria on the same time scales as bulk DOC in the ocean. With prolonged drought and increases in the amount of forest fires, post-fire aquatic DOM will be more nitrogen rich and higher in carbohydrate content (Fig.3).

Human land use disturbances through direct fertiliser application, fossil fuel and biomass burning, and/or landscape destabilisation increase N and P loading in freshwaters, potentially leading to eutrophication. Eutrophication increases autochthonous DOM (Zhou et al., 2018) leading to an increase in algal biomass and hypoxia. As well as fuelling algal blooms, temperature increases can also suppress the accumulation of autochthonous DOM in inland waters by enhancing DOM decomposition (Zhou et al., 2018). These changes in the DOM pool can strongly affect the structure and function of ecosystems and can cause practical problems to drinking water quality. Consequently, investing in catchment management schemes focussed on improving raw water quality by reducing inputs of DOM at source, has the potential to improve the provision of clean drinking water and potentially reduce the need for future capital investment in new treatment technologies.

2.2 Water Treatment and Human Health Implications

Water disinfection has been a crucial step in the drinking water treatment process and the provision of safe clean drinking water to the general population (Cheung, 2017). Since the 1940s the continuous use of chlorine in water treatment plants has virtually eliminated the outbreaks of cholera, typhoid and amoebic dysentery in most developed nations in the world (Richardson et al., 2007). Today drinking water plants use various disinfectants including chlorine dioxide, chloramine, ultraviolet light and ozone (Donald et al., 2025). Chlorine has several advantages including the fact that it eliminates most microorganisms, can oxidize iron and manganese to avoid unpleasant tastes in water, is cost effective, and most importantly maintains residual chlorine content in drinking water distribution systems (Washington State, 2004). For these reasons it remains the most commonly used disinfectant for drinking water worldwide (Richardson et al., 2007). In 1974, Johannes Rook, a Dutch water chemist, reported that THMs and chloroform were produced as a by-product of reaction between chlorine and natural DOM in source water. These compounds were referred to as disinfectant by-products (DBP). Rook demonstrated at the time that it was the polyhydroxy benzene structures of the DOM that were likely the key precursors for THM formation (Hrudey, 2009).

Since then, considerable research has been conducted into DBPs in terms of their formation processes and associated human health effects (Costet et al., 2011; Escobar-Hoyos et al., 2013; Krasner, 2009; Li and Mitch, 2018; Richardson et al., 2007; Siddique et al., 2015). This evolving research has found that DBPs do pose a threat to human health with many DBPs being considered carcinogenic, mutagenic and reproductive toxicants (Cheung, 2017; Freeman et al., 2017; Hrudey et al., 2015). Evidence of bladder, colon, stomach, lymphoma, kidney, pancreas, breast, and esophageal cancers due to DBPs are available (Diana et al., 2019; Font-Ribera et al., 2018; Jones et al., 2017, 2019; Natarajan et al., 2018; Rahman et al., 2007; Villanueva et al., 2015). There is growing evidence supporting a causal relationship between THM exposure and bladder cancer, especially in men (Xie et al., 2025). Bladder cancer is the fourth most common cancer among males in the U.S (lifetime odds are ~4%) (American Cancer Society, 2023). While there is mixed evidence linking reproductive effects such as low birth weight and congenital malformations, with an increased risk of stillbirth of 9% found in individuals with high THM exposure (Nieuwenhuijsen et al., 2010). Human exposure to DBPs is most commonly through drinking water (orally) which contains high concentrations of DBPs, however inhalation of DBPs in the air particularly while taking a shower or at a swimming pool and finally adsorption through the skin is also possible (Villanueva et al., 2015).

In response to these health impacts Canada was first in 1978 to adopt a guideline maximum concentration limit for THM4 (the four most prevalent THMs: chloroform, bromodichloromethane, dibromochloromethane, and bromoform) of 350 mg/L followed by the

U.S in 1979. In 1984, the World Health Organisation (WHO) proposed a guideline for chloroform of 30 mg/ L based on an estimate that this would assure less than a 1 in 100,000 lifetime cancer risk, today this figure is 0.30 mg/L. Current figures for the Canadian and EU limit for total THMs is 100 µg/L in drinking water and since 2006 it is 80 µg/L in the United States (US) (Villanueva et al., 2023). This reduction is an indication of how policy makers have responded to emerging research on the negative impact and toxicity effects of disinfected water on human health. Currently there are over 700 DBPs reported in drinking water, with new DBPs continuing to be discovered such as Halobenzoquinones (HBQs) whose toxicity has been reported to be higher than that of THMs and HAAs (Wu et al., 2021a). Water treatment plants face significant challenges in balancing between preventing harmful bacteria entering the drinking water supply and reducing concentrations of harmful DBPs to drinking water. Consequently, there is a need to identify the toxicity drivers and prioritise which DBPs to control, in addition to identifying ways to mitigate against the precursor of DBP formation at source.

2.2.1 Chemical composition of DOM and link to DBPs

The formation of DBPs in drinking water depends on many factors, such as disinfectant types, source water characteristics, operational conditions, water temperature, and water residence time in the drinking water distribution system (Krasner, 2009). Algal-derived DOM and autochthonous DOM in general is aliphatic, proteinaceous and less oxidised (Cory et al., 2007). This lower aromaticity reduces the formation of THMs, but the higher organic nitrogen present in the DOM increases the formation of N-DBPs. Nitrosamines (NDMA) are associated with increased cancer risks even if present at low levels in drinking water (Weaver, 2021). The hydrophobicity of DOM affects various aspects of its environmental impacts in terms of water quality, sorption behaviours, interactions with other pollutants, and water treatment efficiency. As mentioned previously humic DOM with a high molecular weight and high aromaticity tend to be more hydrophobic and produce aromatic DBPs. During chlorination, DOM with high aromaticity and high molecular weight, like allochthonous DOM found near peatlands, wetlands or mountainous conifer forests, convert into halogenated aromatic DBPs. As the humic and fulvic acids are nitrogen-poor, most aromatic DBPs formed from them are phenyl C-DBPs (Gaffney et al., 1996). Hydrophilic DOM molecules typically contain more nitrogen and have lower molecular size/ weights in comparison with hydrophobic DOM and have few if any UV-Visible light absorbing characteristics. DOM resulting from eutrophication or urbanisation are often considered to be the most difficult to remove from raw water sources. It is colourless and hydrophilic originating from algal and microbially-derived DOM produced within aquatic ecosystems (Liao et al., 2017), rather than the darker DOM that is of terrestrial origin (Golea et al., 2017; Lavonen et al., 2013; Yang et al., 2015). This is due to the absence of electrostatically charged functional groups restricting its solubility bonding capacity with coagulants (Pickard et al., 2021).

For drinking water treatment utilities, understanding water catchment sources of DOM and improved monitoring on the amount and composition of DOM that enters a treatment plant will aid in the implementation of targeted source protection measures to reduce the amount of DOC/DOM entering the water treatment plant, potentially representing a more cost effective means of addressing issues linked to DBPs in treated water than implementing new water treatment technologies on their own (Aiken and Cotsaris, 1995; Reckhow et al., 2004).

2.3 Source Water Protection

Source water protection (SWP) (also referred to as Catchment management, Nature-based Solution for water quality, best management practices (BMPs), streamside management zones (SMZ), sustainable land management (SLM), watershed management or aquatic restoration in the literature) refers to measures implemented in the watershed or catchment with the goal of maintaining or improving raw water quality by limiting or eliminating a potential direct or indirect pollution source into a surface or groundwater resource currently or intended to be used as a source of drinking water (Bresnihan et al., 2021; Islam et al., 2011). A catchment is the entire area from which a water body receives its water including groundwater sources. However, this report will largely focus on SWP measures for surface water that contribute to individual abstraction points for drinking water.

Until recently the focus to deliver clean and safe drinking water has been to develop technological end of pipe solutions to artificially treat water in drinking water utility plants. This is not a long-term viable solution for many reasons. There is the possibility of system malfunctions and failures occurring in treatment plants (Linnane et al., 2011), potentially leading to a disease outbreak in the community. Some of the current and new treatments are also in of themselves creating harmful by-products in our drinking water (Pandian et al., 2022). Small communities in many places do not have the resources to implement costly treatment plants and find it hard to source the highly technical personnel needed to run an efficient water treatment plant (Timmer, de Loë and Kreutzwiser, 2007). When source water quality is poor, effective water treatment often becomes prohibitively expensive (Wilsenach et al., 2003). Investing in mitigation measures at source is relatively affordable and can provide not only a reduction in operational costs for drinking water treatment utilities but also lower microbial regrowth and a reduction in harmful DBPs in the distribution networks (Ivey et al., 2006; Krewski et al., 2004). Good SWP strategies also support the goals of the Water Framework Directive (2000/60/EC) to achieve water quality of at least '*Good Status*' in rivers, lakes, groundwater, estuaries and coastal waters, by 2027 at the latest' (EPA, 2016). Healthy catchments deliver a number of vital ecosystem services such as water filtration, flood control, erosion control, improved soil nutrient status, improve fisheries and create habitats potentially increasing

biodiversity, in addition they also have the capacity to create or support tourism and recreational opportunities (Postel and Thompson, 2005). These co-benefits can both be the primary and secondary motivating factor for communities in engaging with implementation of SWP actions over solely improving the quality of drinking water (NFGWS, 2023). Community engagement is considered essential for the successful implementation of SWP measures as many of these measures require the permission of the landowners and in many instances follow up maintenance and monitoring. SWP preventative measures coupled with relatively simple corrective water treatment measures can be an effective way of ensuring safe drinking water for all stakeholders involved (Robert et al., 1994; Islam et al., 2011; Edition, 2011; Rolston and Linnane, 2020).

Source water protection typically involves assessing water resources in order to identify vulnerable areas and assessing all contaminant sources, before implementing suitable mitigation measures. There are a range of harmful activities within a catchment that can affect the quality of potable or recreational surface water. These can be divided into point sources of pollution, which is pollution arising from an identifiable source e.g. nearby factories and sewage or wastewater treatment plants and diffuse pollution which arises from dispersed sources where the origin is not easily identifiable e.g. pasture runoff of animal wastes, fertiliser and sediments, as well as runoff of pollutants from paved surfaces in urban areas. Source Water Protection can be considered a first stage in a multibarrier approach to protection of drinking water supplies (WHO, 2022). These measures can be considered to be lower cost with potentially fewer negative side effects (e.g. production of DBP via disinfection process) and many SWP measures can have a secondary benefit to nature and climate change, providing both mitigation and adaptation functions (Krewski et al., 2004). Several SWP measures, such as peatland restoration, can additionally act as sinks for carbon, mitigating against climate change as well as potentially addressing water quality issues.

There are a number of important sources of pollution to freshwater systems which can be a risk to the provision of clean drinking water. Organic pollution arising from agriculture activities such as manure spreading or wastewater pollution is particularly important in many countries. In addition, the application of excessive concentrations of inorganic nutrients such as nitrogen (N) and phosphorus (P) provide an environment for rapid microbial growth in surface waters (Carreiro-Silva, McClanahan and Kiene, 2009) leading to eutrophication and algal blooms that deplete oxygen levels creating anoxic conditions and reducing water quality over time (Linnane et al., 2011; Schoumans and Chardon, 2003). Other farming activities such as allowing cattle or other animals access to water courses can increase microbial contamination, nutrient contamination, and sedimentation (O'Callaghan et al., 2018; O'Sullivan et al., 2019). Faecal matter of human and other animal origin contains enterococcal microbes and parasites (e.g. Escherichia coli, Salmonella spp., Giardia spp., Campylobacter spp. and Cryptosporidium spp.).

These organisms may lead to illness if they enter drinking water sources and are consumed (Linnane et al., 2011).

The use of pesticides in a water catchment can also threaten water quality. Pesticides' is the umbrella term for a wide range of chemicals used for the control of pests including insecticides, herbicides, fungicides, nematicides, acaricides, algicides, rodenticides and slimicides (NFGWS, 2023). Harmful pesticides (e.g., Atrazine, diazinon) can enter into source waters not only from agricultural practices but also from gardening (Wittmer et al., 2010). Atrazine is responsible for both acute and chronic toxicity (Warnemuende et al., 2007), while Diazinon is registered as carcinogenic material in the US and Canada (Weichenthal, Moase and Chan, 2010).

In reviewing SWP measures, it is evident that there are many good examples of SWP schemes both within and outside of the EU. However, to date these SWP measures have primarily focused on the mitigation of contaminants such as microbial pathogens, nitrate or phosphate entering the source water**.** Potential mitigation measures can be categorised based on hazards identified in Islam et. Al (2011) as follows; Barrier measures, Stormwater management, Sediment Filter measures, measures which target Onsite Wastewater treatment Systems and Farming Management measures (Fig.4). These measures exist on a spectrum from those that are nature focused to those that use 'green-engineering' to mimic a natural process to provide a desired function. The following is a general overview of some of the different types of SWP measures which are available and have been implemented to address various pollution issues and are summarised in Table

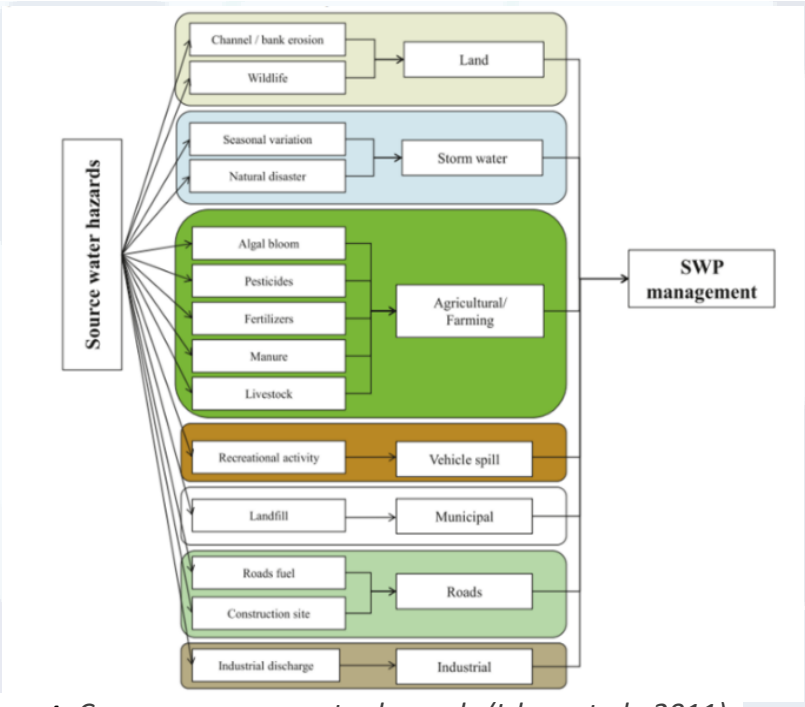


Figure 4. *Common source water hazards (Islam et al., 2011).*

2.3.1 Source Water Protection measures

Barrier measures

Barrier measures to protect source water quality are preventative actions and treatments that prevent contaminants from reaching and polluting water sources. Some examples are as follows:

Vegetated filter strips (Fig.5) are primarily used in agriculture to control nutrients, pesticides and eroded soil. They consist of narrow strips of stiff and tall grass ranging from 0.75 to 1.2 m in width (Kemper et al., 1992; Yuan et al., 2009) that surround the source water. They work best on slopes that are less than 5% and not greater than 15%. Vegetated filter strips reduce water contamination by slowing the flow of water and allowing the soil to filter it naturally. Another benefit is that covered soil does not wash away, so vegetation filter strips also help reduce erosion (Grace, 2002). The slope of the drainage area above the filter strip needs to be 1% or greater to prevent sediment backing-up and allow runoff to enter the vegetation filter strip. Dillaha et al. (1986) recommends removal of woody material from grass vegetated filter strips because it can disrupt the evenness of runoff flow through it, thus impairing its longevity and effectiveness.

Riparian buffer strips (Fig.6) are areas of permanent vegetation established along the



Figure 5. The key design factors of vegetated filter strips (Wu et al., 2014).

banks of rivers and streams to reduce direct sediment and pollutant loads from adjacent farmland entering the water (Kiely et al., 2000). They can be classified as either grass or forest. Buffer strips intercept water flowing towards a water body, allowing particulates to filter out of water and settling to occur. Dorioz et al. (2006) concluded that the efficiency of buffer strips in reducing sediment loads is much greater than that for dissolved compounds. While the majority of sediment (53–86% of the input load) is retained in the first 5 m an increase of the width of the grass buffer strip to 15 m, leads to a reduction in the concentrations and flux of all the dissolved contaminants (Schmitt et al., 1999), with 100% sediment removal being achieved at greater widths of 20-30m (Parkyn et al., 2003). A smart buffer is a buffer which is designed so as to extend in size along a water course as needed and narrow in areas that are not as susceptible to pollution, this ensures a greater protection in higher risk areas, but does not take up valuable

agricultural land in areas of lower risk. Even small buffer strips can have positive effects in relation to bank stability and removing direct cattle access (Laubel et al., 2003). However, buffers can become ineffective if not properly maintained and high levels of nutrients and sediments accumulate over time.

Erection of stock-proof fencing (Fig.7) restricts livestock access to water bodies mitigating against sediment and total coliforms. Indirectly, the regeneration of natural

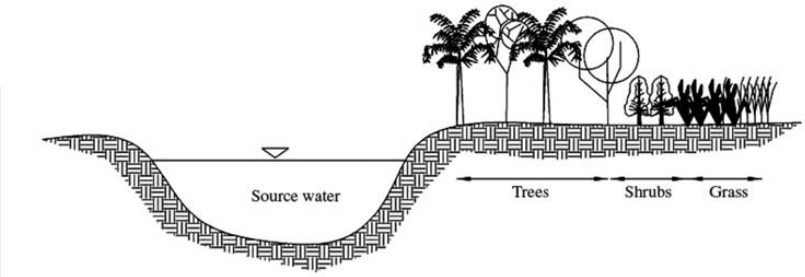


Figure 6. *Example of a buffer strip (USEPA 2001e)*

vegetation inside the fence acts as a barrier for sediment and run-off from grazed fields, prevents bank erosion and promotes bank stabilisation. The National Source Protection Pilot Project at Churchill & Oram Group Water Scheme, County Monaghan, Ireland reported that fencing was most successful at upland sites and lowland areas outside of the floodplain. However, results have indicated that this is a long-term investment and must be maintained to ensure continued incremental improvements. Providing an alternative water source e.g. self-pumping drinkers are important for securing buy-in from farmers (Linnane et al., 2011).



Figure 7. *Fencing erected as part of source protection works in Mid-Roscommon GWS (NFGWS, 2023).*

Bank revetment measures (Fig. 8) are structures placed along the river bank used to stabilize or protect the bank from erosion. Different methods of revetment can be used such as willow spilling, boulder installation and logging with tree trunks. Riverbank erosion is not only a potential source of pollution in and of itself but, in some instances, it can create delivery points for overland flow paths. Where bank revetment was implemented in Stranooden GWS, Ireland, it was decided to plant over 750 fruit trees 4-5 metres apart along the same banks to ensure long lasting bank stabilisation (NFGWS, 2022).



Figure 8. Examples of bank revetment measures carried out by Stranooden GWS. (NFGWS, 2022)

Stormwater management measures

Stormwater management is a means by which surface water runoff can obtain initial natural treatment before entering wastewater treatment plants. This helps to limit untreated runoff from storm events via excess rainfall entering into the source water. There are various source protection measures within this category for example dry detention ponds, wet detention ponds, constructed wetlands and bioretention areas which are aimed to mitigate against a range of pollutants such as removal of nutrients , trace/heavy metal, sediment, and hydrocarbons. Some examples within this category include

Dry detention ponds have the least impact within this category on mitigating against water pollution but instead are targeted at slowing down stormwater flow to prevent flooding. They are shallow basins that detain stormwater temporarily for a minimum time (e.g. 24 hours) to reduce peak flow rates (NPDES, 2019).

Wet detention ponds have a permanent pool of water and may also contain a fore bay to collect the water that can remove suspended sediments. Enhanced vegetation areas like marsh can also increase the effectiveness of wet ponds.

Constructed wetlands follow a range of designs which aim to mimic the natural physical, chemical and biological processes occurring in a natural wetland. They contain both soil, plants and water. Their high vegetation cover has a stabilising effect and enhances sediment retention by mitigating resuspension (Braskerud, 2001). Constructed wetlands have been used as a cost-effective alternative to traditional wastewater treatment plants. For example, a constructed wetland was used as an alternative to chemical strippers to remove phosphorus in the UK initially as a cost benefit solution, but it also had the extra benefit of reducing DOC loads by 53.3% (Souliotis and Voulvoulis, 2022). Positive results like these have resulted in a growth in the use of constructed wetlands for treating agricultural run-off (Wang et al., 2018). A systematic review by Newman et al. (2015) found that all types of on-farm construction wetlands were effective at reducing total suspended solids (TSS), however it was recommended that in order to remove at least 80% of TSS the constructed wetland should have an area of over 2,500 m^2.

Bioretention areas are shallow landscaped depressions filled with sandy soil and vegetation (ground cover, shrubs and trees), which can remove pollution and reduce runoff downstream. They are suitable for small sized areas and infiltrate runoff to groundwater hence they are normally used in an urban environment. Generally, bioretention areas are designed to achieve a TSS removal rate of 75–97%, (Hui Hwang Goh et al., 2019) The filler used captures TSS through sedimentation and filtration; however, the type of filler has little effect on the TSS removal rate (Barrett et al., 2013; Hui Hwang Goh et al., 2019; Hatt et al., 2008). Likewise, Barrett et al. (2013) showed that bioretention areas with plants removed only 1% more TSS than bioretention areas without plants.

Sediment filter measures

There are a number of practices which can help to limit upland sources of sediment from entering rivers and streams, including sediment trapping structures and erosion control strategies (Hargrove et al., 2010). Examples include:

***Sand* filters** are made of a sedimentation and sand chamber to remove mainly the particulate matter with moderate bacteria removal. A simple filter will remove most particles down to 5 µm in size. Multi-media filters which use sand and anthracite, and possibly a third medium, in discrete layers, can yield very efficient filtration down to 2 µm in size (Crittenden et al., 2012).

Silt trap (Fig.9) Sediment settles out of suspension onto the bottom of the trap allowing cleaner water to discharge to the waterbody. It is able to hold more sediment than a sand filter. The size of the chamber needs to be large enough so the flow of water into it does not cause a lot of turbulence which would prevent solids settling. A 180 m^3 linear sediment trap constructed in 2016 as part of The Defra and Environment Agency Demonstration Test Catchment

programme in the U.K resulted in suspended sediment load reduction of 58% in the nearby river Defra (2020). They are cheap to construct and maintain and require a small area of land.

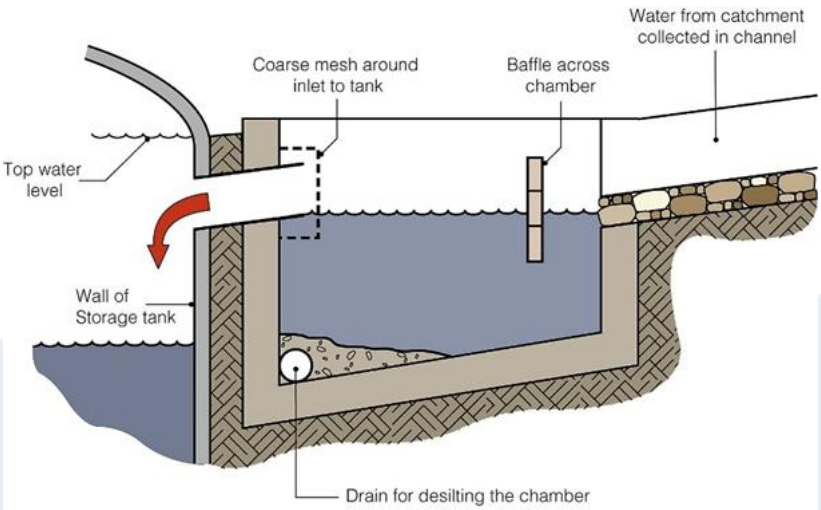


Figure 9. *A simple silt trap. (McMahon et al., 2019).*

Onsite wastewater treatment system measures

Worldwide, 24% of wastewater is treated by the use of onsite wastewater treatment systems (UN Habitat and WHO, 2021). The basic treatment system comprises a septic tank linked to a distribution system that spreads the effluent below the soil surface via perforated pipes, the leaching bed. Between 50% and 90% of the waste treatment takes place in the soil (Gerba et al., 2023). There are also additional technologies designed to increase biological activity within these systems through aeration of the provision of surfaces to increase biofilm formation. These measures are usually required in rural areas where municipal sewer systems are not available. If onsite wastewater treatment systems are not properly designed, installed and maintained they can be a source of nutrient pollution (McCarthy et al., 2008) and need to be replaced with correct installation. Setback distances for onsite wastewater treatment systems from water sources are important in reducing potential pollutants such as Nitrogen, Bacteria, Protozoa and Viruses from entering source water (Dawes & Goonetilleke, 2003). Appropriate setback distances will vary depending on subsoil, geological and hydrological conditions. In addition, newer technologies which include aeration systems and secondary or tertiary treatment are available.

Farming Management Measures

Farming management measures e.g. yard coverage via roofing, improvements to guttering, slurry drains and ditch water pools, with the aim of maximising storage capacity for dirty water and reducing farmyard runoff can be used to reduce aquatic pollution and runoff. Incorporating multi-species swards such as clovers, grasses, brassicas and herbs, as part of the normal spring

reseeding programme for the farm will reduce reliance on nitrogen fertilizers. Additionally, multi-species swards are more resilient to drought compared to monocultures. They recover more quickly after receiving moisture, providing greater adaptability and resilience to climate change (Farming for Water EIP, 2024). Using conservation tillage when cropping covers 30 percent or more of the soil surface with crop residue, after planting, reducing soil erosion by water and the risk of nutrient and sediment loading in surface waters. Using low emission slurry spreading equipment such as the dribble bar and trailing shoe decreases the surface area of the manure in contact with the air and reduces runoff of nutrients and microbial pathogens into nearby surface waters (NFGWS, 2020).

Table 2. *SWP measures used to increase the quality of raw drinking water at source. Colours used to categorise SWP measures as per Islam et al., 2011 SWP management in Fig.4. lue=Stormwater, Dark green=Agricultural, White= Municipal, Orange=Land, Light green=Roads,*

SWP MEASURE	REFERENCE	DESCRIPTION	POLLUTANT measure used to mitigate against	Potential COST and MAINTENANCE	EXAMPLE FROM PAPER
Wet detention basin or pond, retention basin, in-ditch sediment pond	(NCDENP 1999)	Has a temporary pond in addition to the permanent pond and may contain a fore bay. Surrounded by vegetation and contains some marsh. 85% more efficient in removing TSS than dry ponds. See Fig. 10(b)	Stormwater. Sediment removal. Nutrient removal. Heavy metal removal.	Keeping the pipes clear of debris. Repairing areas of erosion. Maintaining vegetation. Large area of land needed. Operational and Maintenance costs are 5% of total costs.	
Stormwater or constructed wetland or reed bed or treatment wetland	(NCDENP 1999)	Contains both soil and special plants generally containing 50% high marsh, 40% low marsh. Longer detention time. See Fig.10(c)	Domestic wastewater Agricultural runoff Stormwater Phosphorous Trace metals Hydrocarbons	Keeping the pipes clear of debris Repairing areas of erosion Large area of land needed.	53.3% reduction of DOC (Souliotis and Voulvoulis, 2022) Area of over 2500 m2 can remove at least 80% TSS (Newman et al, 2015) Retention of up to 82% for TSS
Dry detention ponds or detention basin, extended detention basins or dry ponds	(NCDENP 1999)	Temporarily stores water. Requires a large amount of space. Only controls flood flows, less effective at removing pollutants. See Fig.10(a)	Stormwater	Keeping the pipes clear of debris Repairing areas of erosion	
Bioretention areas or bioretention cells or rain gardens	(NCDENP 1999)	Shallow landscaped depressions filled with sandy soil, topped with a thick layer of mulch, and planted with dense vegetation. Should also contain grass buffer strip, and ponding area See Fig.10(d)	Stormwater TSS Nutrients Trace and heavy metals	Maintenance of all materials necessary. Suitable in small areas Not suitable for areas with slope > 20% Lower cost compared to curbs or gutters in urban areas.	TSS removal rate of 75–97%, (Hui Hwang Goh et al., 2019)
Grass swale or grass waterway, bioswale	(Clary et al., 2020)	A narrow, broad channel, often including plants and trees (bioswale)	Stormwater Sediment removal Trace chemical removal	Low construction and maintenance costs	TSS removal efficiency of 35% (NCDENP 1999).
Sand filter	(NCDENP 1999)	Made of sedimentation and sand chamber. See Fig.11	Stormwater Particulate sediment removal Moderate bacterial removal	Requires annual maintenance.	
Check dam	(López-Ballesteros et al., 2019)	The construction of rock dams across a watercourse	Reduce sediment Reduce nutrients Reduce erosion		
Providing and servicing bins	(NFGWS, 2023)	The abandonment of waste in or near source water	Reduce illegal dumping	Resulted in a 50% drop in litter between 2020 and 2021.	

SWP MEASURE	REFERENCE	DESCRIPTION	POLLUTANT measure used to mitigate against	Potential COST and MAINTENANCE	EXAMPLE FROM PAPER
Filter strips or filter devices, Vegetated filter strip	(Yuan et al. 2009)	Stiff and tall grass ranging from 0.75 to 1.2 m in width surrounds the source water to hold the soil by using the vegetation root. See Fig.6	Stormwater Nutrients Pesticides Agricultural pollution Eroded soil	Low construction and maintenance costs	
Fencing areas, cattle fencing, sheep wire fencing, solar fencing,	(Owens et al.,1996)	Fence needs to erect at least 1.5 metres from the top of the bank or This is a long-term barrier. See Fig.8	Removal of faecal material from watercourses, Mitigating against sediment Mitigating against total coliforms. Improved stream habitat and biological community structure	Cost effective Need to provide alternate water sources for livestock. Fencing will need regular maintenance and access to maintain vegetation area beyond the fencing.	(Miller et al., 2010)
Changing animal diets	(Capper et al., 2008)	Using Low Crude Protein Animal Feeds	Nutrient reduction Nitrate reduction	May be limited in the grass-based grazing systems	
Setback distances for septic tanks	(Linnane et al., 2011)	Soil type and topography must be taken into account when determining set-back distances	Nitrogen Bacteria, Protozoa, Viruses	Need expert advice. One off cost to move a septic tank. Grants may be available.	
Replacement and installation of septic tanks	(McCarthy et al., 2008)	All on-site wastewater septic tanks need to be properly designed, installed and maintained	Nitrogen Bacteria, Protozoa, Viruses	Septic tanks should be inspected annually to ensure that the internal structures are in good working order and to monitor the scum level.	
Land spreading exclusion	(Linnane et al., 2011)	State distances from water bodies where no manure/fertiliser can be applied.	Microbial pathogens	Measures are currently set as part of the nitrates directive	
Weed-wiping service	(NFGWS, 2022)	Free weed/rush-wiping service Using glyphosate instead of MCPA	Control rush cover Reduction of spray drift Less land compaction. Less pesticide demand More control of target vegetation. 50% reduction in MCPA loading exiting the Derryvalley sub-catchment occurred in 2021, compared with 2020	Needs to cut back rushes after treatment. Follow up measure by adding lime where needed to the pasture to address the acidic nature of the soil and help to prevent rush re-establishment.	
Boom Sprayer service	(NFGWS, 2022)	Calibration and certification of boom sprayers in the catchment. Fitting of low drift nozzles	Reduced loss of herbicide into the environment	Boom Sprayers need a service check at least once per year	
Tramline management	(Withers et al., 2006) (Bailey et al., 2013)	Establishment of partial crop cover in the tramline, and establishing tramlines across the slope rather than up and down the slope	Reducing runoff Sediment reduction Phosphorus reduction.	Cost effective	
Conservation tillage (no-till, ridge-till, strip-till, mulch-till, and reduced-till		A non-inversion tillage system, where at least 30 % of crop residues remain on the surface.			(Klik and Rosner, 2020) Mulch tillage reduced the SOC losses by 34–86 % and no-till with cover crops during winter by 58–89 %
Exporting the slurry from the area to	(Linnane et al., 2011)	Excess quantities of organic wastes should be exported from the farm with a soil P index of 4 to a dedicated, centralised regional facility	Nitrogen Ammonia	Short term solution	

suitable areas with low P indices					
Anaerobic digesters, slurry pelleting and/or decanting systems	(Cathcart et al., 2021)	Mechanical separation partitions phosphorus into the solid fraction and further processing into a fuel pellet can provide an additional source of energy and revenue.	Phosphorous Captures methane and Carbon dioxide. Can be recycled into fertiliser, reducing the need for synthetic fertilisers.	Need to be appropriately trained to operate system. Regular maintenance required. Substantial storage capacity may be required Requires significant capital investment. Can improve profitability of dairy cows by 9–20% if used at large scale.	
Targeted information leaflets in relation to farmyard management circulated	(Linnane et al., 2011)	Important to create awareness of good farm yard practices such as clean and dirty water separation on the farm by making improvements to guttering, slurry drains and ditch water pools, the first method of source water protection.	Phosphorus, Biological Oxygen Demand (BOD), ammonium, sediment, MCPA, pesticides, manganese, and microbial pathogens	Dairy farmyards are likely to pose a greater threat than dry stock farmyards. Regular farmyard maintenance required but this will ensure farmer is keeping in compliance with Article 17 of GAP Regulations.	
Silt traps or silts mats or sediment trap or sediment basin	(DTC, 2020)	Particularly beneficial at the bottom of steeply sloping fields, adjacent to water courses. See Fig.12	Sediment removal Reduces turbidity levels	Cheap to construct and maintain	Sediment load reduction of 58%. (DTC, 2020) Average annual STE across the measured data from agricultural catchments was 59%. A storage ratio of at least 120 m^3 ha^{-1} is required to deliver a STE of 55% or better. (L. Chris Smith and Muirhead, 2023)
Sediment pond					Sediment load reduced by up to 21.74% (Strauch et al., 2013)
Buffer strips', grass buffer strip or, Riparian buffers, willow buffer	(Kiely et al., 2000)	Areas of permanent vegetation established along the interface between a water body and land. The wider the strip, the greater the protection. See Fig.7	Eroded soil, Sediment removal Riverbank stabilisation Nutrients phosphorus faecal coliform run-off	A smart buffer will narrow in areas that are not as susceptible to pollution. Willow will need to be cut back every two years and will also prevent the buffer zone from becoming a store for phosphorus.	(Dorioz et al. 2006) A 5m buffer reduced sediment 37%. At 25m to 56% (Zhang and Zhang, 2011) Buffer strips are most effective when the flow is shallow (nonsubmerged), slow, and enters the buffer strip uniformly along its length. Their sediment trapping performance decreases as the sediment particle size decreases. They are better filters of sediment than of nutrients. (Barling and Moore, 1994)

SWP MEASURE	REFERENCE	DESCRIPTION	POLLUTANT measure used to mitigate against	Potential COST and MAINTENANCE	EXAMPLE FROM PAPER
Beetle banks	(Cfeonline.org.uk, 2019)	Grass mounds that cut across the middle of large arable fields, providing permanent vegetation cover for beetles and other beneficial insects.	Improve infiltration and reduce the risk of soil erosion.	Generally appropriate for fields larger than 20ha. Once established, you should only cut the grass strips when there is a need to get the dead tussocks to regenerate (this is likely to be no more than once every three years)	
Mixed cropping/ polyculture/ inter-cropping/ cocultivation, crop rotation.	(Kleinman et al. 2005).	Increase the productivity of the soil and also the improves soil composition	Limits fertilizer use Reduces nitrates	The use of herbicide for weed control and crop control may increase pesticide pollution.	Crop rotation reduced sediment load by up to 20.73% (Strauch et al., 2013)
Contour farming	(Gathagu, Mourad and Sang, 2018)	Contours are level lines across a slope at a constant elevation	Increases the surface roughness, and strengthens the rainfall infiltration on the area. Reduces runoff from scouring of the soil	A small slope gradient along the row is desirable Most effective when combined with filter strips reduced sediments by 63% as opposed to just 36% alone. Marginally more expensive and time-consuming than ordinary cultivation.	
Contour bunding, terraces	(Gebrernichael et al. 2005)	An embankment of stones built along the contour across the marginal sloping, hilly land with poor soil.	Slow surface run-off Reduce soil erosion and hilly land with poor soil quality.	Regular bund maintenance with emphasis on height increment is crucial. Very cost effective	Ability to trap soil lost by sheet and rill erosion, was 68% (Gebrernichael et al. 2005) Terraces could reduce sediment loads by up to 31% (Strauch et al., 2013)
Tree planting	(NFGWS, 2022) (Lazzaro et al, 2008) (Nisbet et al., 2011)	Within buffer zones and along riversides. Willow and poplar can be beneficial as fast growing species to act as a nutrient soak. The associated leaf litter can be a major source of DOM leached into surface waters (Franklin et al., 2021)	Take up excess nutrients, Aid bank stabilisation. Shade influences growth of aquatic plants, freshwater algae and ground plants, and moderates water temperatures. Lower risk of spray drift, have been shown to reduce drift by 60-90 per cent.	Planting on better quality land can result in a reduction in land value, a loss of agricultural subsidies and a reduction in income. There is a need to provide sufficient compensation for these losses by increasing incentives for woodland planting.	(Agouridis et al.,2005)
Reforestation		Reforestation is the conversion of previously forested land back to forest.			
Planting mixed species hedgerows, rewilding	(NFGWS, 2022)	Most benefit provided if planted on poorly draining areas, alongside watercourses, fences and across slopes, following a contour. Also at Livestock access points on watercourses	Enhancing biodiversity, Nutrient absorption, Bank stabilisation, Immobilisation of soluble nutrients in overland flow	Annual maintenance for first 4 years, every 2 years after that. Cost will vary depending on species selected however financial schemes may be able to assist with cost.	
Bank revetment measures	(NFGWS, 2022)	Willow spilling, boulder installation and logging with tree trunks. See Fig.9	Issues of erosion and sediment within rivers and streams	Cost will vary depending on method used.	
Re-establish the pathway to the natural flow path of the river.	(NFGWS, 2022)	Reintroduce the river's natural meanders. Can be done by using boulders or removing dams	Slows river flow, Spreads the water over a wider area. Increases wildlife	Can be costly Requires input from experts. Needs to be viewed based on the whole catchment not just localised to one area of the river.	
Peatland rehabilitation	(Rolston and Linnane, 2020) (Wilson *et al.*, 2011)	Drain blocking / grip blocking, re-vegetated, Core matting.	Reduce the dissolved organic carbon. Reduced peak flows, a longer water retention time, slower run off rates.	Is costly but the long term benefits outweigh the costs.	(MoorLIFE Project., 2020) (Wallage, Holden and McDonald, 2006) DOC and colour values successfully lowered by between 60% and 70%

2.3.2 Source Water Protection worldwide

There are many examples globally of SWP implementation. A recent global inventory of investments in catchment services recorded an average annual growth rate of 12 % in catchment investments between 2012 and 2015 across 62 countries (Bennett & Ruef, 2016). In some countries SWP implementation has a long history and is well established in water governance and institutional policy, whereas in other jurisdictions implementation is restricted to regional or localised initiatives. Nevertheless, there are numerous examples in which implementation of SWP have demonstrated effective protection of source drinking water and reduction in targeted contaminants. The implementation of source water protection measures is dependent on a range of factors which are linked not only to the hydrological and land use conditions within an area but also on a range of socioeconomic and institutional factors such as the legislative and institutional environment and the planning and water resource management (Ivey et al 2006). Source water protection often takes place at a regional or local scale without necessarily formal legislative or institutional policy guidelines regulating administration or funding the activities, nevertheless, in recent years there has been many jurisdictions including the US and Canada which have legislative support for source water protection and, consequently, SWP has gained considerable attention and focus on water management activities.

Both the US and Canada, each have their own Clean Water Legislation (Clean Water Act (CWA), 1972 in the US and the Clean Water Act, 2006 in Canada) which aim to protect existing and future sources of drinking water from threats to quality and quantity. In addition, they also signed the Great Lakes Water Quality Agreement (GLWQA) in 1972 to protect the water resources common between the two countries. The CWA in the US has contributed to reducing water pollution, however, the focus is placed more on ecological parameters than water quality for drinking water purposes and it has been more effective for point sources than non-point sources of pollution (Gullick, 2014). On the other hand, the Safe Drinking Water Act (SDA), 1974 contains measures related to SWP, particularly for groundwater sources and requires all States to create a source water assessment programme (SWAP) which includes an inventory of potential sources of contamination of land areas that provide drinking water (DWSD, 2015). The process of preparing SWAP reports has often acted to motivate or encourage implementation of SWP measures and programmes, but nevertheless, as there is no specific requirement for SWP activities, many programs did not result in actual water quality protection (Gullick, 2014). To encourage SWP measure implementation the US Government introduced a provision in the 2018 Farm Bill to allocate 10% of total funds available for SWP conservation programmes each year (Mehan & Carpenter, 2019). The US Environmental Protection Agency (USEPA) provides many resources on source water and also provides technical support and information on available funding (Gullick, 2014). In the US, the most straightforward way to protect source water is

through ownership of the entire watershed surrounding the abstraction point. In this way municipalities and water providers can control land use directly, however, such large-scale purchase and ownership of land is not always available and consequently, many SWP are still dependent on local and regional scale implementation, often at the community level. Therefore, despite the legislative framework for SWP in the US, its implementation often remains voluntary, which has also been reported to be the case in neighbouring Canada (Ivey et al., 2006). In Canada, approximately 88% of its potable water comes from surface water sources (Government of Canada, 2022). The Clean Water Act, 2006 outlines a multibarrier approach to ensure clean and safe drinking water. The main responsibility for water management, however, falls principally with the provincial government authorities. On this basis, some provinces have established SWP programmes, which form the bases for the development of science-based assessment reports and local source protection plans led by multi-stakeholder source water protection committees. However, given variation across provinces and territorial governments, the approach taken can vary and may contribute to an uneven application of SWP planning and implementation across provincial jurisdictions (Ibrahim et al., 2017). More recently, the Canada Water Agency was established in 2023 as a stand-alone agency to restore, protect, and manage waterbodies of national significance (4 lakes and 4 rivers) and improve freshwater. Establishment of this agency aims to demonstrate the Government's prioritisation of the restoration of large lake and river systems in Canada but also emphasises the importance of the watershed-based approach which is considered to underly Canada's investment in freshwater management.

Canada - Case study (Miller et al., 2010)

Location: The Lower Little Bow River in Southern Alberta, Canada.

Issue: Fecal material accumulating on eroded streambanks.

Measure: Barbed wire fencing was installed on June 29, 2001, on both sides of an 800m reach with a distance of approximately 40 – 80m between the edge of the river and the fence. There is a cattle crossing located upstream that allows cattle to be moved between pastures. An off-stream watering system was installed on the South side of the river.

Result: After a 4 year monitoring period the overall health of the riparian area improved from a score of 65% (healthy but with problems) for pre-fencing phase in 2001 to 81% (healthy) for post-fencing phase in 2005. This was based on a visual assessment, according to the field workbook for riparian health assessment for streams and small rivers (Fitch et al., 2001), of vegetative soils and hydrologic features. Fencing eliminated faecal material washing off the cattle and accumulating on eroded streambanks. Tree and shrub establishment reduced bare ground along the streambank. Turbidity was significantly lower downstream in 2004 and 2005 some filtering of sediment may have occurred along the re-vegetated streambank, lowering turbidity values downstream.

***USA - Case Study* (R. E. Sheffield et al., 1997)**

Location: Two commercial cow-calf operations in southwest Virginia, US.
Issue: Sediment and sediment-bound pollutants entering water source
Measure: Provided off stream water troughs as an alternative drinking water source for cattle.
Result: Cattle drinking from the stream were reduced by 89% and total time spent in the stream area was reduced by 51% following the trough installation. Stream bank erosion reduced by 77%, a 90% reduction in TSS, a 54% reduction in TN, an 81% reduction in TP and a 75% reduction in sediment bound P in stream water.

In contrast, countries in South America generally lack the technical capacity or local expertise to implement regional or local SWP measures. The geographical diversity of this continent results in extreme gradients in water availability and quality. For instance, the Amazon and Orinoco basins and the Colombian and Ecuadorian pacific coast are scarcely populated and receive abundant precipitation (Urrutia & Vuille, 2009), while the Pacific coast of Peru and north and central Chile is densely populated and receives little or no precipitation, except during El Niño events (Wang & Fiedler, 2006). Fragmented national water policies have only exasperated the issue of access to clean drinking water in South America (The Circular Water Economy in Latin America, 2025). Often multi-sector partnerships involving both public and private entities, like The Nature Conservancy with partners like the corporate FEMSA Foundation and the Inter-American Development Bank, pool their investments to set up water funds that pay for watershed protection. For example, in Ecuador the first Water Fund was created in 2000 in Quito and involved the establishment of a trust fund called Fondo del Agua, or FONAG to finance payments to landowners in the watershed in return for their safeguarding the water supply for the city. FONAG is a non-declining endowment fund that can receive money from both government agencies and private organisations (Postel and Thompson, 2005). Today there are 32 Water Fund initiatives providing a steady source of funding for the protection of more than 7 million acres of watersheds across South America (Calvache, 2024).

South American - Case study **(Ozment et al., 2018)**
Location: The Cantareira Water Supply System for São Paulo, the largest city in South America.
Issue: Sediment pollution of water sources.
Measure: Reforestation of 4,000 hectares (ha) of native forest.
Result: Based on the Green-Gray Assessment developed by the World Resources Institute it was concluded that this measure could reduce sediment pollution by 36% within 30 years and reduce turbidity by almost 50%. This could reduce the costs of sediment management to generate an estimated 28 percent return on investment (ROI) in 30 years.

In some regions, access to water often takes precedence over issues related to water quality. In Asia for example, which has the largest percentage of the world's freshwater resources at 32%, has disproportionate access to water between countries. Japan and Singapore scored 91.80 and

99.9 respectively on the Environmental performance Index (EPI) drinking water score index 2024, which measures the quality of a country's drinking water, while Pakistan and India scored 17.4 and 19.4, respectively. Some countries such as China have implemented a legislative framework for SWP such as the State Council's Action Plan for Water Pollution Prevention and Control, which clarifies that the local Governments are the main body responsible for the improvement of water pollution. It also launched several policies in recent years such as the water pollution prevention action plan, agricultural sustainable development plan and industrial green development plan in an effort to reduce water pollution. While there has been some improvement, 5.5% of reservoir water sources and 16.1% of the lake water sources in China are still not compliant with regulations (Shi, 2020).

However, in other countries such as India the issues are more acute, with water supply and access a significant issue, which can often supersede any attention placed on water quality. While water is plentiful in the lower reaches of the Ganges River Delta in the east, deficits are common in the northwest, west, and south. Base flow rates in many rivers are decreasing due to over-abstraction, drought, and degradation of spring sources. All of this has resulted in India being one of the most water stressed countries in the world. India divides its surface water into 22 basins. 60% of India's renewable surface water derives from the Ganges and Brahmaputra Basins but only 37% of this water is exploitable (USAID, 2021). States in India have their own water policies based on the National Water Policy introduced in 2012, but they are not obligated to use integrated water resources management. Today India's Government, voluntary organizations and NGOs are investing in watershed management programmes but more from a water quantity perspective than a water quality perspective (Bouma et al., 2007).

***China - Case study* (Liu et al., 2013)**
Location: Xiangxi River is a tributary of the Yangtze River, which is the longest river in China and third longest in the world.
Issue: Agricultural non-point source pollution contributing to local water degradation
Measure: Used a Soil and Water Assessment Tool (SWAT) to investigate the effectiveness of changes in land use, fertiliser management and tillage management to alleviate water pollution.
Result: When farmland was returned to forests, both runoff and non-point source pollution loads showed a clear downward trend and the non-point source pollution loads in the Xiangxi River watershed decreased by at least 20%. Conservation tillage reduced runoff by 15.99% total nitrogen (TN by 8.99%) and total phosphorus (TP) by 7%. Contour farming reduced runoff by 9.16%, TN by 8%, and TP by 5%. Changing the fertiliser application resulted in little change in local runoff, the N and P loads reduced in direct proportion to the amount of chemical fertiliser applied.

***India - Case study* (Uniyal et al., 2020)**
Location: The Baitarani watershed (1776.6 km2) of the Upper Baitarani River basin, Eastern India.
Issue: Loss of sediment caused by soil erosion
Measure: Evaluated the efficacy of Contour bund, Bench terraces, conservation tillage, contour farming and stream bank stabilization for controlling sediment yields at watershed (overland processes including tributary channels) and sub-watershed (overland processes including tributary channels as well as in-stream processes in the main channels) using SWAT.
Result: The costly measure of streambank stabilization was found to be most effective at Watershed level with an average reduction in annual sediment of 69.54%. Bench terracing was most effective at sub watershed level (the overland processes including tributary channels) with a 32.40% reduction in annual sediment yield. However, the modeling results indicated that if a combination of all eight BMPs are implemented, the reduction of sediment yields is increased by 76% and 80% at sub-watershed and watershed levels, respectively compared to the Base Scenario.

2.3.3 Source Water Protection within the European Union

Within the EU, SWP it is supported through two principal legislative frameworks; the WFD for which catchment management plans are developed typically on six-year cycles and the recast Drinking Water Directive (EU) 2020/2184 which came into force in January 2021 and requires the application of risk-based approach to catchment areas for drinking water supplies. These two directives are complementary in that the Drinking Water Directive states explicitly that the risk-based approach to drinking water safety should be based on the knowledge gained and actions carried out under the WFD (DHLGH, 2024). In all Member States (MS) protection areas are delineated which aim to prevent impact of human activities on drinking water sources and the size of the area delineated is usually linked to the degree of protection desired and varies between MS, but is generally based on factors such as the distance from the abstraction point, time taken for a contaminant to move and time needed for attenuation processes. In some countries additional protection areas are also defined to protect the quantity of water supply. In most countries there are restrictions in the types of activities which can take place within these protection areas. Each MS is responsible for implementing these directives into their own national laws and for developing the necessary monitoring programs and infrastructure. Through the designation of 'nitrate vulnerable zones (NVZ)' in which programs of action must be implemented to reduce nitrate pollution linked to agriculture activities, the Nitrates Directive (91/676/EEC) also acts to improve the provision of clean drinking water. Other EU legislation such as the Environmental Quality Standards Directive (2008/105/EC) and the Urban

Wastewater Treatment Directive (91/271/EEC) despite not directly incorporating aspects relating to SWP measures, nevertheless, contribute to the protection of water resources.

Since 2000, the WFD has been the main legal instrument for water protection in Europe, aiming at achieving good ecological status for all water bodies by 2027. The EU is home to 100,000 surface water bodies with only 37% currently achieving 'Good' ecological status under the Water Framework Directive (WFD) (European Commission, 2025). It is recognised that within the EU, nutrients and pesticides are amongst the most important sources of drinking water pollution (EEA, 2018), and achieving water quality objectives under the WFD is still an ongoing challenge for many countries across Europe (Wuijts, 2021). For some countries within the EU, there has been a long history of SWP measures but the adoption of the WFD, owing to its river basin approach, encourages cross-sectoral cooperation and stakeholder engagement both regionally, nationally and additionally between MS. Nevertheless, as differences exist in the implementation of WFD into national policies, it is often found that the mode of implementation is adapted to existing national policy structures and this can impact the effectiveness of its implementation between MS leading to lack of coherence and inconsistencies (Birkenstock and Roder, 2019; Wuijts, 2021).

In recent years, from a drinking water supply perspective, the greater focus of protection of drinking water sources and the application of risk-based approaches in the most recent iteration of the EU Drinking Water Directive (2020/2184) demonstrates an increasing focus on the source of drinking water compared to previous version of the Drinking Water Directive, which did not explicitly refer to protection of the water at source. Consequently, this represents a shift from a reactive approach to drinking water management to a preventative proactive one (Dunn et al., 2017; Andries et al., 2024), and opens a greater need for improved integration between implementation and governance of the Drinking Water Directive and the WFD across all MS. In addition, the new 2025 European Water Resilience Strategy further aims to address water scarcity and improve water management and is likely to support SWP initiatives as it includes provisions which aim to adopt practices to restore water ecosystems, improve water retention on land and prevent water pollution at source. This strategy aims to improve governance and implementation and support public and private investments in infrastructure while also supporting research and innovation. The strategy, therefore, is also a further attempt to move away from reactive crisis management to more proactive water management.

***Finland - Case study* (Tanttu and Jokela, 2017)**
Location: Jäniksenlinna MAR plant and Rusutjärvi MAR plant are located in the municipality of Tuusula in Southern Finland, 30 km North of the capital city of Helsinki. Raw water source is Lake Päijänne.
Issue: Humic lakes containing natural organic matter(NOM) derived from the decay of vegetation in the forests and peatlands of the catchment areas. While there is no risk of DBP development this case study demonstrates a method to reduce NOM.
Measure: To decompose and remove NOM Jäniksenlinna MAR plant used a combination of basin infiltration (82%), and well infiltration (18%) methods. Basin infiltration consists of raw water introduced to three infiltration basins with cascade aeration. Well infiltration is where raw water is led into the 400 mm diameter well by gravity through the well head casing. At the same time air is sucked into the well through a ventilation pipe. Rusutjärvi MAR plant used the well infiltration method only. The raw water in both plants was infiltrated to an unconfined esker aquifer and resided there for between 30-60 days.
Result: Average TOC reduction is 73 % Jäniksenlinna MAR plant and 66 % for the Rusutjärvi MAR plant.

***Norway - Case study* (Syverson, 2005)**
Location: Vikeby, Mørdre, Grorud and Linnestad in Southern Norway. All four sites are grassland with Linnestad having grassland and trees.
Measure: The influence of four criteria on Vegetated buffer strips: (i) buffer zone width, (ii) amount of surface runoff water entering the buffer zone, (iii) seasonal variation and (iv) vegetation type.
Result: Both simulated and natural run-off events varied between 60-89% reduction in P, 37-81% reduction in N and 81-91% reduction in particles. A buffer zone with 5-10 m width is an effective trap for particles and particle-bound nutrients but there was a significantly higher removal efficiency (%) from a 10 m wide buff zone. Particulate matter was removed more effectively by buffers containing forestry.

***Sweden - Case study* (Brian Omondi Oduor et al., 2023)**
Location: An agricultural catchment in southeastern Sweden within the Lake Malaren basin of Uppsala County.
Measure: Used the Soil Water Assessment Tool (SWAT) model to assess the effectiveness of four BMPs (filter strips, sedimentation ponds, grassed waterways, and no-tillage) in reducing sediment and phosphorus export.
Result: Filter strips were highly effective in reducing sediment (− 32%), soluble phosphorus(−67%), and total phosphorous (−66%) exports, followed by sedimentation ponds with − 35%, − 36%, and − 50% reductions, respectively. Grassed waterways and no-tillage were less impactful on pollutant reduction, with grassed waterways showing a slight increase (+4%) in soluble phosphorus and no tillage having a minimal effect on sediment (− 1.3%) and total phosphorus (− 0.2%).

3.0 Review of potential Source Water Protection measures for mitigation of Organic Matter

3.1 Introduction

This section aims to provide a summary of SWP measures which are considered to be suitable for mitigation of DOM at source, with a potential, therefore, to protect drinking water from DBP contamination. Data collated on SWP measures and summarised in Section 2.3 have been used as the bases upon which to select the most suitable measures likely to be effective against DOM mitigation. As outlined in Section 2.3 most SWP measures have to date focused on contaminants other than DOM and consequently, there are a lack of studies which have fully quantified or attempted to measure the impact of the measures on DOM concentrations within catchments. Consequently, this study has taken the approach of collating the literature describing the main sources of DOM to freshwater taking account of factors such as land cover, land use type, land use management practices and the biogeochemical processes (both biological, chemical or physical) which can lead to an increase (or decrease in DOM production), and have used this information to select the SWP measures which are most likely to also reduce or mitigate DOM. A focus will be placed on both targeting DOM reduction directly at source but also reducing or mitigating against DOM pollution pathways based on understanding of DOM biogeochemical processing.

Following a literature review, five land cover types were identified as the main drivers of DOC export to source water ecosystems: forestry, peatland, agricultural, lakes/reservoirs, and wastewater treatment. The following section will look at each of these land uses in more detail, providing the evidence found in the literature that led to each land use being identified as a driver for DOC. This will be followed by a description of the processes or land management practices driving DOC production under each land use category and the mitigation measures identified which were considered likely to be the most effective in addressing the issue based on this collated knowledge.

An overview of the potential activities that may be a dominant driver of DOM in source water under each identified land use are provided in Table 3. A possible general solution to mitigate against each particular source is provided indicating which SWP would be most likely to be effective in reducing the risk of increasing DOM resulting from these activities. All of the above SWP measures are already in place as a solution to other issues for example nutrient and pesticide reduction, but have not all yet been fully researched with regards their effectiveness

in reducing OM. This table highlights the important link between these SWP measures and their potential to reduce DOM entering the waterways.

3.2 Forestry

3.2.1 Forestry land-use DOM sources

Many studies have concluded that a high percentage of forest-covered area in a catchment leads to an increase in DOC concentrations in downstream rivers and lakes (Hanley, 2012; D'Arcy and Carignan, 1997; Laudon et al., 2011). For example, from a total of 146 samples that were collected from 48 different locations within the Grand River watershed in central Michigan, the average DOM concentration (25.5 mg/L) from forested areas was greater ($p < 0.001$) than from areas classified as agricultural (10.5 mg/L), urban (9.9 mg/L), and suburban (7.9 mg/L) (McElmurry et al., 2014). Likewise, another study found that TOC concentrations in a forested area dominated by sitka spruce (*Picea sitchensis*) plantation were up to 50% greater than the hillslope moorland sites which formed part of the study in the White and Black Laggan sub-catchments of Loch Dee in south-west Scotland a study by (Grieve et al., 2001). They determined that this higher concentration was due to increased biological activity in soils under the planted forest as a consequence of activities such as ploughing and ditch creation prior to planting the Sitka, as well as the application of potassium and phosphorus prior to planting and again seven years later (Christ and David, 1996; Marschner and Waldemar Wilczynski, 1991). In Ireland, a study examining the influence of land cover on the formation of DBPs from their OM precursors, it was found that upland tree cover (a category which had some overlap with peatland or organic soils) showed the highest formation potential for THM and HAA compared with other land cover classes including grassland on minerals soils and grassland on peatland soils (Weatherill et al., 2024).

DOM originating from a forest varies depending on its vegetation. Fresh deciduous litter in forest catchments has a high potential for producing DOC in the short-term during autumn runoff events in temperate areas compared with coniferous litter and organic soils (Hongve, 1999). DOM from the forest floor and organic soil horizon can contribute a large flux of allochthonous DOM to surface waters. Vegetation such as *Sphagnum* moss and feathermosses which often form continuous groundcover on the forest floor yield DOC characterised by high hydrophilic DOC content and high potential biodegradability that is quickly metabolised and respired (Wickland, Neff and Aiken, 2007). In contrast, the DOC leached from vegetation such as black spruce was found to be moderately recalcitrant, dominated by hydrophobic compounds, and generally slow to degrade (Wickland et al., 2007). The authors concluded that it is the chemical

nature of DOC from different vegetation species, rather than differences in the rate of DOC supply, that dictates the fate of plant-derived DOC in soils.

Cycles of drying and rewetting of the coniferous forest floor can have an effect on DOC release and microbial processes (Lodge et al., 1994) with wet episodes during the summer leaching higher proportions of DOC from organic soils and coniferous litter (Hongve, 1999). The molecular weight of DOM collected from forests has been found to be typically approximately 2 kDa in size with a SUVA of 2.84 L mg C^{-1} m^{-1} suggesting an aromatic structure. Waters containing aromatic-rich soil-derived material arising from forested areas has been found to lead to elevated HAA precursors (Carpenter et al., 2013).

3.2.2 Forestry land use activities driving DOM

Clearcutting, timber harvesting, fertilising with urea-nitrogen, burning of post-harvest slash, vegetation type and forest soils have been identified as potential activities from forestry that drive increased DOC in freshwater systems. Clear-felling or clear-cutting is the practice where all the trees in a forested area are uniformly cut down. There are numerous studies pointing to the fact that clear-cutting leads to an increase of DOC in nearby waterways (Hughes et al., 1990; Neal et al., 1998; Cummins and Farrell, 2003a; Tetzlaff et al., 2007). For example, export loads and outflow concentrations of DOC were found to significantly increase as a result of clear-cutting from Norway spruce forests growing on drained productive peatlands and this increase was recorded for the next four consecutive years following clear-felling (Nieminen, 2004). Following a study in Northern Sweden it was found that the increase of DOC found after clear-cutting in a boreal forest was caused by (i) the increased flux of water through shallow flow path in riparian soils and (ii) increased soil temperature increasing the DOC availability in soils during summer (Schelker et al., 2013). In addition, the harvesting of timber and associated road construction can cause erosion that commonly leads to sedimentation of streams and causes elevated turbidity (Carpenter et al., 2013).

The practice of fertilising forestry plantations with urea-nitrogen can increase leaching of DOC by up to 30%, likely due to increased biological activity (McDowell et al., 1998). Nitrogen fertilisers are more soluble in the soil than phosphates and are leached out relatively quickly. The practice of burning post-harvest clear felled land exposes the soil to direct precipitation and can increase the risk of nutrient export from the site. Carpenter et al. (2013) recorded increases of DOC concentrations from 1.0 mg/L to nearly 2.5 mg/L during storms, which lead to higher concentrations of DBPs in treated water supplies 3-weeks after the initial storm. Soil compaction is also a commonly observed consequence of the use of machinery on forest sites. The negative

impacts of soil compaction on these sites include the reduced growth of seedlings and residual trees and, in some cases, increases in surface runoff and erosion.

3.2.3 Potential DOM Mitigation measures for Forestry

There are a range of measures which can help mitigate against DOC export in forested catchments. Leaching of DOM associated with clear-felling can be reduced through the introduction of uncut riparian buffer zones between clear-cut areas and water courses (Nieminen, 2004; Kiely et al., 2000). The wider the strip of permanent vegetation the greater reduction of sediment entering the watercourse, for example in one study a 56% reduction in DOM was recorded at a site with 25m buffer width compared to 37% for a 5m wide buffer (Zhang and Zhang, 2011). Tree planting within buffer zones and along riversides (NFGWS, 2022; Lazzaro et al., 2008; Nisbet et al., 2011) can also aid DOM mitigation in addition to the use of phased felling, which would involve felling an area over several years thus reducing the catchment area felled at any one time (Shah et al., 2022). A study by Shah & Nisbet (2019) in the Flanders Moss in Scotland shows how phased felling successfully reduced DOC concentrations. The area where the study was conducted was ploughed and planted with pine and Sitka spruce in the 1960s and 1970s. Site 1, the smallest was felled in two phases, Site 2 the largest catchment was progressively felled over a 3.5 year period and Site 3 was completely felled over 6 months. The results show how felling elevated the DOC concentrations at both Sites 1 and 3 in the following summer/autumn. With the mean annual DOC concentration increasing by 13.4 mg/L at Site 1 and 18.9 mg/L at Site 3 in the first year after felling began. Summer concentrations on Site 1 remained slightly elevated for the next three years, however, DOC concentrations at Site 3 peaked in the year after felling and remained elevated, although slowly declining over a four year period. While, DOC concentrations were largely unaffected by the phased felling over a 3.5 year period at Site 2, the largest catchment.

Bank stabilisation also known as bank revetment measures has been found to mitigate against soil erosion in forested areas. This can involve the use of willow spilling, boulder installation or building log structures from used logs and old Christmas trees (NFGWS, 2022). Management of the timing of tree harvesting so it occurs during winter when the soils are frozen or snow-covered can also minimise the disturbance of forest soils. The timing of other management activities is also important, for example not applying fertiliser during wet weather or if heavy rain is forecast within 48 hours is suggested as a measure for DOM reduction (Shah et al., 2022). Another potential measure is to use organic, slash mulch or biochar as alternative fertilisers in forestry. Biochar is a charcoal-like substance which is made by burning organic material from agricultural and forestry wastes which increases the proportion of microbial DOM and decreases the

leaching of DOM (Rombolà et al., 2022). Leaving smaller unburnt piles of slash, following clear-felling will provide a temporary shelter for wildlife while the slash is breaking down and prevent large unplanted gaps in forest soils. The impact of machinery and compaction owing to harvesting can be reduced through the use high flotation tyres and steel flexible tracks to reduce impact of machinery in addition to using equipment on established roads and trails only away from riparian zones, and to retain unharvested materials such as fallen trees, branches, snags, downed tops to provide ground cover. As the type of vegetation present in a forest influences both the concentration and characteristics of DOC entering the nearby waterways, planting mixed species forests which take into account soil type, and the degree and level of harvesting which is likely to occur may act as a SWP measure when carefully planned in a site specific way. Mixed species forests also offer increased biodiversity, and less acidification impact compared to monoculture forests (Collier and Farrell, 2007).

3.3 Peatland

3.3.1 Peatland land-use DOM sources

The effects and role of peatlands as a major source of DOC have been observed in many studies (Kortelainen, 1993; Rantakari et al., 2004; Arvola et al., 2016; Dillon and Molot, 1997; Clark et al., 2004; Mitchell and McDonald, 1995; Hope et al., 1997; Chapman et al., 2001; Mattsson et al., 2005). Limpens et al., (2008) estimated that around 10–20 % of carbon losses from peatlands are represented by DOC and Aitkenhead and McDowell (2000), calculated that the mean DOC fluxes in rivers draining peat dominated areas are higher by 50–100 kg ha^{-1} yr^{-1} than in rivers draining most other landscape types. Similar to forestry, vegetation composition can influence the amount of DOC and colour in water draining from peatlands. This is supported by laboratory peat manipulation studies (Live Semb Vestgarden and Austnes, 2009), suggesting that a replacement of *Calluna* and *Sphagnum* with *Molinia* may cause an increase in the flux of DOM from the soil in winters with deeper and longer soil frost. Armstrong et al. showed there are significant differences in DOC associated with different vegetation types. Calluna was consistently associated with the highest DOC, sedges yielded intermediate DOC and Sphagnum low DOC.

The drainage of peatland areas was a widespread practice during the last century and has been identified as a possible contributor of increasing DOC trends in recent years (Worrall et al., 2003), with DOC exports from harvested peatlands in Canada found to be approximately twice those from undisturbed peatlands (Glatzel et al., 2003). Higher DOC concentrations are generally observed in drained areas when plants haven't developed or have withered during early- and end-growing seasons (Xu et al., 2021). This is consistent with a number of earlier studies

investigating drainage impact on DOC and indicates decomposition of peat organic matter by microbial activities contributes to DOC concentrations (Freeman et al., 2004; Evans et al., 2005).

In blanket peatlands, 80% of runoff originates from the top 5 cm of peat (Holden and Burt, 2003; Dawson et al., 2004; Billett et al., 2006; Clark et al., 2008b). Carbon stored within the deeper anaerobic peat layers is not normally a major source of DOC, however, Wallage et al., (2006b) observed that DOC concentrations at 20 cm increased by nearly 40% on a drained site compared to those at intact sites and DOC and colour values at the undrained site were on average 69% and 62% lower than the drained site. This result represents a significant potential carbon source that could be mobilised by water table drawdown.

Some studies suggest drainage can enhance the aerobic decomposition of peat, leading to increased DOC aromaticity (Fenner and Freeman, 2011; Strack et al., 2019) and regardless of the drainage condition is dominated by lignin-like compounds (33–42% in natural samples; 30–41% in drained samples; Xu et al., 2021). These contain more humic-like compounds including polycyclic aromatics. Humic compounds influence the formation of THMs and higher yield of THMs has resulted from the chlorination of humic substances with a higher phenolic content (Kim and Yu, 2007).

3.3.2 Potential activities driving DOC in peatland

Drainage activities, construction of windfarms, surface run-off from bare peat, the degree of slope on blanket peatland and managed heather burning have been identified as potential activities from peatland that drive increased DOC in freshwater systems. Drainage activities lower the water table level in peatlands, resulting in fast decomposition of plant residues and peat (Kluge et al., 2010; Frolking et al., 2011), this can increase aerobic decomposition of peat (Clymo, 1987; Clark et al., 2009) leading to increased DOC (Worrall et al., 2003) and an increase in aromaticity (Fenner and Freeman, 2011; Strack et al., 2019). The location of windfarms in peatland areas can be problematic. During windfarm development activities such as clear-felling, keyholing and general construction activities result in bare peat and sediment entering nearby waterways. Grieve and Gilvear (2008) estimated the DOC attributed to windfarm-related disturbances was approximately 5 g m^{-2} with elevated suspended sediment loss continuing even after construction activities have ceased. Vegetation cover in peatland areas is very important with bare peat producing more colour when saturated than other cover types (Millar, 2008), with 80% of surface runoff in blanket peatlands originating from the top 5 cm of peat (Holden and Burt, 2003). The slope mean was found to be the strongest determinant of DOC and water colour in blanket peatland stream waters (Parry et al., 2015), with steeper eroded slopes

showing the highest DOC concentrations of humic-rich compounds (Boothroyd, Worrall and Allott, 2015). Managed heather burning has been shown to profoundly impact on peatland carbon cycling (Garnett et al., 2000, Beharry-Borg et al., 2009; Grayson et al., 2008), resulting in water colour increases (Holden et al., 2012) and aromaticity in peat pore water above the water table. Similarly, wildfire was found to increase aromaticity of DOC in peat pore water above the water table, but had no effect on the concentrations or composition of peatland groundwater DOC or mineral soil DOC (Olefeldt, Devito and Turetsky, 2013).

3.3.3 Potential DOM Mitigation measures for Peatland

As water level in peatlands is a key determinant of DOC export, rewetting peatlands can be an important mitigation measure. The presence of drains in peatlands strongly impact water levels, reducing water quality and increasing carbon export. There has been extensive efforts in many areas to block ditches and drains in an attempt to restore the hydrological and biogeochemical functions in peatland catchments, with a number of studies indicating the effectiveness in reducing concentrations of DOM in pore water, although corresponding impact on surface water DOM concentrations is less clear (Williamson et al., 2023). Wallage, Holden and McDonald, (2006) found drain blocking to be effective either using peat or heather bales, with DOC and colour values at the blocked site on average 69% and 62% lower than the drained site.

Revegetation of bare peat has the potential to decrease DOM concentrations by stabilising systems where exposed peat has led to erosion and water quality issues. Research on its effectiveness is limited, and in some cases initial revegetation may lead to short-term increases in DOM, although particulate losses from peatland systems decreased following stabilisation of the peat surface through revegetation (Pilkington et al., 2015). Increasing surface roughness through revegetation has been found to reduce peak flows by a quarter and doubles the time it takes for flow to reach its peak (Holden et al., 2008). The type of vegetation likely has an impact, with laboratory experiments indicating that some species could impact the type of DOM leached, with that arising from *Sphagnum* being more easily removed by conventional coagulation processes than DOM released from other vegetation (Ritson et al., 2016). Actively spreading *Sphagnum* (Armstrong et al., 2012) through seeding and the introduction of pre-grown seedlings known as plug plants (Parry, Holden and Chapman, 2014) encourage its propagation and regeneration (Campeau and Rochefort, 1996). Available evidence suggests that revegetation has the potential to stabilise bare peat and reduce particulate organic matter, although evidence regarding DOC export is more limited (Williamson et al., 2023). Reprofiling of the sides of gullies is also an effective SWP measure to slow down water and reduce erosion rates. Burning is often used as a way of controlling the growth of heather in peatland areas. An alternative to burning

is to use sheep to graze the heather between March and October only so as to avoid overgrazing. Mowing or cutting of heather is also an alternative measure however this method requires low slope angles and smooth terrain to avoid machinery damage to the peatland.

If construction of a windfarm in a peatland area is unavoidable extensive mitigation measures must be implemented pre-construction, such as, carrying out detailed surveys and careful planning, design slopes gradient less than 30 degrees, ensure any ditches are a max of 0.5m deep and only excavate in peat only up to 2 m depth to reduce the risk of peat landslides (Ehsan Jorat et al., 2024). Following construction SWP measures can be used to rehabilitate the peatland site such as brash mulching (cut heather) on flat areas and shallow slopes to protect bare peat from erosion and create stable conditions for seed germination (MoorLIFE2020, 2020). Geo-jute (a biodegradable textile made from natural fibre) can be attached to bare peat surfaces using metal pins to provide protection from erosion (Parry, Holden and Chapman, 2014).

3.4 Agricultural land

3.4.1 Agriculture land-use DOM sources

Agriculture extent and crop selection have a strong influence on DOC loading to freshwater systems (Stanley et al., 2012). In addition, the composition of DOM arising from agricultural catchments is often more reactive in aquatic ecosystems, therefore, potentially increasing rates of production in aquatic ecosystems (Graeber et al., 2015). Studies have shown that agricultural activities have resulted in both increased and decreased or even undetectable changes in DOC, which is likely owing to the range of agricultural activities and management practices which are possible (Stanley et al., 2012). Nevertheless, as agriculture, particularly tillage, is associated with reduced storage of terrestrial organic carbon, it is also likely that this will have consequences on aquatic DOC (Sickman et al., 2009; Stanley et al., 2012). Studies showing changes in DOC composition, as opposed to concentration, as a consequence of agriculture are more clear cut. The type of agriculture, the land type and the land management practices will all influence DOC export. For example, a global study examining the C:N content of a number of crops has ranked crops in order of their C:N content and the extent of their coverage with wheat, maize, rice and Barley ranking highest, but with a large variation in C:N content amongst all major crops investigated (Leff et al., 2004). Agriculture activities which produce high concentrations of nutrient waste such as livestock operations, have been shown to positively influence the production of more protein-like DOM leading to an enrichment of microbial-like DOC along with increased microbial biomass and labile components of DOC (Graeber et al., 2015). These changes in comparison to undisturbed land leads to changes from high to low-molecular weight DOC, reduced aromaticity and increased lability of DOC entering freshwater systems (Wilson and

Xenopoulos, 2008; Petrone et al. 2008). Nitrogen fertiliser application, agricultural drainage especially on dairy farms, surface run-off and slurry spreading have all been identified as potential agricultural activities that drive increased DOC in freshwater systems (Table 3).

Larson et al., (2014) found the most important predictor of DOC at nearshore zone sites of large lakes was cropland extent with DOC yields increasing up to 1.29 g m^{-2} during 6 months of intensive agricultural activity which formed part of the study. This corroborates a study in the Sacramento River Basin in the US where stream DOC concentrations peaked at 18.9 mg L^{-1} during summer irrigation in the sub-watershed with the highest percentage of agricultural land use, demonstrating the strong influence of agricultural activities on summer DOC dynamics. However, of most concern is the finding that only 12% of agricultural land use within the Sacramento River Basin contributed to 30% of regional DOC loads (Oh et al., 2013).

3.4.2 Potential activities driving DOC for Agricultural land use

Studies have found that intensive agricultural practices such as the intensive use of fertiliser, heavy machinery, tillage and drainage and the use of pesticides alter the microbial processing of DOM (Graeber et al., 2015). Increased erosion and decomposition rates are associated with the physical disruption and aeration associated with tilling land, this in combination with drainage activities, which lower the water table, can impact DOC stored in soil (Jarecki & Lal, 2003). Much of agriculture around the globe occurs on land in low-lying areas associated with wetlands which have consequently experienced a high level of drainage in order to ensure their agricultural productivity. Wetland areas in the US, for example have been reduced by up to 85% in some areas (Dah, 1990), and in areas such as Ireland and other parts of Northern Europe farming has impacted peatland areas which have been drained for conversion to agricultural land (Armstrong et al., 2010). Agricultural drains especially in dairy farms were found to contribute approximately one-third of the DOC load in the California State Water Project in the US (Sickman et al., 2009). Installation of drains and ditches in addition to irrigation can change the rates of evapotranspiration and infiltration of farmland, and consequently the hydrological connectivity between land and water is altered leading to changes in flow pattern and timing of DOC transport to streams and rivers. The presence of buried drainage pipes in agricultural fields can increase movement of water from land to water during high rainfall events. Floods have been found to be responsible for the majority of annual DOC export in areas with large amounts of field drain networks (Ruark et al., 2009). In addition, with approximately 40% of the world's food production dependent on irrigation, it has been found that DOC concentrations in drainage water increased on irrigated land (King et al., 2009), but as with studies investigating the link

between land drainage and DOC, those looking at a link with irrigation are also rare (Stanley et al., 2012).

The conversion of riparian areas for agricultural purposes can impact river and stream DOC concentration and content. Export from these riparian zones can be a major input of DOC particularly during high flow periods (McGlynn & McDonnell, 2003; Bishop et al., 2004). In addition, the vegetation of riparian zones is often altered in agricultural areas, even if the riparian zone is not in agricultural production, this also has the potential to alter the quantity and type of DOC loading to freshwater as a consequence of the likely impact on rates of litter production and bioavailability of DOC (Stanley et al., 2012). DOC input from surface run-off is also an issue in agricultural areas, particularly as a consequence of disturbed and bare soil owing to tillage or livestock damage, increasing the potential of soil erosion and runoff. Climate change is resulting in the increased frequency of extreme rainstorm events. These rainstorm events together with the intense management of upper soil layers can cause a significant amount of runoff and loss of DOC (Yue et al., 2020).

Application of organic manures have been found to increase soil OC to a greater extent than inorganic fertilizers (Gattinger et al., 2012; Huang et al., 2010; Li and Han, 2016). Fertilisation has a noticeable impact on total organic carbon (TOC) fluxes with an increase of five to seven fold for pig slurry and cattle manure respectively. Winter spreading especially results in a major increase for TOC fluxes impacting runoff water quality degradation (Delpla et al., 2011). A significant positive correlation between DOC export and rates of nitrogen fertiliser have been recorded (Mattsson et al., 2005). However, increases in nitrogen and phosphorus concentrations in of themselves, can lead to eutrophication in freshwater systems and consequently greater autochthonous production of labile DOC.

3.4.3 Potential DOM Mitigation measures for Agricultural land

There are many management practices on farms which are likely capable of influencing DOC export. Many management practices utilised for other pollutants are likely to be effective against DOC mitigation, however, owing to a lack of studies specifically targeting DOM as a pollutant of interest there is little data demonstrating direct measurable impact (Kay et al., 2009).

Management of riparian zones are likely to be one of the most important interventions for DOC mitigation on agricultural land. The capacity of a riparian buffer strip to impact DOC inputs to freshwater systems will depend on the land use type and on the geographic setting in addition to the extent and composition of the buffer strip. Buffer strips are commonly defined as an area

of land which has been separated from agricultural land to protect aquatic or valued terrestrial habitats and can include grass buffer strip, buffer strips planted with willow buffer or other woodland vegetation (Prosser et al., 2020). They have been used as effective measures for reducing diffuse pollutant, including sediment, into surface water including sediment entering surface waters (Aguiar Jr. et al., 2015; Vormeier et al., 2023; Plüskow et al., 2025), although evidence for their impacts on DOM inputs to freshwater is sparse. Riparian buffer strips will also impact bank stability and effect sediment loading through coarse woody debris supply (Stanley et al., 2012). A study investigating the role of different types of buffer strips on runoff and sediment loss in a three year study found that reductions in sediment loss compared with the control varied with regards the vegetation type with willow buffer strips (44%) performing better than deciduous woodland (30%), which was better than grass buffer strips (29%) (Dunn et al., 2022).

Fencing off- or excluding livestock access to freshwater can also act to potentially decrease DOM input to freshwater, both directly through mitigation against increased soil erosion, turbidity and defecation into rivers and streams, it can also act indirectly in creating vegetated buffer strips between the fence and the watercourse. A study in Ireland examining the effect of cattle exclusion from streams on water quality found improvement in water quality indicators such as sediment, phosphorus and biological parameters between fenced and unfenced watercourses over a period of one year (O'Neill et al. 2023). Installation of fencing for livestock exclusion should consider distance, with at least 1.5 metres from the top of the bank recommended, alternative drinking sources for livestock and regular maintenance of the fencing and the vegetated area established beyond the fencing is a necessity (Miller et al., 2010). The evidence of the effectiveness of fencing in reducing diffuse pollution in agricultural land is considered to be sufficient enough, that a number of programs and policies have been implemented in countries in Europe, where mandates and legislation for minimum buffer strip distances and livestock exclusion to water courses have been implemented (Plüskow et al., 2025).

The use of sediment traps placed strategically in existing surface drains can also be used to reduce OM input to aquatic systems. Average annual sediment trap effectiveness across measured data in agricultural catchments from a review of 23 international publications was 59% (Smith and Muirheaad, 2023). Various SWP measures can also be used to mitigate against the risk of surface run-off. Stormwater or constructed wetland also known as reed bed or treatment wetland resulted in nutrient biological oxygen demand reduction (Souliotis and Voulvoulis, 2022), with larger areas of over 2500 m^2 removing at least 80% total suspended sediments (Newman et al., 2015).

Implementing effective management practices on farms such as altering ploughing depth or conservation tillage methods have been shown to reduce soil organic carbon losses (Smith, 2004; Ogle et al., 2005). Conservation tillage such as no-till, ridge-till, strip-till, mulch-till, and reduced-till have been shown to retain at least 30% of crop residues near the soil surface increasing water holding capacity and soil stability (Klik and Rosner, 2020). Measures that can increase the productivity of the soil and improve the soil composition such as mixed cropping, polyculture, inter-cropping, co-cultivation and crop rotation can improve soil organic carbon content (Kleinman et al., 2005). According to Strauch et al., (2013) crop rotation reduced sediment load by up to 20.73%.

Other practices such as improved tramline management (marked wheelways through crops) can also be effective. Tramlines can often be a source of runoff and sediment loss on farms, however, practices such a partial crop cover of tramlines or running them across slopes rather than up or down slopes was found to produce the same amount of runoff of sediment and nutrients as plots without tramlines (Withers et al., 2006, Bailey et al., 2013). Creating awareness of good farmyard practices such as clean and dirty water separation on the farmyard can be effective. For example, making improvements to guttering, slurry drains and ditch water pools can reduce OM runoff directly from farmyards (Linnane et al., 2011). Effective treatment or removal of waste material on the farm such as slurry is also important. Exporting slurry or animal waste from farms could be an option where alternative disposal mechanisms are possible such as a dedicated centralised regional facility or to an area with more suitable ground conditions or capacity (Linnane et al., 2011). Treating slurry with Liquid polyaluminum chloride (PAC) was found to reduce the TOC in runoff from dairy and pig slurries by 52% and 56%, respectively (Murnane et al., 2016). Using anaerobic digesters, slurry pelleting and/or decanting systems (Cathcart et al., 2021) to process the slurry into a fuel pellet can provide an additional source of energy and revenue.

There are various SWP measures that mitigate against the risk of manure or fertiliser application to land. For example land spreading exclusion where no manure or fertiliser is applied can be effective (Linnane et al., 2011). This measure could also include avoiding spreading nitrogen fertilisers or manure during high-risk periods, for example, when there is a high risk of surface flow, rapid movement to field drains from wet soils or when there is little or no crop uptake. Rather than complete absence of fertiliser application, practices such as the use of a boom sprayer can be effective in targeting the application of fertiliser to the soil directly and thereby reducing drift (NFGWS, 2022). Fitting of low drift nozzles allows farmers to apply fertilizers more precisely reducing runoff and leaching. Additionally, liquid fertilizers are more easily absorbed by plants, reducing the risk of nutrient loss to the environment. Planting mixed species

hedgerows or rewilding on poorly draining areas, alongside watercourses, fences and across slopes, following a contour is another option for reducing soil runoff and erosion (NFGWS, 2022).

Finally, it is important to raise awareness of these measures with farmers by providing regular workshops and demonstration days. Appropriate information on correct management practices is vital to encourage uptake of best practice and provide guidance on the likely effectiveness of various measures.

3.5 Lakes/Reservoirs

3.5.1 Lake/Reservoir DOM sources

Lakes (particularly upstream lakes) can act as important sinks (Mattsson, Kortelainen and Räike, 2005) and transformers of terrestrially derived DOM (Hanson et al., 2003), which should reduce DOM concentrations. However, lake algal or macrophyte production has been observed to contribute significant quantities of DOM to outflowing streams (Kaplan and Bott, 1982; Martin et al., 2005) and in cases where lakes act as source water for drinking water purposes, internal production of DOM can be an important driver of DBP in treatment plants (Gough et al., 2015). In a study conducted by Tamara et al., (2010) there was a 10 to 60% increase in DOC concentrations flowing out of the two reservoirs relative to an upstream site. Concentrations of DOM in this study were significantly higher in November and March compared to August and September, which may reflect high flow events. This also points to the fact there are periods when a reservoir or lake is a net source of DOC due to the production of algal in summer and a net sink due to the predominance of degradation that occurs in the autumn and winter. DOM in water leaving reservoirs contains a mixture of material that has entered the reservoir over time and any in-reservoir processing that has taken place during its residence time. Precipitation can also be considered an allochthonous source of DOM to larger rivers and lakes where precipitation falls directly onto the water surface. With increasing precipitation and longer residence time, Kothawala et al., (2014) found the quality of DOM changed, with greater proportions of a protein-like component, and lower proportions of the terrestrially derived humic-like component.

3.5.2 Potential activities driving DOC in lakes/reservoirs

High nutrient levels (phosphorus and nitrogen) can cause a dramatic increase in autochthonous production leading to eutrophication. There is an expectation, therefore, that this increased biological production will lead to higher inputs of relatively labile DOC (Hilton et al., 2006; Khan et al., 2021), with harmful algae blooms (HABs) or macrophyte production in lakes likely

contributing significant quantities of DOM (Martin et al., 2005; Kaplan and Bott, 1982). Nevertheless, studies examining the relationship between algal blooms and DOC have shown an increase in DOC concentrations but not always an increase in DOC lability (Benstead et al., 2009). This may be a consequence of the enhanced microbial degradation and mineralisation with increased nutrient inputs and production. The liable fraction may be rapidly reduced as a consequence (Benstead et al., 2009). DOC arising from autochthonous production has been found to have higher nitrogen content than humic material owing to its higher protein content (Fang et al., 2010) containing more hydrophobic and less aromatic compounds (Zhou et al., 2014). Consequently, autochthonous DOM produced by algae is an important source of DBP precursors and is particularly reactive concerning HAAs with a greater link to the formation of N-DBPs such as haloacetonitriles and haloacetamides owing to its proteinaceous and low molecular weight compounds (Kraus et al., 2011; Chen et al., 2008; Liao et al., 2017). In addition, THM precursors can also be associated with carbon having a lower aromatic content. This pattern suggests a potential link between THM precursors and algal-derived carbon from material such as planktonic species of blue-green algae and sloughed filaments, stalks, and cells of benthic algae (Carpenter et al., 2013). Following experimental nutrient addition, the resultant algal bloom showed a lower standardised THM formation potential associated with algal derived DOC compared with humic DOC, with this varied depending on the algal growth phase. The DOC produced during the exponential and death phases of algal growth formed THMs at a lower rate than humic DOC (Gough et al., 2015). Kraus et al. (2011) found that DBP precursors (particularly HAAs) increased during the summer months because of high phytoplankton activity, however, the reservoir was a sink for DBP precursors during the winter months when decomposition processes predominated. The types of DBP formed after chlorination will, therefore, depend on the origin and species of algae, the growth stage and other environmental factors. For example it was found that HAAs were higher in algal derived OM from species of algae such as *Microcystis aeruginosa*, *Chlorella vulgars*, *Chlorella obliqua* and *Cyclophylum* following chlorination (Zhai et al., 2022). The formation of DBP is particularly linked to the presence of cyanobacteria owing to their tendency to form dense blooms (Tomlinson et al., 2016). Phytoplankton population densities are strongly influenced by seasonal fluctuations typically peaking in summer when temperatures are at their maximum and declining in the winter. Algal biomass may continue to rise in coming decades (Gough et al., 2015) as a result of increased temperature and algal growth due to atmospheric deposition of inorganic N (Hood et al., 2005) and climate change, negating the benefits of degradative processes that reservoir storage can provide. In addition, extreme weather events such as extended dry periods with high temperatures followed by storms, expected to increase in frequency and intensity owing to climate change, will likely lead to increased algal growth and the risk of blooms (Piccolroaz et al., 2020).

Mixotrophic lakes (brown water lakes) have naturally high DOC concentrations (Jonsson et al., 2001). These lakes predominantly contain terrestrial sources of DOM, humic substances with higher aromaticity and a low autochthonous component (Sepp et al., 2019). A substantial proportion of DOM (8 to 22%) of terrestrial origin, can be lost naturally from the water column solely from sedimentation processes (Von Wachenfeldt et al., 2008). Organic Carbon is also lost through bacterial mineralisation with smaller lakes having shorter residency times and therefore less opportunity for the DOC to be mineralized (Algesten et al., 2003), increasing the risk of DOC entering water treatment plants. Catchments with finer-textured soils, deeper soil layers, and higher elevations contribute more organic carbon (OC) to lakes (Herreid et al., 2024). While catchments with deeper, coarser-textured soils may act as a buffer against the mobilization of terrestrial OC resulting from precipitation events, coarser soils facilitate more rapid water infiltration, reducing surface runoff and limiting the transport of OC to aquatic systems (McDowell, 2023). Greater annual surface runoff could result in shorter lake water retention times, decreasing the opportunity for in-lake processing and primary production, shifting the quality of DOM to contain a greater proportion of humic-like DOC (Kothawala et al., 2014).

3.5.3 Potential DOC mitigation measures in lakes/reservoirs

Mitigation against DBP formation as a consequence of autochthonous carbon production and algal bloom formation will encompass any measure aimed at reducing nutrient influx to freshwater systems, which is the principal driver of excessive algal growth and bloom formation. Consequently, the wider list of source water protection measures, many of them targeting nutrients such as nitrogen and phosphorus, will similarly work to reduce the impact of phytoplankton contribution to DOM. This includes actions such as fencing, buffer strip and riparian zone protection, improved farmyard management, sediment traps, earth bunds etc. A combination of improved catchment management alongside improved understanding of phytoplankton community structure within a lake or reservoir will enable early detection of increased risk from DBP formation potential within drinking water sources (Tomlinson et al., 2016).

Other effective management actions such as selective withdrawal, water diversions, nutrient control, and algaecide applications can be applied to the reservoir to reduce HABs (Kraus et al., 2011). For example, alum treatments cause impurities to flocculate and settle, decreasing algal blooms and improving water clarity and the addition of aluminium to a small acidic lake was found to cause a two-fold decline in DOC (Schindler et al., 1992). In addition, implementing Natural Water Retention Measures (NWRM) to increase the retention time of water in catchments, for a period before it is passed downstream can help to increase mineralisation

process and reduce the concentration of liable DOC and decrease suspended solids. These measures may include bioretention areas or bioretention cells (NCDENP, 1999) which have been found to have a TSS removal rate of 75–97% (Hui Hwang Goh et al., 2019). These bioretention ponds fall into a range of pond features often constructed next to a watercourse to intercept pollutants including nutrients and sediments during their instream or overland pathways. There are a range of designs and features which can be included, but they are variously referred to as constructed wetlands, retention ponds, in-line/on-line ponds, settling ponds, run-off attenuation features and rural sustainable drainage systems (RSuDS) (Ockenden et al., 2012; Barber et al, 2012). Design specifications are matched to the particular context, both rural and urban and they have been implemented in many areas in Europe including their use adjacent to motorways to trap sediments and other road pollution run off (Cooper et al., 2019). Bioretention areas can also consist of shallow landscaped depressions filled with sandy soil, topped with a thick layer of mulch, and planted with dense vegetation. They can also contain a grass buffer strip, and ponding area but are not suitable for areas with a slope > 20%. In a study of the use of in-line ponds (ponds located along at intervals along a stream) to retain dissolved nutrients and suspended solids found that during small or moderate storm events some ponds reduced peak loads of suspended sediments and phosphorus, however they were less successful during larger magnitude storm events with re-sususpension of bottom sediments within the ponds resulting in net losses (Robotham et al., 2021). This highlights the complexity of the pollution retention dynamics and pond design which can be deferentially affected by timing and scale of extreme weather events.

Healthy forests can also help regulate water flow into reservoirs and large lakes (Calder, 2007). Additionally the use of earthen or stone bunds when located appropriately can be used to intercept overland flow pathways and can temporarily slow runoff of water and sediments including topsoil. Often used to mitigate against flooding (Quinn et al., 2022; Teale, 2023), they sometimes involve the inclusion of a pipe through the bund to aid with drainage, but this can also be raised to allow some water retention, thereby allowing more sedimentation. These bunds are an example of a number of agricultural practices which aim to prevent soil erosion and sediment loss through soil and water conservation measures and include grassed waterways, the use of soil or stone bunds to act as temporary storage areas and the use of vegetation strips and contour planting (Keesstra et al., 2018; Wilkinson et al., 2019). In a study in the UK, ditch modification to create sediment traps and addition of a permanent pond for flood attenuation led to an average of 49% removal of suspended sediments and 30% of total phosphorus over 30 measured storm events (Barber et al., 2012).

3.6 Wastewater Treatment

3.6.1 Wastewater Treatment DOM sources

The objective of waste water treatment is to remove polluting material so that the treated water can be released safely back into the environment. Wastewater can either be treated at centralised municipal plants or at individual onsite wastewater treatment systems such as septic tanks. A range of technologies are available for onsite wastewater treatment which enhance the biological breakdown of the waste material and remove larger solids including filtration, sedimentation or mechanical aeration, nevertheless, in all case final effluent treatment will rely to some extent on the soil percolation area and the biogeochemical process which occur within the soil matrix in the unsaturated (vadose) zone (Krasner et al., 2009). In addition, effluent treated in centralised systems will be discharged to nearby aquatic systems. Globally, it is estimated that approximately 47.2% of wastewater is released untreated directly into the environment (Jones et al., 2021).

DOM in effluent arising from wastewater treatment plants often contains a higher concentration of microbial metabolites and hard-to-degrade synthetic compounds with complex compositions (Li et al., 2020). The results from a study conducted by Huber et al. (1994) found that TOC increased up to 5 mg/l while humic constituents decreased down to 30% downstream of sewage plants. A detailed analysis showed that the humic fraction was composed of fulvic acid precursors with associated non-humic matter. It concluded that the quality and quantity of organic constituents in the stream had been dominated by the secondary effluents. Domestic sewage contained a significant number of hydrophobic neutrals, indicating the presence of synthetic detergent linear alkylbenzene sulfonate (LAS)-like DOM (Imai et al., 2001). The increasing discharge from wastewater treatment plants to water sources will cause DOM composition of the source water to become more hydrophilic with low aromaticity and smaller with respect to molecular weight than before (Imai et al., 2002). This hydrophilic DOM in treated wastewater may contribute more to total trihalomethanes formation during the chlorination process in drinking water treatment (Galapate et al., 1999).

3.6.2 Potential activities driving DOC from wastewater treatment

Urbanisation and population growth contributes increasing pressure on wastewater treatment plants and can also lead to a growing volume of domestic wastewater systems in some regions. This is an important driver in the increase of DOC concentrations in source water (Zhang et al., 2022). Combined sewage systems and those who are operating at capacity have overflows that discharge excess flows to rivers and streams during heavy rainfall events. These systems are a

source of pollution and a driver of increased DOM, especially when the receiving body of water is too small. Heibati et al. (2017) have used fluorescence spectroscopy to detect sewage-derived DOC in domestic tap water. As the number of extreme rainfall events rise as a consequence of climate change it is likely that overflow events at wastewater treatment facilities will increase. In addition, pressure from malfunctioning or poorly maintained onsite wastewater treatment systems will intensify, particularly in locations with unsuitable and saturated soil conditions. In order for effective treatment to occur it is vital that effluent flows into the subsoil and remains in the vadose zone until properly treated. In addition, the ability of an on-site wastewater treatment system to treat household wastewater is determined by the number of people in the household and the degree to which maintenance is carried out such as desludging or upgrading and repair or replacement of the various mechanical components of the system. The failure of any of these will reduce the effectiveness of the effluent treatment process. Increased rainfall is likely to increase the hydrologic connectivity between the percolation area and nearby water courses while also decreasing the depth of the unsaturated zone in which the soil treatment attenuation processes occur, increasing the likelihood of increased OM entering the water course from poorly treated wastewater.

3.6.3 Potential DOC mitigation measures for Wastewater Treatment

Constructed wetlands have become extensively employed for treating both domestic and industrial wastewater, as well as for advanced water treatment from centralized systems (Vymazal, 2009; Zhang et al., 2023; Wu et al., 2023). Constructed wetlands for wastewater treatment are located around the world (Pinney et al. 2000), and have been introduced in many areas as a cost-effect approach to wastewater, known to enhance microbial activity and reduce pollutants such as nitrate and biological oxygen demand. However, the role of constructed wetlands in reducing DOC is less well studied than some of the other pollutant parameters, with indicators suggesting that wetlands can act to increase or decrease DOC, depending on their design and hydraulic retention time. A constructed wetland in Norfolk in the UK designed to reduce pollution arising from a water recycling centre recorded a 53.3% reduction of DOC with the system acting as an overall DOC sink with a 43.5% lower discharge from the wetland outlet compared with the inlet (Souliotis and Voulvoulis, 2022). Nevertheless, in a study examining the performance of a constructed wetland treating wastewater effluent, it was found that DOC removal varied seasonally, with maximum net removal rates of 47% in February, but with minimal removal rates of only 9% in June. During summer when plant growth was at its highest DOC decreased in the first part of the wetland, but increased in the second half as a consequence of high proportions of plant derived refractory DOC (Pinney et al., 2000). The potential of DOC to form THMs did not change significantly across the constructed wetland. Follow up modelling

indicated that wetlands with shorter hydraulic retention times will experience less DOC leaching arising from plant material. In terms of design, short residence time may not be suitable for systems concerned with removing contaminants such as ammonia which requires sufficient time for conversion to nitrate and finally nitrogen gas (Pinney et al., 2000). This has been backed up in another study specifically examining the effect of constructed wetlands on DBP formation from six different systems receiving agricultural return flows in California, US. Small wetlands with short hydraulic residence (< 2 days) did not produce significant changes in DBP precursors. There was insufficient time in these smaller wetlands for processes such as evapoconcentration and leaching from vegetation which can DOC quantity. However in the larger wetlands (>100 ha) with hydraulic retention time greater than 10 days there were higher recorded DOC levels and an increase in DBP formation factors (Diaz et al., 2009). Consequently, it is important to consider factors such as constructed wetland design, management practices and the composition of the influent material when considering the use of constructed wetlands to mitigate against DOM as precursors to DBP formation and there may be trade-offs between effective design for DOM removal and that required for nutrient removal.

In addition to constructed wetlands there are some other solutions that could be considered which aim to provide solid adsorbents which can act as a low cost and eco-friendly alternative to other wastewater treatment technologies such as chemical precipitation, ultrafiltrating and reverse osmosis. Activated carbon is a commonly deployed adsorbent material but its cost can be prohibitive. Natural waste materials, such as milled eggshells could be used as an alternative (Low et al., 2022) and have been shown to be effective for adsorption of phosphorus, heavy metals and other contaminant, with a phosphorus removal of 96.2% obtained from salted eggshell calcined at 700°C for 4hrs (Yirong and Vaurs, 2019) and have been shown to remove 35.6% of total phosphorus, 44.7 % total nitrogen and 69.7% of total suspended solids from contaminated river water (Low et al., 2022). Reduction in organic matter following laboratory scale experiments using eggshell powder at 35 ℃ for 15 min under constant stirring reduced organic matter by 80.6 % in water samples (Narwati et al., 2023).

Table 3. *Six land cover types that are the main drivers of DOC export to source water and potential activities within six different land cover types that are the main driver of DOC export to source water and potential mitigating measures considered to be most effective to address each activity.*

FORESTRY				
Potential DOC Source	**Potential solution to mitigate DOC**	**SWP Measure**	**SWP Measure**	**SWP Measure**
CLEAR-CUTTING (Nieminen, 2004) or clear-felling (Hughes et al., 1990; Neal et al., 1998, Cummins and Farrell, 2003a, Tetzlaff et al., 2007, Schelker et al., 2013)	Uncut riparian buffer zones (Nieminen, 2004).	Riparian buffer (Kiely et al., 2000).	Tree planting of native species NFGWS, 2022, Lazzaro et al, 2008, Nisbet et al., 2011)	Phased felling (Shah et al., 2022)
TIMBER HARVESTING (Carpenter et al, 2013)	Controlling soil erosion from forested land.	Bank stabilisation/Bank revetment measures (NFGWS, 2022) .	Winter harvesting	
FERTILISING WITH UREA-NITROGEN (Carpenter et al, 2013).	Management of fertiliser use	Using organic fertiliser or slash mulch or biochar (Rombolà et al., 2022)	Not applying fertiliser during wet weather (Shah et al., 2022)	
BURNING of post-harvest slash (Carpenter et al, 2013)	Repurpose the slash to a valuable by-product like chippings	Leaving smaller unburnt piles of slash	Spread the slash as mulch on agricultural land	
VEGETATION type or Tree species	Deciduous native forests (Cronan and Aiken, 1985)	Strategically plant deciduous trees further away from water sources and conifers closer to water sources	Planting Mixed species forests (Collier and Farrell, 2007)	
Forest SOILS (Wickland, Neff and Aiken, 2007)	Operate equipment on established roads	Retain unharvested materials for ground cover.	Use high flotation tires and steel flexibles tracks	
PEATLAND				
Potential DOC Source	**Potential solution to mitigate DOC**	**SWP Measure**	**SWP Measure**	**SWP Measure**
DRAINAGE activities (Kluge et al., 2010; Frolking et al., 2011, Fenner and Freeman, 2011; Strack et al., 2019, Worrall et al. 2003)	Partially blocking drains	Peatland rehabilitation involving a combination of all SWP measures suitable for peatland (Rolston and Linnane, 2020, Wilson et al., 2011)	Drain blocking / grip blocking, using peat or heather bales (Wallage, Holden and McDonald, (2006),	Re-vegetated, core matting. (Wallage, Holden and McDonald, 2006)
WINDFARM development	Brash mulching (cut heather) (MoorLIFE2020, 2020).	Geo-jute attached to bare peat to prevent erosion (Parry, Holden and Chapman, 2014).	Detailed pre-construction planning e.g detailed surveys to map peat depth and condition, carry out a hydrological assessment, minimise peat excavation (M. Ehsan Jorat et al., 2024)	
SURFACE RUN-OFF (Holden and Burt, 2003),	Stabilize Bare peat (Millar, 2008).	Revegetation.using using *Sphagnum* plug plants (Parry, Holden and Chapman, 2014; Campeau and Rochefort, 1996)	Gully blocking, using peat or heather bales (Wallage, Holden and McDonald, (2006),	
SLOPE (Boothroyd, Worrall and Allott, 2015; Parry et al., 2015)	In gentle hillslopes (8-30% slope), riparian soils contributed between 73 and 84% of the stream DOC export. (Hinton, Schiff and English, 1998)	Reprofiling of the sides of gullies effective on slopes greater than 45 degrees.	Geotextiles can be used on slopes steeper than 20 degrees	
HEATHER BURNING (Garnett et al., 2000, Beharry-Borg et al. 2009, Grayson et al. 2008).	Sheep grazing between March and October	Cutting / mowing of heather if the area has low slope angles and smooth terrain.		

AGRICULTURAL LAND				
Potential DOC Source	**Potential solution to mitigate DOC**	**SWP Measure**	**SWP Measure**	**SWP Measure**
HUMAN ACTIVITIES, (Zhang et al., 2023)	Agricultural industry optimization	Making improvements to guttering, slurry drains and ditch water pools (Linnane et al., 2011	Good farmyard management (Linnane et al., 2011) for example regularly cleaning dirty areas, diverting rainfall from roofs, regularly scrape and clean soiled areas, especially high-traffic zones, to reduce contaminants.	
NITROGEN FERTILISER (Mattsson et al., 2005).	Land spreading exclusion (Linnane et al., 2011)	Use of boom sprayers for fertiliser application, while ensuring that equipment is regularly serviced (NFGWS, 2022).	Planting mixed species hedgerows, rewilding (NFGWS, 2022). Mixed cropping or polyculture or inter-cropping or co-cultivation, crop rotation (Kleinman et al. 2005; Strauch et al., 2013).	Buffer strips', grass buffer strip or, Riparian buffers, willow buffer.(Prosser et al., 2020; Stanley et al., 2012; Dunn et al., 2022)
AGRICULTURAL DRAINS especially on dairy farms (McTiernan et al., 2001; Sickman et al., 2009)	Sediment traps in existing surface drains (L. Chris Smith and Muirhead, 2023).	Create awareness of good farm yard practices among farmers (Linnane et al., 2011).	Cattle fencing, sheep wire fencing, solar fencing (Owens et al.,1996; O'Neill et al. 2023).	Setback distances for septic tanks and annual inspection (McCarthy et al., 2008).
SURFACE RUN-OFF (McGlynn & McDonnell, 2003; Bishop et al., 2004; Yue et al., 2020).	Stormwater or constructed wetland or reed bed or treatment wetland (Newman et al., 2015; Souliotis and Voulvoulis, 2022).	Buffer strips', grass buffer strip or, Riparian buffers, willow buffer.	Conservation tillage (no-till, ridge-till, strip-till, mulch-till, and reduced-till. (Smith, 2004; Ogle et al., 2005; Klik and Rosner, 2020)	Provide alternative drinking water source for livestock away from river banks for example solar-powered pumps, animal activated nose pumps and gravity fed system
SLURRY APPLICATION (Delpla et al., 2011)	Liquid polyaluminum chloride (Murnane et al., 2016)	Exporting slurry to a dedicated centralised regional facility (Linnane et al., 2011).	Anaerobic digesters, slurry pelleting and/or decanting systems (Cathcart et al., 2021).	Regular workshops or demonstration days to raise awareness of alternative methods(Linnane et al., 2011).
LAKES / RESERVOIRS				
Potential DOC Source	**Potential solution to mitigate DOC**	**SWP Measure**	**SWP Measure**	**SWP Measure**
SURFACE RUN-OFF (Tamara et al., 2010)	Implement Natural Water Retention Measures to increase the mineralisation process.	Healthy forests help regulate water flow into reservoirs(Calder, 2007).	Bioretention areas or bioretention cells (NCDENP 1999; Hui Hwang Goh et al., 2019) constructed wetlands, retention ponds, in-line/on-line ponds, settling ponds, run-off attenuation features and rural sustainable drainage systems (RSuDS) (Ockenden et al., 2012; Barber et al, 2012).	Buffer strips', grass buffer strip or, Riparian buffers, willow buffer (Kiely et al., 2000) Earthen bunds (Keesstra et al., 2018; Wilkinson et al., 2019).
Finer-textured SOILS, (Herreid et al., 2024).	Watersheds with deeper, coarser-textured soils (McDowell 2023; Solomon et al. 2015).	Mixed cropping or polyculture or inter-cropping or co-cultivation, crop rotation (Kleinman et al. 2005; Strauch et al.,2013).		
HARMFUL ALGAE BLOOMS (HABs) or macrophyte production (Martin et al. 2005, Kaplan and Bott 1982) particularly the presence of cyanobacteria (Tomlinson et al., 2016) and planktonic species of blue-green algae and sloughed filaments, stalks, and cells of benthic algae	Effective management actions (Kraus et al., 2011) All source water protection measures aimed at reducing nutrient	Improved farmyard management and reduce use of Nitrogen fertiliser	Riparian buffer zone(Kiely et al., 2000) fencing, sediment traps, earth bunds	A hybrid-constructed wetland (Wu et al., 2023)

(Carpenter et al., 2013) and the presence of cyanobacteria (Tomlinson et al., 2016)	influx to freshwater systems (Tomlinson et al., 2016).			
MIXOTROPHIC lakes (Dark water lakes)(Jonsson et al., 2001).		Flocculation to lake sediments (Von Wachenfeldt et al., 2008).	Smaller lakes (Algesten et al., 2003)	
SULPHATE DEPOSITION DECREASE Monteith et al. 2007, Skjelkvåle et al. 2005, Erlandsson et al., 2008, Driscoll et al., 2016, Gavin et al., 2018, Evan Et al., 2012, Evans, Monteith and Cooper, 2005)	Addition of aluminium(Schindler et al., 1992)	All source water protection measures		
WASTEWATER TREATMENT				
Potential DOC Source	**Potential solution to mitigate DOC**	**SWP Measure**	**SWP Measure**	**SWP Measure**
Poorly functioning onsite wastewater treatment systems. Wastewater Treatment Plants at capacity and population growth (Zhang et al., 2022), Increased rainfall from climate change causing overflow events)	Constructed wetland (Vymazal, 2009; Zhang et al., 2023)	Stormwater or constructed wetland or reed bed or treatment wetland(NCDENP 1999).	Milled egg shells (Yirong and Vaurs, 2019).	

4.0 Feasibility and Potential for implementation of SWP for the mitigation of DOM: Case-Study Ireland (specific reference to provision of water through Group Water Schemes)

4.1 Overview

This section aims to provide a review of the potential and feasibility of the implementation of SWP measures to mitigate against DOM for provision of clean drinking water using Ireland as a case study site. Specifically, the focus is on the Irish Group Water Scheme (GWS) sector, which is a relatively unique system of distributing and supplying drinking water, operated through a series of (usually) privately run co-operative schemes in which the local community come together to source and distribute their own water. Almost 20% of households in Ireland have drinking water supplied either through GWSs or through private wells. The National Federation of Group Water Schemes (NFGWS; https://nfgws.ie/) is the representative organisation which supports these schemes, providing training and acting to lobby the government on behalf of the schemes. Ireland and particularly the GWS sector provides a unique opportunity to reflect on the implementation of SWP for mitigation against DOM as they have a history of supporting SWP schemes both through research projects (eg. The National Source Protection pilot Project, 2006-2010 (Linnane et al., 2011); NFGWS Source Protection Pilot Project Phase 2 (NFGWS, 2023) and support for the development of SWP plans for member schemes through targeted funding with support from National Agencies and Government (e.g. Department of Agriculture, Food and the Marine (DAFM)).

4.1.1 Irish Context

In Ireland, approximately 80% of Ireland's drinking water is abstracted from surface water and groundwater sources are often influenced by surface water infiltration linked to rainfall events particularly in Karst regions. Despite significant resource investment, almost half of all of the surface water in Ireland is in an unsatisfactory condition, achieving less than 'Good' status for WFD implementation. Water quality reporting conducted by the Irish Environmental Protection Agency (EPA) has found that agriculture is the most common significant pressure impacting water bodies in Ireland (DeptHLGH, 2024). In 2018 more than 70% of Ireland's peat bogs and moors were used for agriculture, primarily extensive grazing (CSO 2021). Higher total trihalomethanes (TTHM) concentrations in drinking water in Ireland have been found to be associated with the presence of peaty soils and shallow topographical slopes (<5.25%) in areas with >1400 mm of annual rainfall (O' Driscoll et al., 2018). In Ireland chlorine is used as a primary disinfectant in water treatment, but additional chlorine can also be added to provide a stable disinfectant residual throughout the widely dispersed distribution network. In 2015, the European Commission started infringement proceedings against Ireland for failure to comply with the Drinking Water Directive (98/83/EC) THM standard of 100 µg/l. In 2020, the EU Commission escalated its infringement proceedings against Ireland by issuing a Reasoned Opinion stating that Ireland had failed to take the measure necessary to ensure THM

compliance in 31 public water supplies and 13 private GWSs. Based on the 2023 EPA Drinking Water Quality Report 1 in every 20 public water supply in Ireland had failed the THM limit (EPA, 2023), with 21 GWSs supplying 22,000 people recording exceedances. In 2024, The European Court of Justice ruled that Ireland had failed to take the measures necessary to ensure THM compliance in 9 private GWSs and failed to give priority to enforcement actions.

4.1.2 Objectives

As part of this project, we aimed to investigate and assess their perspective on the main issues associated with DOM input to source water and the impact on treated water quality in terms of DBP formation. This was achieved through a combination of focus groups, interviews and survey in which the feasibility of implementation of SWP solutions for managing DOM loading to drinking water supplies were explored by assessing the perceived issues, barriers and solutions to their effective implementation.

4.1.3 Participatory stakeholder analyses

Within environmental decision making the importance of stakeholder participation has long been recognised at the international and local level (Reed et al., 2009; UNECE, 1998) and has been identified as essential for fair, sustainable (Gokhelashvili, 2015; Reed et al., 2009) high quality and durable decisions (Beierle, 2002). Participation inherently implies a two-way process whereby information moves between researcher and participants towards a mutual goal of shared knowledge creation and collaboration (Pain, 2004). Carrying out participatory group-based research can offer an informative and potentially empowering tool for gathering stakeholder knowledge.

The stakeholder forum approach taken for this study combined both stakeholder engagement and participatory engagement with the aim to both consult and engage the stakeholders (Pyrialakou, Gkritza and Liu, 2018). Thus, providing the stakeholders an opportunity to engage with the intoDBP project, discuss their needs and issues in relation to reducing disinfectant by-products (DBP) in drinking water through source water action and to help guide the project. This collaborative approach was taken to strengthen relations between key stakeholders in the GWS sector and project researchers, create a space to exchange knowledge, concerns and possible solutions and at the same time provide a structured method of collecting individual responses to specific research questions. This approach provides an environment where stakeholders with different viewpoints can come together to identify problems, advance solutions, and produce a collective vision for the future (Maskrey et al., 2020). One of the key features of focus groups is that they can easily facilitate the discussion among policy makers or other professionals, researchers, and stakeholders, and as literature suggests, discussion is “the essential link between analysis and decision making” (Willson et al., 2003).

To include voices from a wider audience and enable methodological triangulation an on-line survey was also carried out. The results of this survey will be used to test and enhance the outputs from the focus group. This mixed method approach facilitates the comparison of quantitative and qualitative data sets to produce well-validated conclusions (Migiro and Magangi, 2011).

4.2 Methodology

4.2.1 Data Collection

4.2.1 Quantitative data – Questionnaire/Survey

The online survey method was used to reach active GWS committee members and water utility practitioners operating in Ireland. The purpose of the survey was to gain an understanding of current stakeholders' knowledge of DOM and its connection with DBP formation and to assess the community buy-in for the SWP measures identified from the literature review process. Buy-in of SWP measures was examined by asking the participants' opinion on how effective each of twenty listed SWP measures are in addressing water quality pollution and asking to what extent they agree or disagree that certain factors may be considered barriers and incentives for landowners to implement SWP measures.

The survey was designed using the electronic-based platform Qualtrics. It was distributed from 28th May 2025 to 26th September 2025. The survey consisted of 12 questions and a free text option at the end for feedback. Scale questions were chosen instead of open-ended questions so that respondents would be more likely to respond to all questions without getting survey fatigue (Jeong et al., 2022) (see Appendix B for the complete questionnaire). A draft survey was tested on NFGWS staff to determine their opinion on the clarity of the proposed questionnaire, and to obtain their suggestions for further information, clarifications, and questions. The survey can be divided into five sections. The first section included questions on demographics including respondents' occupation/expertise or association with the GWS sector, location including county and town name and if they live close to a water source. A question on the principle land type in their area was included to examine any correlation between land type and perceived effectiveness of particular SWP measures. Section two elicits information on the respondent's knowledge on factors relating to drinking source water quality. This section included and assessment of the respondents knowledge of terms like Dissolved Organic Matter (DOM), Trihalomethanes (THMs), Disinfected by-products (DBPs) and Haloacetic acids (HAAs). The third section introduced the concept of SWP measures and asks participants to evaluate different measures according to their perceived overall effectiveness at improving source water quality, with a qualitative evaluation performed using a 5-point scale. This section included the option to select 'I am not aware of this measure' and 'I don't know' to assess the knowledge or lack of knowledge for certain SWP measures and also the lack of knowledge in relation to a measure's effectiveness. In the fourth section, participants were asked, using a 5-

point Likert scale from strongly disagree to strongly agree, to evaluate a list of ten barriers to the implementation of SWP measures. Finally, section five comprises eleven suggestions that might incentivise landowners to implement SWP measures and asked participants to assess each suggestion using a five-point Likert scale ranging from strongly disagree to strongly agree. A free-form section was included at the end of the survey to allow participants to include any relevant feedback. The on-line survey took on average approximately 12 minutes to complete.

The survey was distributed online to GWS members though the NFGWS and to the 149 delegates who attended the Irish Rural Water Conference 2025, which is an annual conference organised by the NFGWS and attended by GWS members, local authority and water utility and governmental representatives and researchers. In total, 68 people scanned the QR code and initiated the survey, with 28 respondents abandoning the survey prior to completing question 6. The survey was completed by 40 people, this is a response rate of 26.8% which represents 1.3% of active GWS committee members across Ireland.

4.2.2 Qualitative data – Focus Group

Focus groups are small groups of people guided by a facilitator to answer questions on a particular topic (Then et al., 2014). By allowing the researcher to concentrate more time and resources on creating a relaxed and safe group environment, focus groups are a useful method to gain a deeper and richer understanding of a topic. There are a number of formats through which a focus groups can be structured including; 1) facilitator led in which the facilitator asks a set of questions and the group members respond to those set questions with no deviation, 2) semi-structured, where the facilitator asks guiding questions but allows for group interaction before responding to those questions, and finally 3) unstructured where the group discussion is free flowing. The benefit of using the semi-structured approach is that there is a structure of set themes for the group members to explore and group interaction allowing the exchange of ideas and a deeper exploration of these themes by the group members (Wilkinson, 2004). Qualitative methods are important because they are less structured, more open, and flexible than quantitative approaches and enable opportunities for reflexivity of responses, in-depth analysis, and the generation of novel findings (Drury et al., 2011). However, using the two approaches will improve evaluation and ensure the limitations of one type of data are balanced by the strengths of the other.

The methodology used for data collection during the focus group was the participatory qualitative phase of the KCP methodology (i.e. K for knowledge, C for concepts and P for proposals) from Pluchinolta et. al (2021b) and Pluchinolta et.al (2019). C–K theory is based on the distinction between two expandable spaces; a space of Concepts (C-space), and a space of Knowledge (K-space). Within the C–K theory, the design activity is defined as the process by which a concept generates other concepts or is transformed into knowledge, i.e. the co-evolution of the C- and K-spaces (Masson et al., 2009).

The stakeholders attending the focus group included representatives from the NFGWS, Group Water Scheme members from the case study sites in Co. Mayo alongside stakeholders from Uisce Éireann and Local Authority Waters Programme (LAWPRO). Uisce Éireann is Ireland's national water utility regulator. They are responsible for providing safe, clean and affordable water and wastewater services to approximately 80% of the population in Ireland. LAWPRO works on behalf of Ireland's 31 local authorities to protect and improve water quality in rivers, lakes, estuaries, ground and coastal water. Its work is driven by the WFD and involves coordinating efforts between local authorities, government agencies, catchment science and local community engagement to achieve 'good' or 'high water quality' in all rivers and lakes in Ireland as part of WFD implementation. The focus group aimed to identify the issue by exploring prior knowledge and stakeholder understanding of issues related to DOM and source water quality, the solutions to these issues, their feasibility and the barriers to implementing these solutions. It also aimed to obtain input on the proposed outputs of the project and assess stakeholder needs and requirements with specific focus on the development of a risk assessment tool for DOM impacts on drinking water quality.

In order to collectively build and share the available knowledge about DOM and risk of DBP formation in drinking water, several presentations (Fig.10 Image. 1) were delivered by the project team (K-space). These included an overview of the issues with DBP in drinking water, a summary of the literature review of source water protection measures for the reduction of DOM in drinking water as well as an overview of the progress with regards developing the modelling framework for forecasting organic matter in Irish source waters (IntoDBP Deliverable 5.1).

The C-phase, after each presentation, aimed to activate and encourage unexpected concept-exploration. This phase involved the stakeholders writing down as many answers as they could (one per post-it), variables of identification (Fig.10 Image.2) to each of the following questions: (D1) In your opinion what are the **main issues** with regard to dissolved organic carbon and water quality?; (D2) In your opinion, what are the **barriers** to implementing solutions?; (D3): In your opinion, What are possible **solutions** and the **feasibility of their implementation**? and (D4) What information would **you find beneficial in a risk assessment tool** informing decision makers on potential solutions to protect drinking water quality?

After this process there was a short, recorded discussion between all participants, including the researchers to encourage engagement and exchange of ideas. During this phase, participants started learning from other stakeholders' knowledge and experience, which had the potential to lead to a realisation of missing knowledge elements. At the end of the participatory qualitative phase, as described in Pluchinotta *et al*. (2021), participants individually prioritised these variables via a voting poll (Fig.10 Image 3).

Image 1 *Image 2* *Image 3*

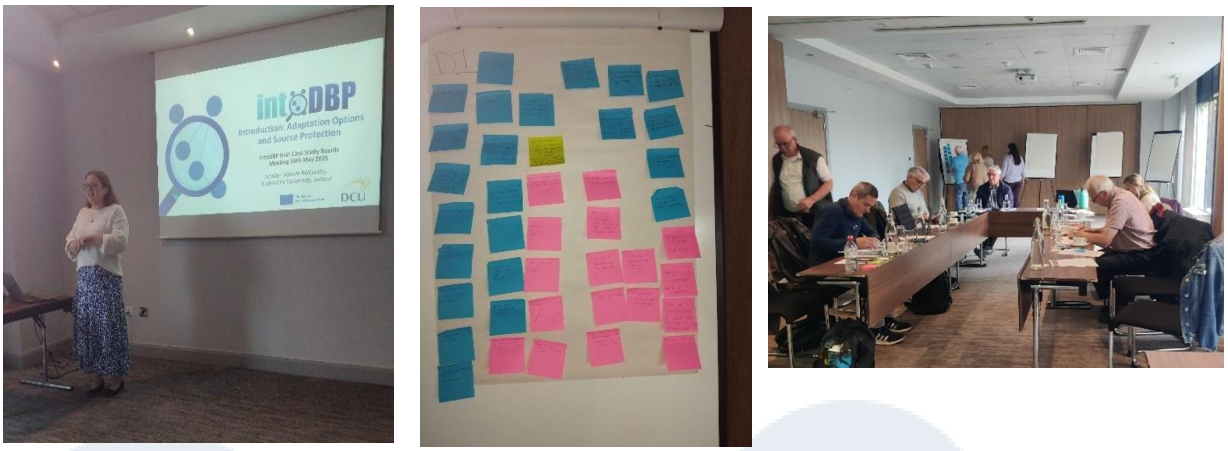


Figure 10. *Image 1 - As part of the K space in the KCP methodology, presentations were given by WP5 researchers. Image 2 - Shows the list of post-its with the participants' variables of identification for D1. Image 3 - Each participant used their 5 votes by placing a tick or ticks on the variable/variables they felt were most important under each discussion group.*

In a deviation from the methodology described by Pluchinotta et al. (2021), owing to time constraints researchers linked variables to build a causal loop diagram (CLD) rather than the focus group participants. A second focus group will be carried to validate the work of the first focus group (not presented here) and to refine the results. T

4.3 Data Analysis

4.3.1 Quantitative data – Questionnaire/Survey

Quantitative data from the questionnaire survey was exported from Qualtrics into Microsoft Excel and descriptive statistical analysis was applied to determine the relative frequencies and the percentage response of participants. There are some limitations to the results from the survey as not all terms that can be used to describe specific SWP measures were provided for reasons of clarity and survey size; which may have affected some responses. In addition, there was a relatively low response rate for the completed surveys. Nevertheless, as the intention of the survey was to further inform and provide a quantitative supporting framework to outputs arising from the stakeholder forum, the responses are considered useful in this context.

4.3.2 Qualitative data analysis – Focus group

In the stakeholder forum, under each discussion theme (D1,D2,D3 and D4) the project researchers selected variables for removal if they were found to be repeated, tangential to the key issues or ambiguous. Similar variables were grouped together under one variable heading

for example under D1: *Impact of climate change, Variability of rainfall, Climate change and unpredictability of rainfall, Increase soil erosion due to heavy rainfall and human activities, Changing climate* and *Weather events* were all grouped under the one variable *climate change* (further details of these groupings can be found in appendix A). Following the focus group, the research team created a Causal Loop Diagram (CLDs), which shows how the variables from D1, D2, D3 and D4 connect. While the preliminary CLD was developed by the research team alone, the knowledge it represents was originally sourced from the stakeholders. The preliminary CLD were produced in Vensim® Software (by Ventana Systems).

The qualitative data from the audio recorded discussions of the focus group were analysed using a thematic analysis process based on Braun and Clarke's (2012) framework. This involved familiarisation with the data, generating initial codes, searching for themes and reviewing potential new themes when compared to the CLD variables. The preliminary findings were firstly examined by the research team individually and were then followed by a group discussion on the discrete interpretations of the data through the lens of the four research questions which produced richer and deeper understandings. Table 6 lists the variables from the discussions showing any variables that did not appear on the CLD highlighted.

4.4 Ethical considerations

The research ethics application and supporting documentation was completed and submitted to the DCU Research Ethics Committee. The Ethical approval for the study was obtained from the Research Ethics Committee in Dublin City University in April 2025. The application was found to comply with university requirements and best practices for research ethics, and with GDPR guidelines and requirements where personal data is processed in the project. A plain language statement outlining the aims and objectives of the study, use and storage of the data, issues of confidentiality and data protection were provided to each participant along with an informed consent form to be signed before the focus group began. The online survey provided a plain language statement before the participant began answering any questions. The survey used an opt-in approach whereby participants indicated their informed consent by submitting their survey response. No incentives were offered for participation. All participants of the focus group were informed prior to the start of the focus group that the discussions would be recorded and transcribed. All the data was anonymised. Participants were reminded that involvement in the research was voluntary and they were advised that they could withdraw from the research at any time. The focus group took approximately 5 hours with an hour break for lunch.

4.5 Results

4.5.1 Survey Results

Respondent Demographics

A total of 40 survey responses were received. The majority of respondents were Group Water Scheme members (55%), with the majority living in Co. Monaghan and Co. Mayo (15%), followed closely by Co. Cavan and Co. Laois (10%). The majority of respondents were living or farming near a lake, river or stream (65%), with grassland (68%) described as the principal land use type in their area. Participants living close to a lake graded their water quality an average of 27.8 out of 100 for lakes, 60.8 out of 100 for rivers and 52 out of 100 for streams. However, only 32% of respondents living adjacent to a waterbody said it was a source of drinking water (Table 4).

Table 4. Demographic characteristics of survey respondents. Frequency refers to the count

Variable	Categories	Frequency	Percent
Location	Cavan	4	10
	Clare	1	3
	Cork	2	5
	Galway	3	8
	Kildare	2	5
	Kilkenny	2	5
	Laois	4	10
	Leitrim	1	3
	Limerick	3	8
	Mayo	6	15
	Meath	2	5
	Monaghan	6	15
	Roscommon	2	5
	Tipperary	1	3
	Wexford	1	3
Principle land type	Cultivated land	6	15
	Forestry	3	8
	Peatland	2	5
	Grassland	27	68
	Artificial surfaces	0	0
	Wetland	1	3
	Heath and bracken	0	0
	Not sure	1	3
Identified as	Agricultural advisor	0	0
	Group Water Scheme member	22	55
	Policy maker	6	15
	Rep of a farmers organisation	0	0
	Water utility practitioner	5	12.5
	GWS and Water utility practitioner	7	17.5
Live/farm adjacent to	Lake	2	5
	Lake and River	1	2.5
	Lake and Stream	1	2.5
	River	10	25
	Stream	10	25
	River and Stream	2	5
	None	14	35
Is it a source of drinking water	Yes	8	32
	No	17	68
Average Water quality out of 100	Lake		27.75
	River		60.84
	Stream		52.46

Perception of impacts on drinking source water quality

'*Animal manure*' was selected as the most important factor impacting drinking water quality by 90% of respondents (Fig. 11) followed closely by '*Pesticides*' (88%) and 'Septic tanks' (83%). However, '*Nitrogen*' and '*Phosphorus*' did not receive the same level of importance (78% and 73% ,respectively) even though they are the main pollutant compounds in manure impacting the quality of source water. On the other hand, '*Heather burning*' was considered to be the least important factor (10%), while '*Erosion*' and '*Drained peatland*' received the most 'I don't know' responses (13%). '*Organic matter*' was selected as a very important factor by 68% of respondents, moderately important by 23% and slightly important by 10%.

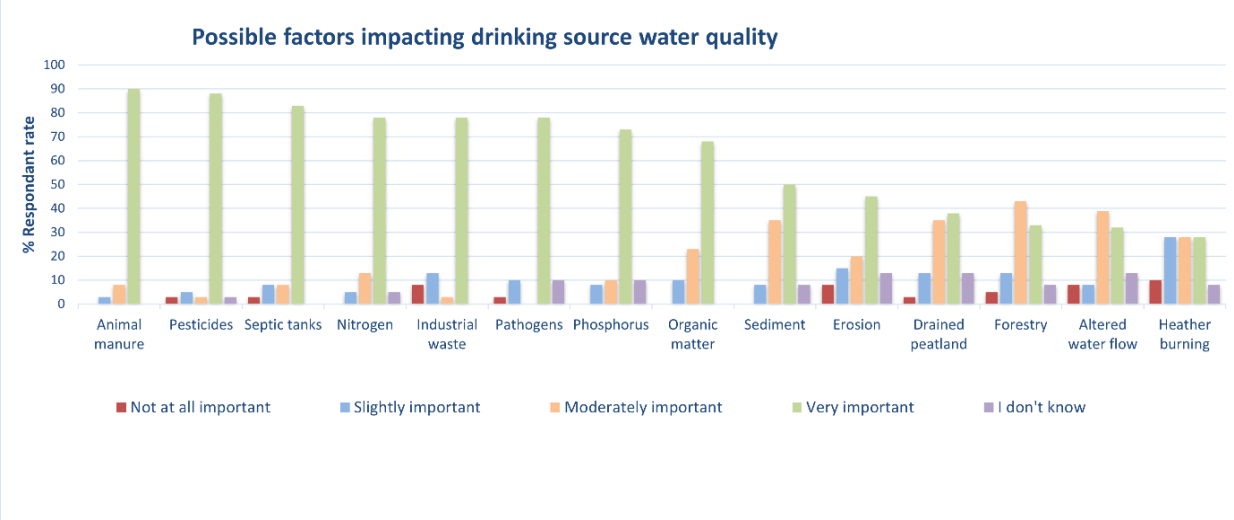


Figure 11. *Percentage survey responses for how important the factors are in impacting drinking source water quality.*

Knowledge of respondents

63% and 53% of respondents reported being extremely or very familiar with the terms Trihalomethanes (THMs) and Dissolved Organic Carbon/Dissolved Organic Matter, respectively (Fig. 12), with 46% of respondents very or extremely familiar with DBPs. The largest number of respondents (45%) are not familiar at all with Haloacetic acids (HAAs).The majority of survey participants think that 'landowners close to source water' are the most responsible for protecting source water while they think '*Water treatment plants*' are the least responsible (Table 5).

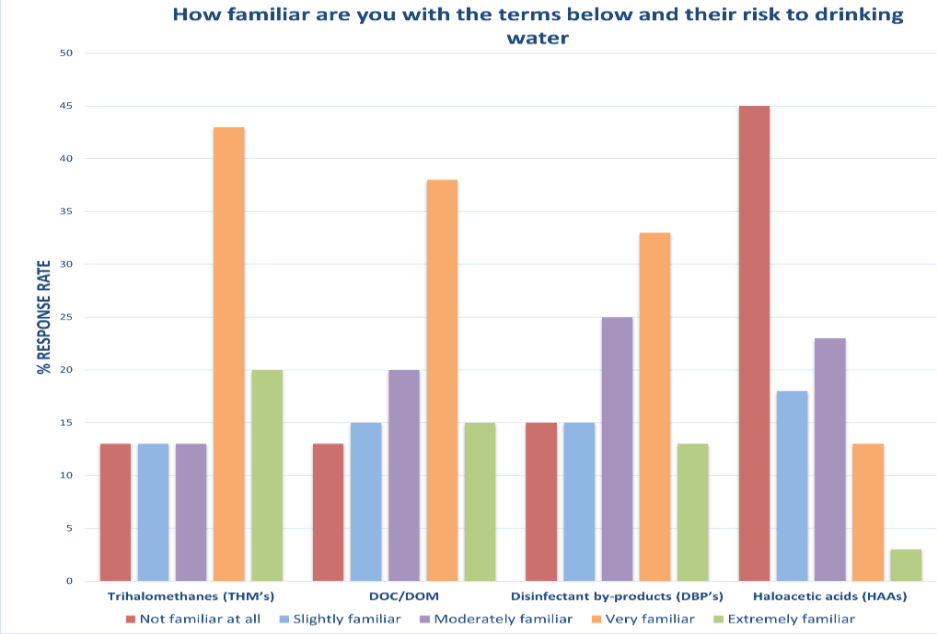


Figure 12. Percentage responses for how familiar participants are with the terms THMs, DOC/DOM/DBP's and HAAs and their risk to drinking water.

Table 5. Frequency results showing the ranking order participants of the survey gave to who they think is responsible for protecting source water in order of importance 1 being the most important and 9 being the least important.

Who do you think is responsible for protecting Source Water?									
	Ranking of importance								
	1	2	3	4	5	6	7	8	9
Landowners close to source water	14	7	5	3	4	4	1	0	2
Farmers	6	11	9	3	4	3	4	0	0
Local community	1	5	7	10	2	6	4	3	2
GWS	7	2	2	9	6	3	2	3	6
Local authorities	2	8	3	2	11	7	4	1	2
Uisce Éireann	2	2	4	3	2	7	5	8	7
EPA	8	3	5	3	3	2	6	5	5
Private businesses	0	0	2	3	4	7	7	11	6
Water treatment plants	0	2	3	4	4	1	7	9	10

Effectiveness of SWP measures

The majority of respondents perceived '*Buffer strips*' and '*Fencing along waterways*' (combined 69%) as being the most effective SWP measures of the twenty listed in the survey. In contrast '*Using organic fertiliser*' and '*Sheep grazing heather*' were the SWP measures considered least effective (17%). The majority of respondents are aware of the measure '*Tramline management*', however, 47% of them do not know if it is effective or not. '*Crop rotation*' is the

only SWP measure that is known by all respondents yet 25% of them do not know if it is effective or not.

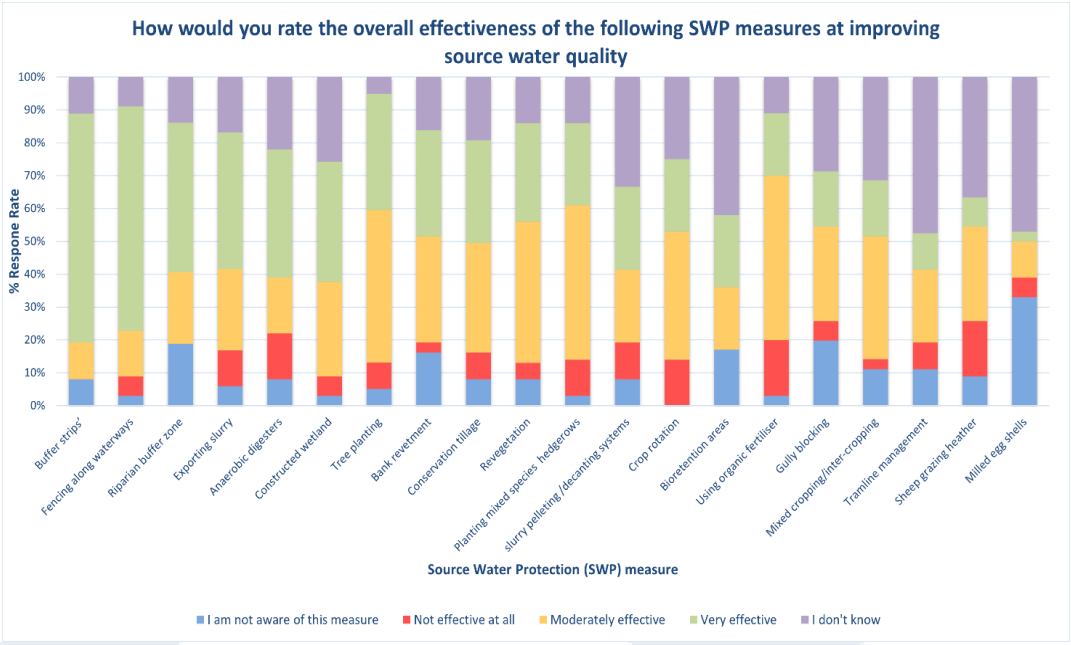


Figure 13. *Percentage responses showing how participants rate the overall effectiveness of each SWP measure at improving source water quality*

Barriers to implementing SWP measures

41% of respondents strongly agree that a barrier to implementing a SWP measure is if the '*measure is not a legal requirement*'. 89% strongly also agree or somewhat agree that '*cost*' is a barrier to SWP measure implementation. 14% strongly disagree with '*Negative impact on productivity*' and '*Not a priority for landowner*' as barriers to implementing SWP measures. While 39% either strongly or somewhat disagree that the '*Belief that measures will not improve water quality*' is a barrier to SWP measure implementation.

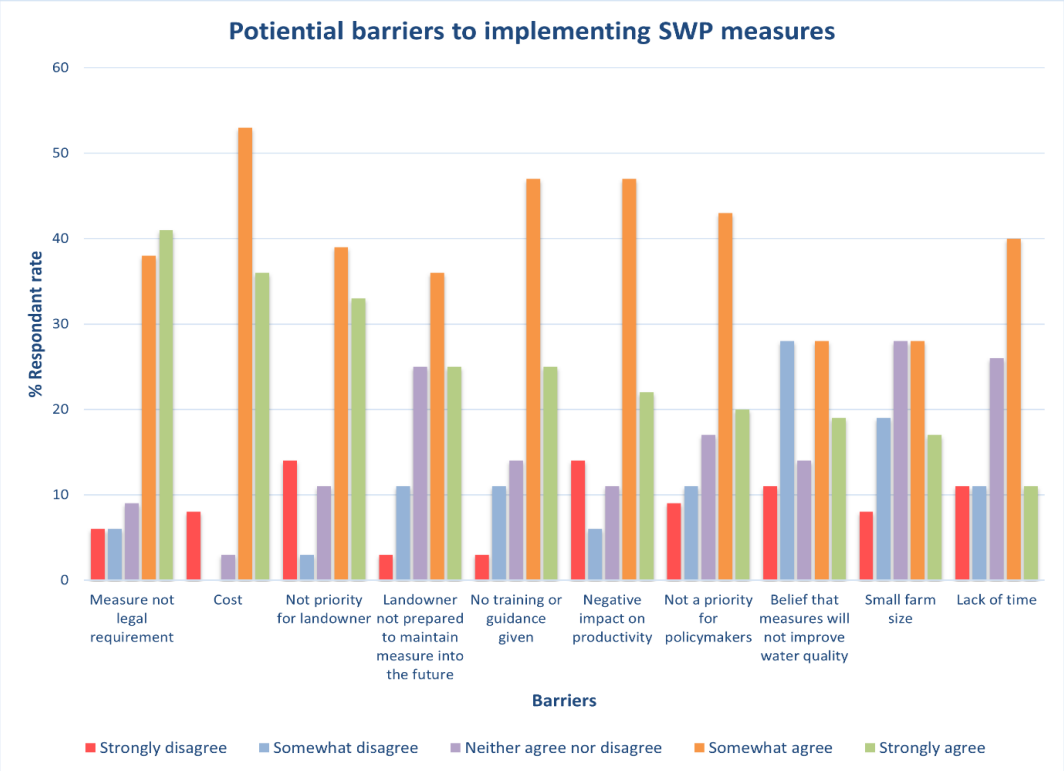


Figure 14. Percentage responses showing how respondents agree or disagree that certain factors are barriers to implementing SWP measures.

Incentives to implementing SWP measures

While many survey participants (51% somewhat agree) indicate '*Peer pressure from friends, family, neighbouring farmers*' to be an incentive to implementing SWP measure, the primary incentive identified was '*Training and guidance programmes provided to landowners*' (47% strongly agree), followed by a '*Grant scheme made available to landowners*' (46% strongly agree). '*The avoidance of environmental penalties*' also received support as an incentive with 83% of respondents strongly and somewhat agreeing. On the other hand, '*Creating a recreational space for the community*' received the least support (18% strongly agree) as an incentive to implement SWP measures. Likewise, 20% of respondents either strongly or somewhat disagreed with '*increasing productivity on the farm*' as being an incentive to implement SWP measures.

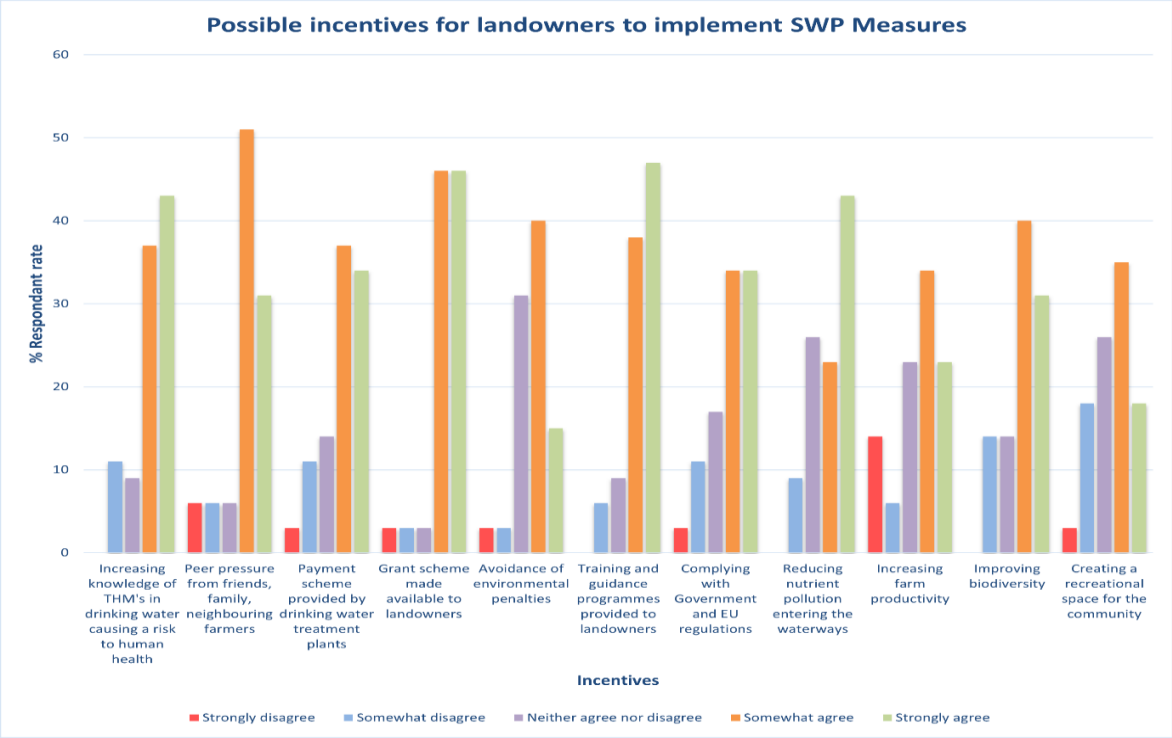


Figure 15. *Percentage responses showing how respondents agree or disagree that certain factors may be an incentive to implementing SWP measures.*

4.5.2 Focus group results

Casual Loop Assessment

A CLD was produced based on the outputs of the stakeholder focus group (Fig. 16). This shows the interrelationships and connectedness between each of the discussion areas (D1, Issues, D2 Barrier, D3 Solutions and D4 Needs). All of the variables under each category are provided in further detail in the appendix A.

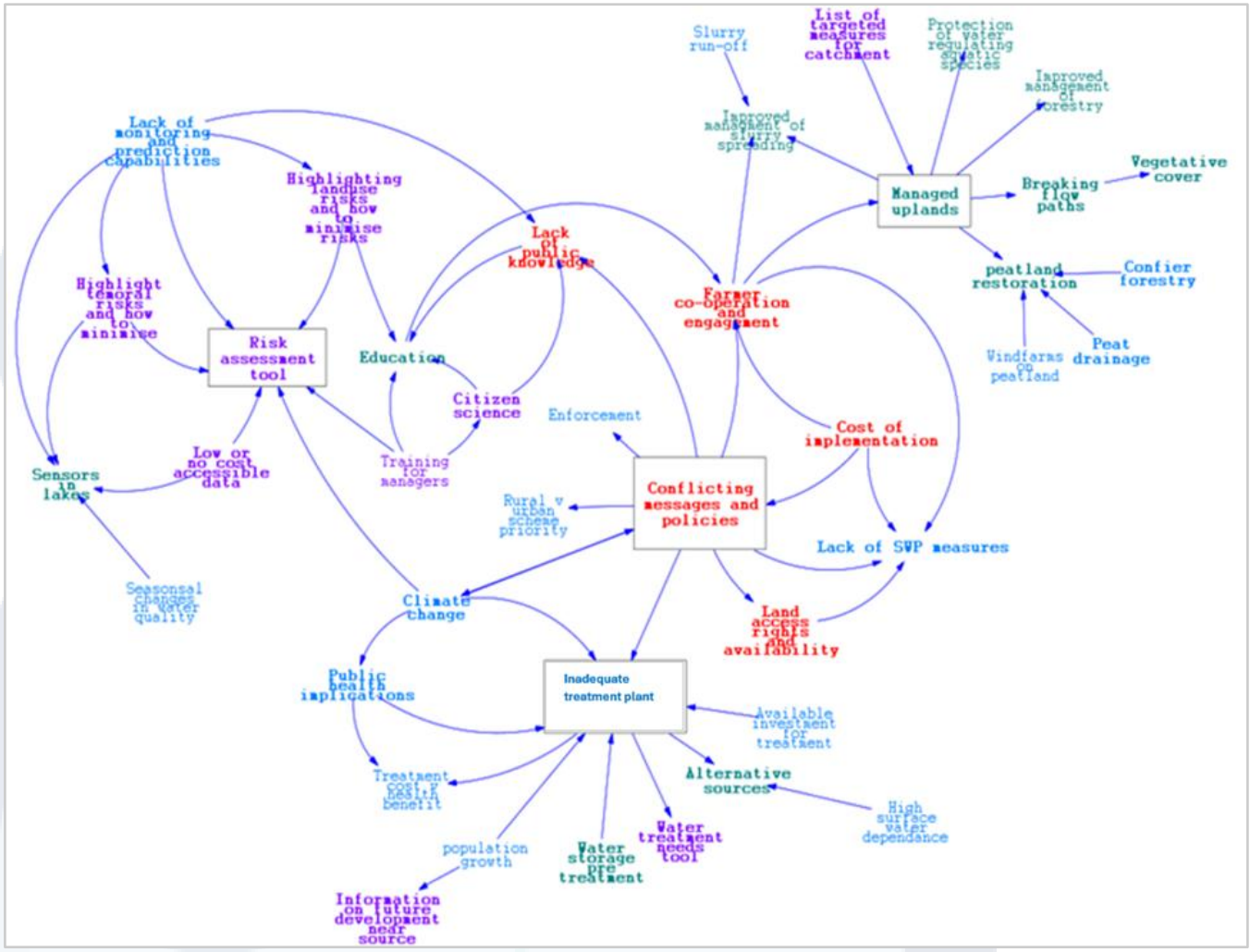


Figure 16. The final causal loop diagram created in VenSim. Blue = issues variables, Green = solution variables, Red = barrier variables and Purple = needs and wants of the stakeholders. The blue arrows are how the different variables connect. Highlighted variables are those which received the most votes. Variables in Boxes indicate a central theme or concept which acts as a focal point for variables.

Under D1(Issues), participants ranked the following variables '*Source protection measures', 'riparian areas not being implemented leading to further pressures down the road'* and *'Increased public awareness of health issue associated with water quality'* highest with a total of 5 votes each. '*Source protection measures, riparian areas not being implemented leading to further pressures down the road'* were grouped together with the variable *'legislation'* and

'*enforcement'* and are represented on the CLD as the variable *'enforcement'* (Fig. 16). *'Increased public awareness of health issue associated with water quality'* was grouped with the variables *'Educate'* which received one vote, '*Lack of understanding of raw water character and behaviour in treatment context'* which received three votes, '*Public understanding most people not aware of issues'* and '*Lack of knowledge on agricultural organic matter'*. These variables were considered to overlap with the barrier variable of '*Lack of public knowledge'* and therefore are not represented as a separate variable under D1. The variable *'inadequate treatment plant'* incorporates the following three variables grouped together *'Removal of DOM at the treatment plant to avoid secondary chlorination in the network', 'Settlement tank/pretreatment tank to remove organic material'* and *'Filter water within lake sources prior to delivery to treatment plant. Lake is too large a source not to apply prior filtration to plants, too many inputs to lake, heat, rainfall dust etc.'*. While this variable was not given the highest number of votes for importance, the stakeholders did give one vote each to the variable *'Settlement tank pretreatment tank to remove organic material'* and *'Filter water within lake sources prior to delivery to treatment plant.* '*Public health implications', 'climate change', 'population growth'* and *'available investment for treatment'* are all issues that feed into the variable *' inadequate treatment plant'*. While *'water storage pre-treatment'* and finding *'alternative sources'* of drinking water are possible solutions to '*inadequate treatment plant'* (Fig.17).

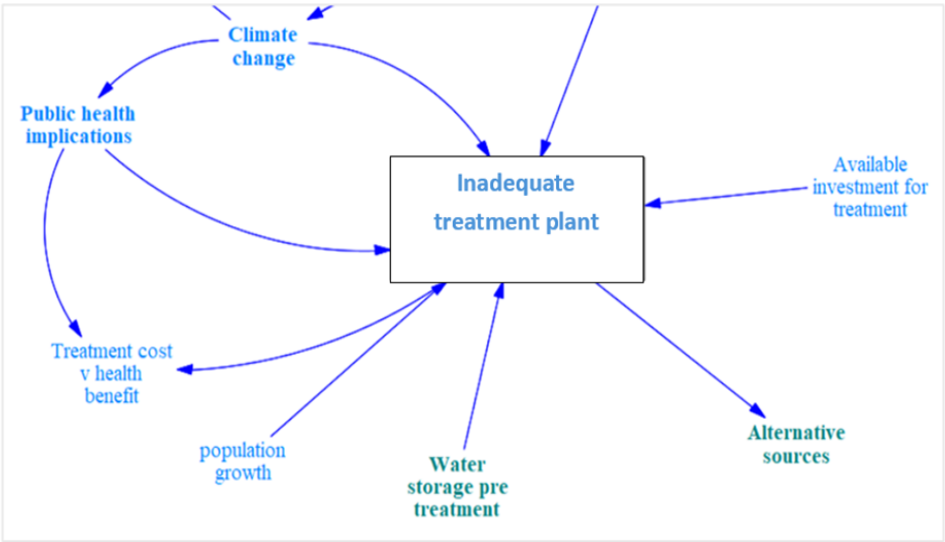


Figure 17. Section of the CLD showing the connections to the variable 'inadequate treatment plant' from D1 (issue). The box around 'inadequate treatment plant ' signifies it has a high number of connections.

Under D2 (Barriers), participants ranked the following four variables the highest with all four variables receiving three votes each; '*Public ignorance of a problem in the first place', 'Farmer cooperation and intensification'* and *Mindset for landowners to change way of working'* and *'Stakeholder engagement and implementation'. 'Public ignorance of a problem in the first place'* was grouped together with the variables '*Lack of awareness'* which received one vote, '*Lack of*

awareness of the issues of activities that will impact water quality', '*Public knowledge of effects of any source protection measure'* which received one vote, '*Getting information out there* and *Knowledge dissemination'* which received one vote. All of these variables are represented on the CLD as the variable '*Lack of public knowledge'* (Fig.18). The variables *'Farmer cooperation and intensification', 'Mindset for landowners to change way of working'* and *'Stakeholder engagement and implementation'* are all grouped together and represented on the CLD as the variable *'Farmer co-operation and engagement'* (Fig.18). The boxed Barrier '*Conflicting messages and policies'* is located between Issues and the Solutions in the CLD (Fig.16), which consists of the following variables grouped together *'Conflicting messages'* which received two votes, '*Public/landowners need a clear strategy from Ireland's Government with regards to the goals they are trying to achieve', 'Complex issue at Local Authority or Government level'* received one vote, '*Lack of visibility of the full picture of inputs* and *Conflicting policy and government department working in isolation from one another'*. This barrier influences the barriers of a *'lack of public knowledge', 'farmer co-operation and engagement'* and *'land access rights and availability'*. As well as having influence over the issues of *'enforcement', 'rural vs urban scheme divide', 'climate change', 'lack of SWP measures'* and '*inadequate treatment plants'*.

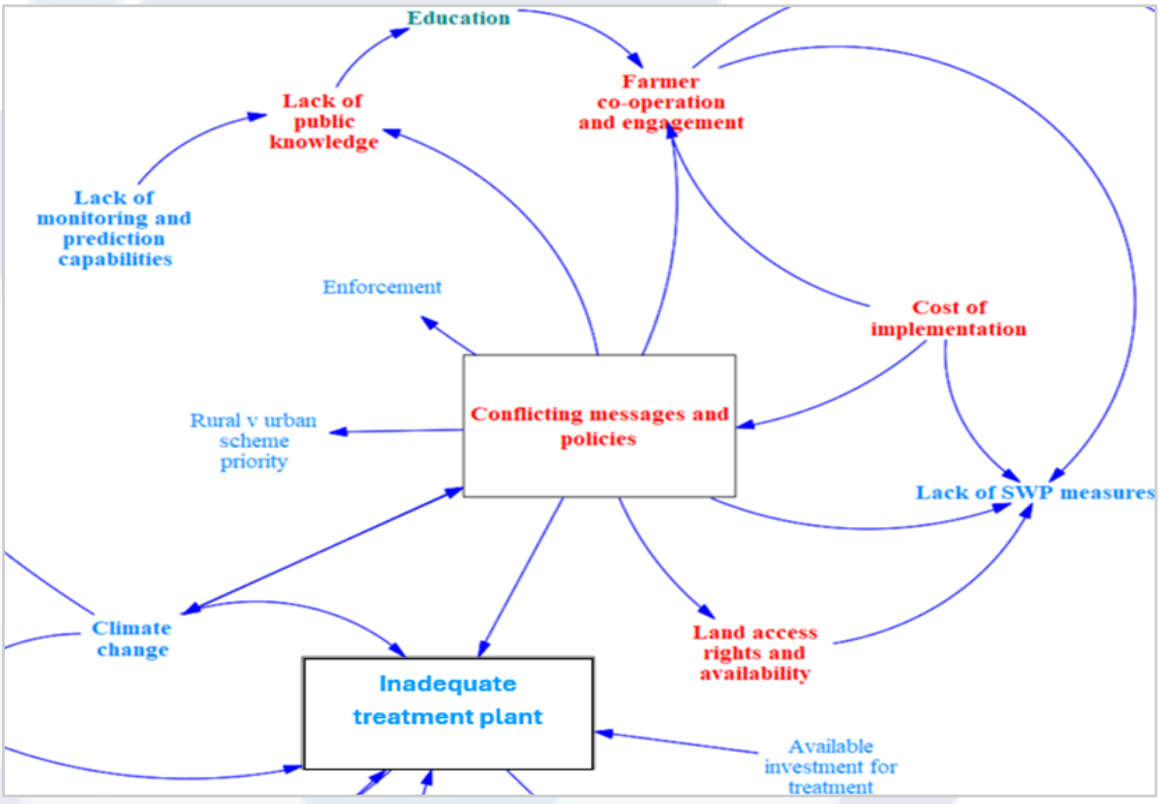


Figure 18. *Section of the CLD showing the connections to the variable Conflicting messages and policies from D2 (barriers).*

Under D3 (Solutions), participants ranked *'Sensors in lakes'* and **'***Drain blocking/rewetting'* the highest variables with three votes each. *'Drain blocking/rewetting'* was grouped together with '*raising water table in peat soils'* which received two votes*, 'Traps on inlet drains'* which received one vote, '*Managing water levels on peatland'* which received one vote and '*peatland restoration'* which received two votes. All these variables are represented on the CLD as the variable '*Peatland restoration'* (Fig. 19). The variable '*Managed uplands*' connects to many other solutions such as '*Improved management of slurry spreading', 'Protection of water regulation aquatic species', 'Improved management of forestry', 'breaking flow paths* and *peatland restoration'*.

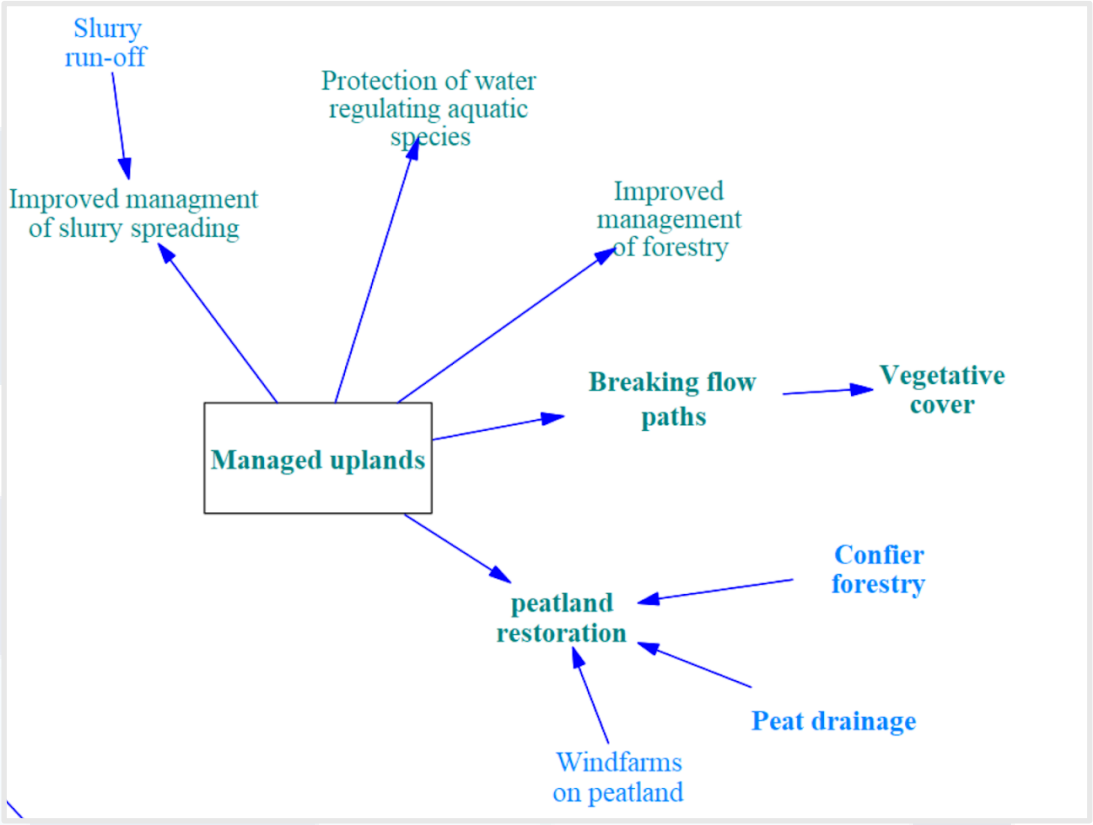


Figure 19. *Section of the CLD showing the connections to the variable Managed uplands from D3 (solutions). The box around 'Managed uplands ' signifies it has a high number of connections.*

Under D4 (Needs), participants ranked the variable '*Feasible data requirements low or zero cost'* the highest with four votes*. 'Feasible data requirements low or zero cost'* was grouped together with '*Data for model from the scheme not the contractor'* which received two votes and '*Accessible in cloud'* and they are represented on the CLD as the variable *'Low or no cost accessible data'* (Fig. 20). Fig. 20 shows how the majority of the needs of the stakeholders represented by the variables '*Highlighting land use risks and how to minimise risks'*, '*highlight temporal risks and how to minimise'*, '*low or no cost accessible data'* and '*training for managers'* feed into a '*risk assessment tool'* that addresses the issues of '*climate change'* and '*lack of*

monitoring and prediction capabilities' and supports the solutions of '*sensors in the lakes'* and '*education'*.

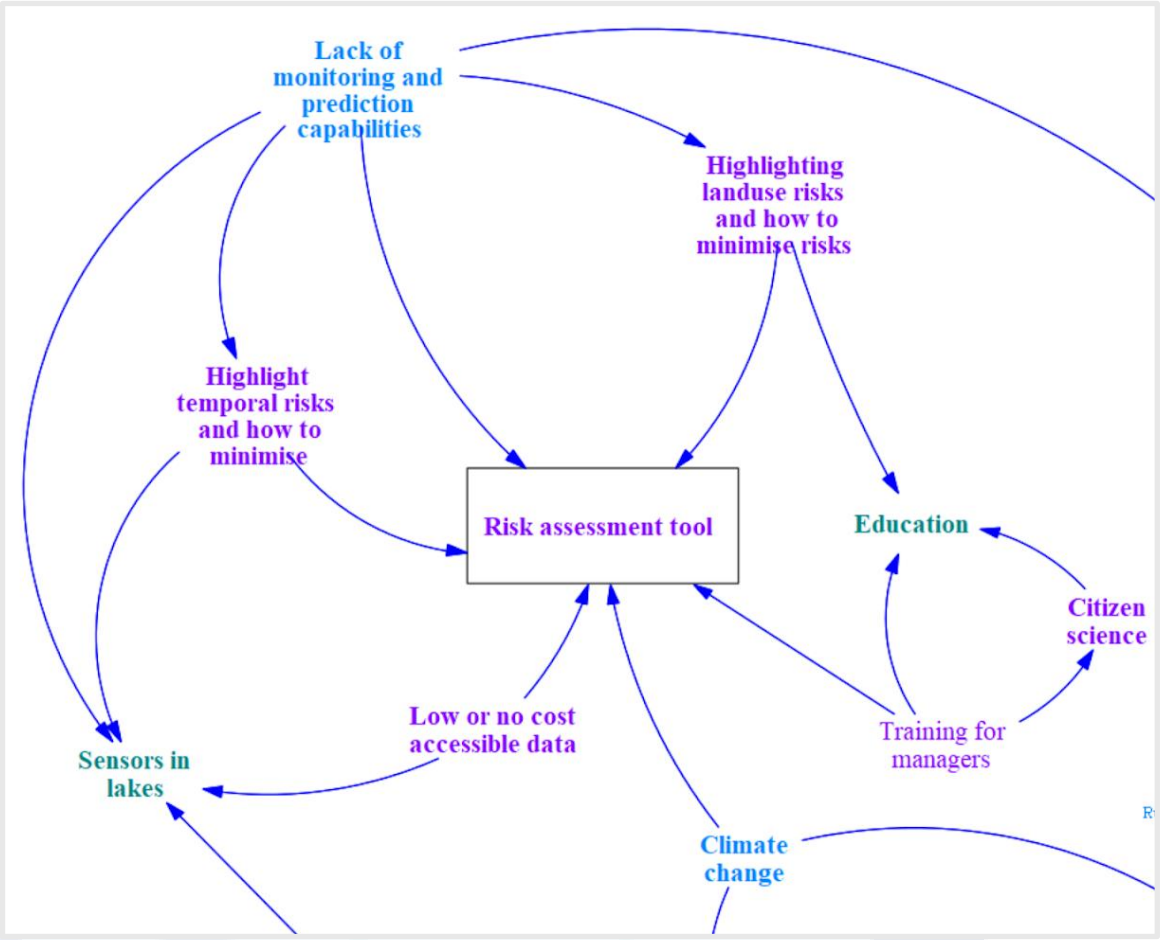


Figure 20. Section of the CLD showing the connections to the variable Risk assessment tool from D4(needs).The box around 'Risk assessment'' signifies it has a high number of connections

Thematic Analyses of Open Discussion

Additional topics to those identified and included in the CLD were raised during the discussion sessions of the Stakeholder forum. These topics, highlighted in Table 7, are new variables in addition to those which formed part of the CLD. The new variables under D2 (Barriers) are more specific than those in the initial CLD process, with a strong theme concerning the availability of volunteers and personnel within the GWS sector. The members on the GWS committee boards are aging '*it's run by a lot of elderly people'* and there seems to be little interest in the younger generation to volunteer '*no-ones replacing us*' '*the time is going to come when committees are going to be gone'*. Perhaps, as a consequence of the voluntary nature of the role '*all boards are voluntary*' and the responsibility attached to the role '*we have full corporate responsibility for anything that could go wrong with water'* there is a lack of leadership in the GWS '*no-one in charge*'. There is also a fear felt by the GWS members that they will be told what they can or

cannot do within their own catchment rather than be consulted and *'..engaged..'* with, *'frightened of is being told what we can do in terms of catchment'.* This theme of no control follows through with accepting contracts with water treatment companies that are not fit for purpose '*legislation that was in the original build we don't write contracts to say you must conform to future legislation*' being raised as a barrier. The theme of alternative sources was mentioned as a variable on the CLD, however, more specific suggestions were given during the discussion section such as *'rationalisation'* and *'interconnections'*. Rationalisation is when you streamline the management and operation of multiple schemes through physical connections or shared resources and interconnections involving connecting different water sources and distribution networks.

The majority of new variables compared with the CLD were raised during D4 (Needs), and are more action orientated than the written variables forming part of the CLD. One of the main themes focused on the identification of the next research project on SWP (following from previous projects led by the NFGWS) 'you can identify in advance the next project' and considered the value of starting a pilot project to create baseline quality monitoring of what is already in the GWS areas '*you need to have a baseline for what happening at the minute to see if those measures are working or not*' and to reassess the effectiveness of SWP measures already implemented in the GWS areas '*facilitating a grant that would allow a reassessment of measures like a Phase 3* (SWP Pilot Project)'. Unlike the variable '*lack of education and public awareness*' that came up as a variable under D1 (Issues) on the CLD the theme of raising awareness from this discussion topic focused on increasing awareness among all GWS by widening out the reach of this project '*good to see this disseminated out to other groups*'. However, it was strongly suggested in order to get people's buy-in it would be better to talk about organic carbons being an issue in water and not to mention THM's '*research project is investigating carbons and organic carbons in water one of the big issues with organic carbons in water is that they build to inefficiencies in the plant and they can lead to complaints further downstream, what we'd like to do is do a presentation on some of the source water management systems and what you maybe can think about as an organisation to maybe help your plant to operate better and to think about doing things…*'**.** It was considered that this gentle method of raising the awareness among GWS members will empower them with the knowledge of issues in their area and the actions they can take to mitigate against them '*we have an understanding of what is happening on the site'*, '*that they can manage their source*', '*some direction on where they can make interventions and how they make interventions*.' There appeared to be a shift from a sense of helplessness *'..no clear vision..*' during the first discussion to a willingness to take control back expressed during the final discussion '*we can start actually managing that a little bit to make the plant more effective if we can make the plant more effective then we can get better operations off those operators if we can do that we can get better quality water out the other side'*.

Table 6. Summary of major themes grouped as variables within the four main discussion themes, based on the transcription of the open discussion. The highlighted variables in bold are additional variables that did not appear under the post-it variables under each discussion

D1. ISSUES	D2.BARRIERS	D3.SOLUTIONS	D4.NEEDS
Population growth	No education of what is possible	**NFGWS to be more involved on the ground**	**Quantitative**
Political problem	**Fear of being told what to do**	Land management	**To include data on alkalinity**
Lack of funding	**No-one in charge**	Preventative measures	**Identify next research project**
Negative impact of public awareness	**GWS personnel issues**	**Water supply project**	**Pilot stage**
Public health linkage	Conflicting messages	**Rationalisations**	Increase public awareness
Urban v Rural	**Contracts with water treatment companies not fit for purpose**	**Interconnections**	**Reassessment of measures already implemented**
Lack of accurate data		New/different/blending sources	**Recommend up to date distribution networks**
Intensive agriculture		Increase nutrient storage	**Disseminate information to all GWS**
Long pipe-runs		Increase awareness of possible interventions	
		Wetland pond	
		Pre-filtration stage	
		Pre reservoir	
		Sunlight UV breaks	
		Easier access to data	

4.6 Discussion of case study results

The aim of this study was to explore prior knowledge and stakeholder understanding of issues relating to DOM and source water quality, solutions to these issues, their perceived feasibility and the barriers to implementing these solutions. Our results from the causal loop assessments showed that *inadequate treatment plants* emerged as the main issue, *conflicting messages and policies* was the main barrier connecting to this issue and also a strong barrier to the main solution of *managed uplands*. In contrast the survey results suggest that *landowners close to the source water* are responsible for the water quality and *animal manure* and *pesticides* are the main factors impacting on the source water quality. The main barrier to implementing SWP measures is similar to the results in the focus group in that having no legal requirement to implement SWP measures was seen as a major issue. The results from the focus group also show how a *risk assessment tool* can help address the needs of the stakeholders by providing accessible data that will highlight spatial and temporal risks of DOM impacting on drinking water quality, and provide tools to mitigate and minimise these risks The results from the open discussion highlighted a shift from an initial focus on the treatment plant for solutions and a

feeling of helplessness by the participants to a realisation of the potential usefulness of SWP measures and a more proactive feeling by the final discussion.

4.6.1 Issues in relation to dissolved organic carbon and water quality

While there was a variety of issues mentioned by the participants during the C-phase, such as peat drainage, lack of monitoring and lack of SWP measures, the issues of population growth, climate change, public health implications and cost of treatment/lack of *investment* were the drivers of the main issue which were focused on problems with the *treatment plant*. This was reinforced during the first discussion by a GWS member who highlighted that the upgrade to water treatment plant which is due to begin construction shortly at their scheme, will be built to accommodate projected population growth over the next five years but not for the next 50 years. *P1: 'we're looking at a population of about 650 we're probably going to grow to well over 750 probably over the next 5 years now our plant is going to be sized to an approximate size to deal with that but if I took this over the next 50 years which is a more important length of time for us to be looking at these sort of infrastructure projects then you are talking about what does it really look like in 50 years' time we don't have that'…. 'no clear vision for me of how infrastructure is going to develop'.* This short-term thinking was seen to be leading to a lack of investment, especially in rural areas, resulting in water treatment plants which despite recent upgrades will not be fit for purpose in the relatively near future.

At the end of 2024 the Irish EPA and the Health Service Executive (public sector body responsible for health care in the country) issued a joint policy statement on THMs and HAAs in which they recommended 'optimising treatment for removal of organic matter and maintenance of distribution networks' as an approach to minimise DBPs in drinking water (EPA/HSE, 2024). Water treatment plant upgrades can be effective in reducing THMs to safe levels which often involves implementing advanced filtration techniques like Granular Activated Carbon (GAC) filtration (Çapar and Yetis, 2002), improving chemical dosing and pH control, and modifying the disinfection process through ultraviolet (UV) light (Jing et al., 2018) or replacing chlorination with chloramination (Guay, Rodriguez and Sérodes, 2005). The GWS Sector has received centralised funding to begin a process of upgrading several treatment plants which are recognised as having issues with DBP exceedances. This is funded by the Government through the Multi-Annual Rural Water Programme (MARWP) 2024-2026 an initiative in Ireland focused on improving water and wastewater services in rural areas where there are no public services. The EPA's remedial action list (RAL) identifies "at-risk" supplies that require improvements to safeguard public health. Uisce Éireann successfully reduced the number of RALs specifically for THMs from 25 in 2023 to 19 in 2024 by investing €65 million in plant upgrades as part of their National Disinfection Programme. However, these end of pipe solutions are costly and desired results are not always a guarantee. Using chloramination, for example, can reduce regulated DBPs but it can also increase certain N-DBPs (Bond et al., 2011). Uisce Éireann uses mono-chloramination, a process combining chlorine and ammonia, to

disinfect drinking water in areas with 'long pipe networks, high levels of THMs and raw water sources that are high in colour and organic material' (Uisce Éireann, 2023). It is virtually impossible to establish a single optimal configuration with operational conditions, economic and energy factors being site-specific (Meritxell Valenti-Quiroga et al., 2024).

The second most important issue that emerged in the C-phase was the *impact of climate change* especially in relation to the unpredictability of heavy rainfall. Climate change was mentioned at the beginning of the focus group leading to the overall feeling of helplessness that was expressed at the start of the day. Climate change can affect both water quality and water supply. Rising air temperatures and heatwaves can increase the temperatures of water bodies, especially lakes and wetlands (Feuchtmayr et al., 2009). These warmer temperatures can increase waterborne pathogens and cyanobacterial blooms (Paerl et al., 2011), and also enhance DOC production by stimulating microbial activities in OM decomposition (Fenner & Freeman, 2011). Severe drying of peatlands will cause accelerated peatlands decomposition, exacerbating the export of DOC and DOM in surface waters (Fenner & Freeman, 2011). In addition, climate models indicate there will be an increase in the frequency and duration of heavy rainfall events especially during autumn and winter in Ireland. Storm events with high rainfall can lead to untreated sewage entering surface waters and accelerated rates of erosion can increase the particulate material loading in surrounding water bodies resulting in increased DOM loading to rivers and lakes (Williamson et al., 2015). These high levels of OM can lead to substantial costs for water managers and mitigation of their effects will be a pressing need into the future. For example, the aftermath of Storm Éowyn in January 2025 caused a week-long power outage for one of the case-study GWS. At this time, the water managers had reduced the water storage in their reservoirs in order to mitigate against DBP formation which is often an issue at that time of the year. By reducing residence time and therefore reducing contact time between DOM and disinfectant it can be possible to reduce the risk of DBP formation compared to storing the treated water for longer periods in the reservoir before distribution. However, the power outage following Storm Éowyn, which lasted for just over a week, led to an issue for the treatment plant which could no longer pump water to replenish the reservoirs and consequently ran out of treated water, leaving consumers with neither water or electricity for an extended period of time. This case demonstrates how not only climate change is increasing the amount of DOC in raw water, but also the additional complexities which can arise in both the treatment and distribution of water hampering efforts to mitigate against THMs at the treatment plant.

Climate change was not included as an option on the list of fourteen factors impacting water quality on the survey. Animal manure and pesticides were considered to be a greater risk to drinking water quality than erosion, drained peatland and forestry based on survey results. This suggests that forestry and peatland are not perceived to be linked to water quality directly but are being linked to their impact on biodiversity and climate change. This is just one of several

knowledge gaps exposed from this research. Slurry-run is an issue that was raised in the focus group aligning with the survey response of *animal manure*. However, the fact that *nitrogen* and *phosphorus*, the main pollutant compounds in manure, did not receive the same level of importance (78% and 73%, respectively) as *animal manure* points to a knowledge gap amongst GWS members. This knowledge gap also extends to DBPs. While the majority of respondents (63%) were very or extremely familiar with the term trihalomethanes, haloacetic acids was the least familiar term among the participants of the survey. This suggests that they understand DBPs but only in terms of THMs and are not as aware of HAA. This is concerning given that new legal limits for HAAs will be added to the monitoring of drinking water in January 2026. However, this is only one of the approximately 100 DBPs that have been identified for their occurrence, formation, and quantitative analytical biological toxicity (Wagner and Plewa, 2017) out of a possible 700 DBPs identified to date (Richardson and Plewa, 2020). Unfortunately, many unregulated DBPs are more toxic than the regulated DBPs, for example, THMs, which are regulated, have a relatively lower toxicity than halonitromethanes which are not regulated (Kundu et al., 2004). Lack of understanding of raw water character and behaviour in treatment context came up as an issue in the focus group and public ignorance of the problem in the first place was raised as a barrier during the focus group.

4.6.2 Barriers to implementing solutions

The strongest barrier to SWP which emerged from the survey was considered to be that SWP implementation was not a legal requirement. This aligns with the issue of enforcement that came up in the focus group, in which it was emphasised that where legislation was in place, it was not effectively enforced. In addition, the focus group also highlighted the conflicting messages and policies coming from various governmental departments as a major issue, with advice to farmers coming from the Department of Agriculture often not aligned fully with the needs for sustainable water resource supply which falls under the remit of the Department of Housing, Local Government and Heritage, while water quality protection and implementation of the WFD is the responsibility of the Department of Environment, Climate and Communication. For example, policies on the expansion of agricultural production that conflict with policies to protect rural rivers and lakes from pollution by agricultural waste. The Common Agricultural Policy (CAP) (European Commission, 2023) and the Food Vision 2030 Strategy (Department of Agriculture, Food and the Marine, 2022) are key policy frameworks, but their implementation can lead to increased production and potentially higher environmental impact. The Agri-Climate Rural Environment Scheme (ACRES), part of Ireland's CAP Strategic Plan for the period 2023-2027, will financially compensate and reward farmers up to 52,500 euro over a 5-year period for undertaking any restoration work recommended by ACRES advisors that has improved biodiversity and/or water quality on their land. However, the CAP also provides income support to farmers based on land area, which can incentivise maximising production on available land, potentially leading to more intensive farming resulting in increased nutrient pollution, further degrading water quality. Under the EU Nitrates Directive,

farmers have to ensure that the total amount of nitrogen from organic manure applied to their land does not exceed 170kg per hectare per year. However, only 20% of survey respondents strongly agreed that implementing SWP measures is 'not a priority for policymakers' and the majority of survey respondents felt that 'landowners close to source water' were the most responsible for protecting source water, highlighting their view that responsibility lies with individuals compared with a view amongst the focus group participants that primary responsibility lies with central and local government, which is hampered by conflicting messaging and misaligned policies.

The barrier of 'conflicting messages and policies' is at the centre of many of the issues raised by the participants at the focus group e.g. 'climate change', 'treatment plant inadequate', 'enforcement', 'lack of SWP measures'. '*P1: "So we have the Department of Environment, Department of Agriculture, maybe a department of infrastructure and all of them are doing their own thing because they all have their own political agendas"*. Government policies aimed at ensuring quality drinking water can conflict due to differing priorities and responsibilities across various agencies and levels of government. Ireland is the only country left in the EU seeking to retain a nitrates derogation (Department of Agriculture, Food and the Marine, 2025), allowing them to farm at the higher stocking rates of up to a maximum of 220kg or 250kg per hectare per year. This is despite the EPA reporting in 2024 the levels of nitrogen in Irish water are still too high in the Southeast of the country (EPA, 2025). This is a region that, according to the CSO, accounts for the production of 19% of Irish milk with livestock generating 34% of the value of its Agricultural Output at Basic Prices in 2023

The cost of implementing the measures for landowners came up as a strong barrier in the survey and as a barrier in the focus group. There is a common perception among private landowners that the implementation and especially maintenance of SWP measures involve high costs (Sarabi et al., 2020; Campling et al., 2021). Yet, there are several studies showing that Nature Based Solutions are often cheaper than engineered solutions (Li et al., 2017). Generally, funding schemes are provided for short-term projects, payments to landowners may cover the initial cost of the implementation of a SWP measure but not the regular upkeep and maintenance of that measure. This creates future uncertainty and results in a reluctance to engage with source water protection projects.

Survey respondents did not see 'lack of time', 'small farm size' or a 'negative impact on productivity' as being strong barriers to implementing SWP measures and 39% disagreed with the belief that SWP measures would not improve water quality. This points to a willingness to accept the science and an openness to change with no resistance to the idea of implementing the measures. Therefore, the barriers of 'cost' and 'conflicting messages and policies' are the likely catalysts for the lack of co-operation and engagement which was identified as a barrier. 89% strongly agree or somewhat agree that 'cost' is a barrier to SWP measure implementation.

4.6.3 Possible solutions

The participants of the focus group identified 'Education of landowners to issues of DOM' as a solution to this barrier. This finding aligns with a study by Shahvi et al., (2021), which suggests that a positive influence on implementation of best management practices comes from keeping farmers' knowledge at a high point and a belief the measures which are implemented on the ground will work effectively and that the farmer has the potential to benefit from this outcome. Without the co-operation and engagement of landowners the main solution identified during the focus group of 'managed uplands' will be severely limited.

'Managed uplands' is an umbrella concept that encompasses a variety of potential SWP measures which were listed by the participants. Buffer strips and fencing are the most effective of these measures according to the survey respondents. When implemented, SWP measures could result in the identified solutions of 'peatland restoration', 'breaking flow paths to surface water', 'improved management of slurry spreading' and 'improved management of early forestry and deforestation stages'. These source protection strategies need to be tailored to the specific characteristics and challenges of the water source and the local environment. These solutions can only be implemented if landowners and farmers are willingly onboard and eager to get involved.

The survey results highlighted a lack of knowledge of the more specialised SWP measures for example, gully blocking, bank revetment, bioretention areas. This may be a combination of less commonly used SWP measures and perhaps the wording used to describe the measure for example 19% of respondents were not aware of riparian buffer zones but only 8% were not aware of buffer strips. Bioretention area may be more commonly known as a swale or bioswale to landowners. This highlights there is a real need for the popular incentive, with 85% of survey respondents agreeing that providing a training and guidance programme would be beneficial and aligns with the focus group which also viewed landowner education as important for improved implementation of SWP and response to the issue of DBP in drinking water.

The availability of grant aid for SWP was highlighted as an important solution to the barrier of cost. While there was no specific mention of grant schemes during the focus group, '*not enough long-term realistic payments to farmers for the restoration of nature*' was considered a barrier. In recent years in Ireland there has been a growing number of projects funded by the Irish Government and the EU such as Farming for water, ACRES and the Water European Innovation Partnership (EIP). Recently, the Department for Housing local Government and Heritage announced a third round of funding of almost €74 million for 291 individual capital projects across Ireland under the multi-annual Rural Water Programme 2024-2026. Yet the perception from landowners according to the survey is that they would like grant schemes to be made available to them to implement SWP measures. To examine this gap in detail would require

future research but one explanation is likely related to the barrier of conflicting governmental messages and policies identified by the focus group, with a multitude of different grant schemes of varying longevity being offered by various groups, using different eligibility criteria and having different payment schemes and purposes. This can be very overwhelming and confusing for landowners leading to a lack of engagement and a perception that there are no grant schemes that would be suitable for them.

Interestingly, peer pressure from friends, family and neighbouring farms was considered to be an important incentive for SWP implementation by 82% of the survey respondents. Previous studies have also found that social influence is a strong factor for landowners to take up measures (Sampson and Perry, 2018). Farmers from Hungary and the UK were found to be using farming social media as a key source of agricultural information and some were motivated to change their farming practices based on information received from digital farmer influencers and validated by their peers. Identifying farmer influencers will be critical for disseminating reliable and trustworthy agricultural information to ensure and accelerate the adoption of sustainable farming methods. This coincides with the need for increased public awareness which was highlighted in the focus group as a catalyst for peer pressure. Leveraging peer influence and working with known and trusted influencers, early on and throughout the knowledge exchange process could help policy makers and promoters of SWP measures share information more effectively with farmers (Breetz et al., 2005; Rust et al., 2021), which may result in greater uptake.

In the focus group the solution of 'managed uplands' seems to be in contrast to the main issue of 'inadequate treatment plants' which was raised. However, the effectiveness of water treatment plant upgrades in reducing THMs depends on the quality of the source water. This was acknowledged by one of the stakeholders during discussion 3 on solutions. *P7: "That's where your measures come in to try and maybe implement things on the ground that might prevent those spikes you know if its run-off coming in so it's kind of a mix of both is perfect."* It has also been acknowledged in many countries that inclusion of SWP measures can be considered an important part of their drinking water quality protection. For example, the EU's WFD mandates integrated water management including source protection and the EU recast Drinking Water Directive also includes provision for SWP. In addition, the US Safe Drinking Water Act and the WHO's Guidelines for Drinking-water Quality also include SWP provisions. As well as providing benefits to biodiversity, air quality and carbon sequestration SWP measures can reduce the costs of water treatment companies. The importance of continuously evaluating and adapting SWP strategies to address changing conditions and emerging threats to drinking water quality was also emphasised by forum participants.

4.6.4 Stakeholder needs going forward

The deployment of advanced monitoring tools and early warning systems, to track DOM impacts on drinking water quality are both a recommended preventive measure (Meritxell Valenti-Quiroga et al., 2024) and a welcome development by stakeholders. They highlighted their needs and requirements for this risk assessment tool to assess climate change impacts and help identify specific high risks factors within catchments. The focus group also highlighted the need for an advanced warning system with understandable tool outputs. Additionally, It was recognised that improved monitoring and prediction tools and access to accurate data will open further opportunities to lobby for funding from centralised government to mitigate against future risks to drinking water quality based (*P1: "…with the predictions that we have… we can at least start lobbying… to get the funding for that knowing it can take several years so we have some scope to do that in 10 years' time"*). The stakeholders recognise that sensor technologies and reliable data are essential to feed into the modelling workflow to forecast short-term changes in DOM in source water and longer-term simulations of projected changes in lake DOM concentrations related to climate change. Sensor technologies provide continuous and accurate data on key water parameters enabling real-time monitoring, early detection of contaminants, allowing for timely responses to potential threats and efficient water management (Aragón-Barroso, Ribes and Osorio, 2025). Automatic High Frequency Monitoring has been successfully used to assist water managers identify various land uses and human activities that have negatively impacted water quality and separately as a warning system for the development of algal blooms or additional pollution inputs from the catchment as a consequence of extreme weather events (Jennings et al., 2012; Marcé et al., 2016).

Perhaps the most interesting observation was the group's shifting perception from not being in a position to improve the situation at the beginning of the focus group (*P6: "…. the ship has sailed.. because those plans were put in place last December/ January so the plant has been built and specked"*), to being open to achievable action by the end of the focus group. This occurred as a result of the knowledge transfer between researchers and participants during the presentations and between the stakeholders themselves during the open discussions (*P1: "You've got us thinking about what we can do to control what is going into the plant and to take some measures around where we can do that we wouldn't have thought of that before"*). Research has found that discussions are more effective for changing behaviours than lectures (Lewin,1952; Werner, Sansone and Brown, 2008; Bandura, 1991). Individuals need to be invited to participate in devising their own solutions (Heiskanen et al., 2010). Participatory Action Research (PAR) focuses on understanding problems while solving them at the same time (van der Vlegel-Brouwer et al., 2023). The participatory qualitative phase of the KCP methodology was a successful method to encourage the engagement and exchange of knowledge that allowed the participants the space to focus on their decisions for action (Chiu, 2003). After successfully using PAR to gain insight in how prevention and health promotion could become successful in a deprived neighbourhood, van der Vlegel-Brouwer et al. (2023) recommended

PAR as a method which should be used at a policy level to align goals of different organisations collectively. This type of collaboration among various stakeholders is necessary to raise the awareness needed for effective action that will improve the quality of our drinking water (Hynds et al., 2013).

4.7 Conclusions of the case study

This study highlights useful insights into how stakeholders involved in drinking water management in Ireland perceive the issue of DOM and DBP formation in drinking water supplies. Principle issues identified concerned effective treatment plant infrastructure and operation. In addition, effective implementation of SWP measures were perceived as being obstructed by the lack of consistent Government policy and compounded by issues related to climate change and lack of knowledge amongst the public as well as landowners (Fig 21). This created a feeling of frustration and helplessness among the participants. However, through knowledge exchange and discussion as part of the participatory stakeholder focus group, there was a realisation of the important role of SWP as a potential additional solution to the management of water resources acting in combination with improved water treatment for effective mitigation against DBP formation.

The importance of long-term monitoring and the provision of data for early warning systems were identified as an important need amongst the water managers, in addition to a better modelling to predict the long-term risks of DOM in drinking water sources as a consequence of climate and land use changes. This will aid treatment plant operators to more effectively respond to specific risks of DBP formation and reduce their costs. In addition, it was also recognised that improved monitoring would also help to generate data on effective implementation of SWP measures which could provide an evidence base to aid government lobbying for improved funding and investment in SWP measures. Improved enforcement of current legislation was also seen as a priority, and the value of education in terms of improving the publics, landowners and water mangers knowledge was recognised as an aid to effective enforcement.

Overall SWP was recognised as an important additional measure for effectively addressing DBPs both as an outcome of the stakeholder forum and the survey. This aligns with a growing general recognition of the role of SWP in water resource protection with its inclusion in recent legislative provisions in Europe. However, currently the focus is still on upgrading water treatment plants as a solution to reduce DBPs in drinking water, with less direct and coherent mechanisms in place to drive SWP nationally. This study shows this may be owing to a lack of information on the issue and a lack of historical focus of DOM as a pollutant of concern for implementation of SWP measures. Active and participatory approaches to education and support in this area will encourage stakeholders to shift their perception from an end of pipe

only solution to a multi-barrier approach to reduce the overall risk of DBP contamination of drinking water.

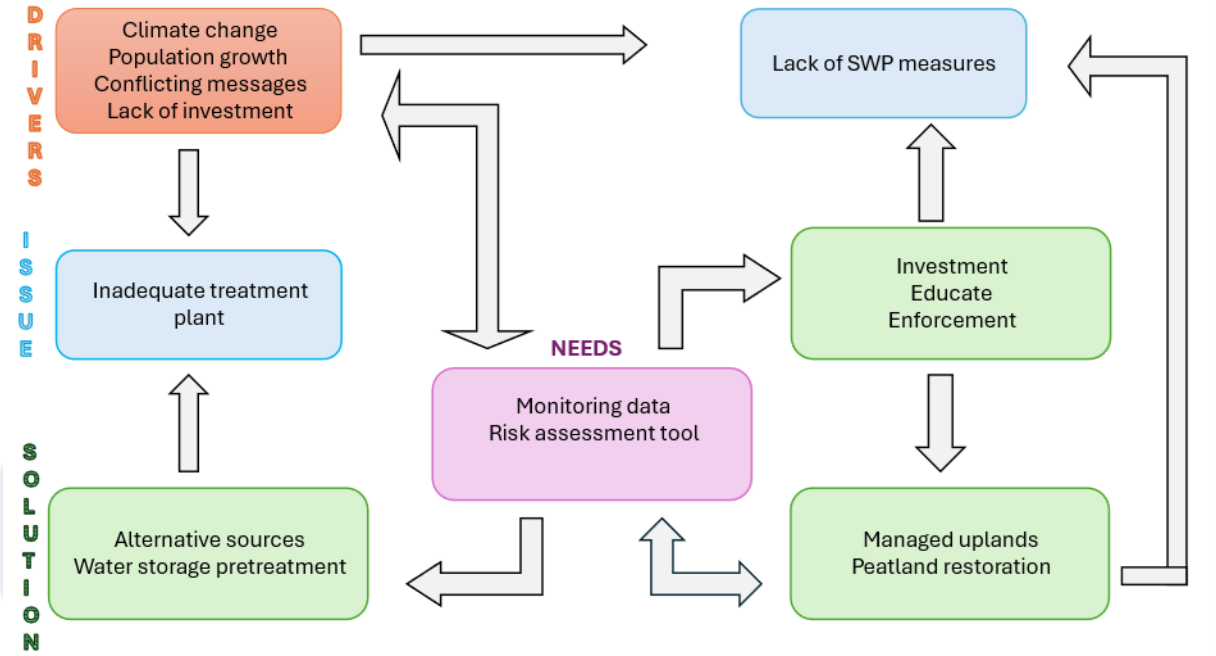


Figure 21. *Summary of the CLD showing links between the main drivers, issues, solutions and needs of the stakeholders present at the focus group.*

5.0 Feasibility and Potential for implementation of SWP for the mitigation of DOM: Case-Study Spain and Cyprus.

5.1 Introduction

In order to gain insight into SWP implementation in a wider European context, a combination of literature review and interviews were used to examine SWP implementation in Spain and Cyprus, both countries have case study sites involved in the intoDBP project and also have significant issues with DBP in drinking water supplies. In addition, owing to differences in climate, typology, land use activities and water treatment infrastructure and governance they also provide an interesting contrast to the Irish case study, both in terms of water governance and water quality and quantity issues and allow a broader consideration of the usefulness and feasibility of SWP measures for DOM reduction across different jurisdictions in Europe.

In Spain, the intoDBP case study involved two drinking water treatment plants, the Ter Drinking Water Treatment Plant in Barcelona and the Val mayor Drinking Water Treatment Plant in Madrid. The Ter Drinking Water Treatment Plant receives water from the Ter River catchment which has a series of three dams. It is managed by Ens d'Abastament d'Aigua Ter-Llobregat (ATL) and provides drinking water for the city of Barcelona and the metropolitan area. The plant has been operating since 1966 and has a capacity of 691,200 m^3/day. The Val mayor Drinking Water Treatment Plant, operating since 1976, receives water from the Val mayor Reservoir and has a capacity of 1,036,800 m^3/day. It is the second biggest drinking water treatment plant in Spain and is managed by Canal de Isabel II. The case study site in Cyprus consists of the Water Distribution Network of Limassol and Limassol Drinking Water Plant. The Water Distribution Network of Limassol is managed by the Water Board of Limassol. The system serves 115,000 consumers, and the annual average water demand is estimated to be 17 million m^3. The network includes 31 water tanks, 37 pumping stations and approximately 1,150 km of pipes with 100 km of transport pipes and 1,100 km of distribution pipes. The Limassol Drinking Water Plant is managed by the Water Development Department. The plant has been operating since 1994 and its capacity is 80.000 m^3/day. It receives water from the Kouris reservoir and upon treatment, it supplies clean water to the city of Limassol, villages west of Limassol, and the British Base of Akrotiri. As with the case study in Ireland, this section will consider the issues at a broader national and regional scale for each of the case study sites reporting on wider perspectives from both Spain and Cyprus.

Information on water governance, catchment management practices and SWP implementation for both Spain and Cyprus were summarised based on a desk-based review of the literature. In addition, interviews with stakeholders representing the Water Development Department in Cyprus were conducted to provide a practice based insight into the issues raised in the

literature review. This provided an understanding of the stakeholders' knowledge of DOM and their experience of implementing source protection or nature based solutions for mitigation and restoration of freshwater in their own country.

5.2 Cyprus

In Cyprus, the Water Development Department (WDD) under The Ministry of Agriculture, Rural Development and Environment is responsible for the protection, sustainable development, and management of the country's water resources. This includes the planning, construction, operation, and maintenance of water infrastructure like dams, irrigation and water supply networks, desalination plants, and sewage and water treatment plants. The protection of waters from pollution is driven by national legislation (Law for Water Pollution Control, 1991), which was introduced as part of the broader environmental legislation of the island. The department handles water allocation and rationing, implements flood risk management plans, and ensures the safety and quality of water infrastructure. The WDD also sells water through the Governmental Water Supply Systems (GWSS), of which there are currently four (Nicosia, Limassol, Larnaca/Famagusta and Paphos) that supply drinking water to local water supply authorities, municipalities which in turn distribute water to the consumers of their areas through their own distribution networks (Fig. 22). The WDD manages these systems and determines the prices for this water supply.



Figure 22. *Location of main dams in Cyprus and the major water works that have been happening in Cyprus (Source: Water Development Department, 2014)*

The Ministry of Health is involved in the implementation of legislation related to drinking water, which is harmonized with the European Directive 98/83/EC and its amendments. It manages, through its Public Health Services, an annual national control program to monitor drinking water quality. This includes monitoring for THMs and HAAs, lead, pesticides, nitrates, nitrites, ammonium, and TOC. While the WDD focuses on the ecological health of all water bodies in Cyprus according to the EU's WFD (DITS 2018).

In Cyprus the WFD is implemented under the Water Protection and Management Law 2004 (Law 13 (I)/2004). Cyprus has developed a series of River Basin Management Plans, with the 3rd River Basin Management Plan covering the period 2023–2027. A key focus is the sustainable provision of clean drinking water, with a view toward developing a Drinking Water Safety Plan approach. The measures within the River Basin Management plan consist of a mix of mandatory EU requirements such as ensuring compliance with several related EU directives, such as the Nitrates Directive (91/676/EEC) and the Urban Wastewater Treatment Directive (EU 2024/3019) and supplementary, locally tailored actions such as hydromorphological rehabilitation, integrated catchment management and addressing agricultural pressures. The main agriculture in Cyprus includes crops like potatoes, citrus fruits, grapes, and olives. Livestock, particularly sheep and goats, is also a significant part of the sector, producing dairy products like Halloumi cheese (Fig. 23). The provisions of the Code of Good Agricultural Practice are applied through the island, i.e. control of fertiliser use, use of improved irrigation systems and preparation of irrigation schedules, relocation (wherever is possible) of animal husbandry units, slurry collection, mechanical separation and land application of piggery waste, on-going farmer training programmes. While historically, subsidies in Cyprus have prioritised increasing productivity and competitiveness in the agricultural sector (Markou et al., 2005), EU policy reforms are introducing new funding for sustainable practices through "eco-schemes" and increased environmental obligations for farmers (European Commission 2022). The government provides financial incentives and training to encourage the adoption of more efficient irrigation systems (e.g., moving to drip irrigation from traditional methods) and other environmentally friendly practices, such as maintaining ground vegetation under tree crops to reduce soil erosion, and using protective nets or grafted seedlings to reduce the need for pesticides. The life project– AgrOassis promotes soil improvement through reduced tillage and mulching. It has successfully completed planting over 3,200 deep-rooted trees and shrubs, creating 7.6 km of hedgerows to combat desertification in Cyprus. The project is ongoing, with a goal to plant 18,000 trees and shrubs by 2026 (LIFE AgrOassis, 2024).

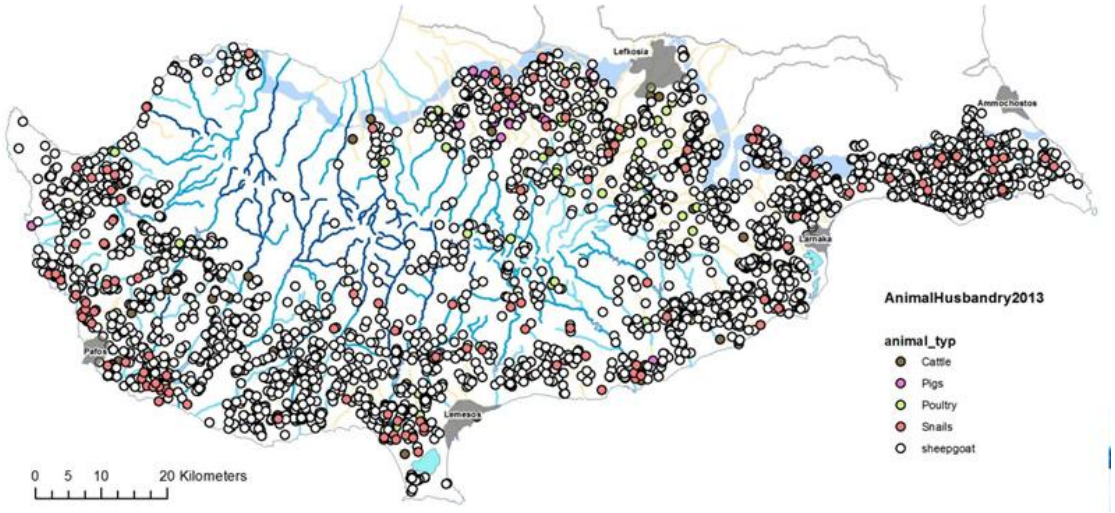


Figure 23. *Distribution of livestock in Cyprus highlighting the large number of sheep and goats farmed in Cyprus. (Source: Water Development Department (2013)*

5.2.1 Source Water Protection in Cyprus

Studies show that forests and semi-natural areas make up the majority of the catchment land use for most of Cyprus' reservoirs, typically greater than 55%. As such there are a number of measures which are taken in the catchment which focus specifically on issues related to this landcover. For example, to mitigate against sediment and pollutant runoff from logging operations Cyprus has specific forestry standards that include measures like maintaining a setback width from streams during reforestation and setting up exclusion zones during felling to prevent bank erosion. The standards also require the use of silt traps in forest drains, creation of native woodland buffers, and careful application of fertilizers. The national forest policy prioritises objectives related to water conservation, which guides management decisions and helps protect water resources (Plevri, 2019). Cyprus is experiencing an increase in wildfires due to climate change. The last major wildfire in Cyprus started in mountainous terrain North of Limassol and the island's largest reservoir, the Kouris Dam. The fire burned through a significant portion of the area, destroying homes and killing two people as it spread towards the dam.

Cyprus experiences the highest level of water stress among European Union (EU) countries due to several factors such as rainfall variability and increasing water demand. Most of the rivers in Cyprus rise from the Troodos area. However, due to the rising temperatures and lower precipitation rates caused by climate change only the sections of some rivers found upstream in the Troodos area have a constant flow (Xeros, Dhiarizos, Kargotis Marathasas, Kouris and Germasogeia rivers). According to the Cyprus WDD, evaporation accounts for nearly 90% of annual precipitation loss. Tourism is also a very important sector in Cyprus, as a consequence Cyprus can experience extreme short-term variation in population at certain times of the year. For example, the population of approximately 1 million in Cyprus increased by 602,026 in

August 2025 as a result of an increasing tourist industry. This increasing demand on water resources is resulting in water scarcity. In response to this, seawater desalination plants were introduced in 1997 and the country started using recycled water in 1998 for irrigation of agricultural crops and green areas, in accordance with good agricultural practices for the use of recycled water (Kathijotes and Panayiotou, 2013). Desalination plants supply almost 50% of domestic water. To increase the storage capacity of its freshwater Cyprus has constructed 108 dams, the most dams of any EU country (Sofroniou and Bishop, 2014). The Cyprus WDD takes samples in every dam to ensure the raw water meets the required abstraction standards before passing to one of the five water treatment plants. Four years of consecutive drought from 2004 saw reservoir reserves dry out in Cyprus. As an emergency measure in 2008, water had to be transported from Greece at a cost of over 40 million euros. For a resilient future Cyprus is taking steps to invest in measures that will improve its soil quality, invest in reforestation and educate its population on the long-term benefits of Nature Based Solutions to improve its water retaining capacity. As well as investing over €140 million of the 2026 budget to the procurement of desalinated water, the Government approved a package of measures totalling €5.25 million aimed at reducing wildfire hazards, and the implementation of controlled grazing in areas susceptible to wildfire risks and stimulating agricultural activity by offering incentives to rehabilitate neglected or abandoned agricultural land. This two-pronged approach aims to secure both the present and future of Cyprus's water resources and agricultural potential.

Consequently, SWP in Cyprus is often focused on water conservation or mitigation against wildfire and drought. Mitigation measures for example for restoring degraded or burnt agricultural land include installation of drought resilient hedgerows, which will combat desertification but will also reduce soil erosion. Soil improvement by mulching and minimum or no-tillage are also beneficial to DBP mitigation. Nevertheless, the long-term focus on desalination will likely reduce dependency on surface water and groundwater sources and consequently, SWP may be less important in the overall management of DBP formation in drinking water.

5.3 Spain

Approximately 74% of the water in Spain is sourced from surface water, 19% comes from groundwater and 7% from springs and desalination processes. Spain has 25 river basin districts for WFD implementation, eight of which are part of international river basin districts: Portugal (Miño-Sil, Duero, Tajo and Guadiana), with France (Eastern Cantabria, Ebro), with Andorra (Ebro) and Morocco (Ceuta and Melilla) (BIGDATA4RIVERS, 2023). The four largest river basins in Spain are Ebro, Segura, Guadalquivir and Tagus which account for more than 50% of Spanish territory. 78% of Spain's water consumption is used by Agriculture with confined livestock farming prevalent in areas such as northern Spain. Agriculture and wastewater effluent have been found to be important drivers of nitrogen-related parameters in water, whereas drought conditions were identified as a driver of DBP non-compliance (Andries et al. 2025). The central

government in Spain is responsible for water management through one of its ministries (Ministry of Ecological Transition and Demographic Challenge), the Ministries actions are implemented by nine river basin authorities. However, regional governments are responsible for managing urban polling, agriculture and natural heritage and this complex administrative organisation require significant coordination and has led to inefficiencies and conflicts between regions (Sanchis-Ibor et al., 2022).

Spain's water policy has traditionally largely been driven by hydropower and the need for irrigation in the agricultural sectors (Fornés et al., 2020). Instead of focusing on sustainable water use, past approaches often relied on short-term fixes like large-scale water transfers from other basins, which created new problems in the recipient basins and didn't solve the underlying issues. This has resulted in Spain having to implement emergency measures to tackle the effects of climate change. However, a change in Spain's approach became evident in the early 1990s in which the principle of integrated water resource management by water professionals was adopted. Catchment protection zones were already outlined in Spanish water law (La Ley de Aguas) in 1985 prior to WFD implementation, but were revised in 2001 in order to transpose the WFD into National legislation. The success of Spain's river basin plans is mixed, the restored health of rivers like the Segura has allowed for the return of flora and fauna, with projects including the restoration of wetlands and the creation of new public uses and recreational activities. However, half of Spain's water bodies are not in 'good' WFD status today and are not likely to achieve this status by 2027 (Garcia, 2024).

Spain protects its drinking water supply through the Royal Decree 3/2023, which implements the Drinking Water Directive and takes a risk-based approach to water management. The regional, local and central administrations are in charge of managing water quality within the nine river basin authorities or Hydrographic Confederations whose main role is the protection and sustainable use of water. The population is supplied by both private or mixed private-public water companies with work under contract with municipalities, but most of the large cities are serviced by public companies. The National Water Council is the highest national advisory body for water in Spain. By 1990, Spain had constructed more than 1,000 dams with the ability to store approximately 50% of its total natural runoff. However, the average water levels of Catalonia's reservoirs were down to 14% on March 8, 2024. Consequently, water availability in addition to water quality issues are a concern in Spain with climate models predicting a decrease of the water supply of up to 25% in the coming years. All Spanish river basins experience a certain degree of water stress, with some areas for example the Segura which has experienced significant pressure in recent years despite transfers from other basins or the use of desalination.

In recent years water policy has become more decentralised and inclusive, largely driven by the principles of the WFD. In 2022 Spain announced they will be investing up to 29 billion euro as

part of their third River Basin Management Plans (2022-2027) and an estimated investment of 2.5 billion euro into restoring 3,000 kilometres of rivers between 2022 and 2030 (Zarza et. al, 2022). Citizen action is seen as an integral component of good water management in Spain, which can help balance between what is socially or economically viable and technically and environmentally sustainable (Fornés et al., 2020). Similar to Cyprus, there are a range of measures which are focused on fire management, both in prevention and remediation which can be of some relevance to DOM reduction. Strategies can range from emergency stabilisation to rehabilitation and Restoration (Robichaud et al., 2020). The aim of these methods is to reduce runoff and associated processes such as sediment loading. Strategies include log erosion barriers, contour felled log debris, mulching and use of grass seeding on hillslopes (Fernandez et al., 2016), have potential to also mitigate against DOM. The wider rehabilitation efforts which include afforestation are also important, but are dependent on the types and location of species used in these methods (Vallejo and Alloza, 2012).

***Spain - Case study* (Almagro et al., 2013)**
Location: Murcia Region, South East Spain.
Measure: To assess the effects of different tillage treatments (conventional, reduced, reduced tillage combined with green manure (leguminous species cover crops), and no tillage) on soil structure and soil water content, runoff and erosion control. Under reduced tillage and reduced tillage combined with green manure fields were ploughed using a cultivator to 0.15 m depth twice a year (spring and autumn). The green manure used was a mix of barley or common oat and common vetch in 1:3 proportion at 150 kg ha−1 , manually sown during early fall and incorporated into the soil by ploughing with a chisel plough in May. Under no tillage (NT) treatment, the weeds are manually cut off in May and left on the soil surface
Result: Soil organic carbon concentration at the plough layer (0–15 cm depth) was about 1.5 times higher in both reduced tillage and reduced tillage combined with green manure. The incorporation of green manure resulted in about 26 % more carbon in soil than under reduced tillage and 18% more under no-tillage. Conventional tillage displayed three times more total erosion than reduced or reduced tillage combined with green manure. This led to higher amounts of organic C mobilized by erosion in conventional tillage.

6.0 Conclusion and Recommendations

Despite recognition of the importance of source water protection as a management tool for the provision of safe drinking water, there has been very little focus on SWP as a means to mitigate and manage DOM precursors to DBP formation in treated drinking water. This is owing to a combination of factors, including a primary focus on updates to water treatment infrastructure and improved treatment technologies, but additionally, there is a lack of research demonstrating the effectiveness of SWP measures in reducing DOM loading to drinking water treatment plants. This is particularly challenging, as the complex processes involved in determining not only the quantity of DOM produced within a catchment, but additionally the characteristics, with changes for example in molecular weight and aromaticity having the capacity to differently impact drinking water quality, with each having variable responses to a wide range of physical, biological and chemical processes at play both within the catchment, in the lake/reservoirs and additionally in response to the range of disinfectants and treatment processes in the treatment plants themselves. Nevertheless, DOMs low profile in the context of SWP and catchment management is in contrast to the prominent role of carbon cycling in determining ecosystem structure and function in freshwater systems. Consequently, understanding how human activities alter natural OC regimes and the ecological consequences of these changes in streams and rivers in human-dominated landscapes should be considered to be an important part of an overall approach to the long-term management and sustainability of water resources.

In this study, five principal land use types were identified as being particularly important with regards DOC production; forestry, peatland, agricultural, lakes/reservoirs, and wastewater treatment and within each of these categories a range of biogeochemical processes and land management and land use practices were identified as likely to lead to increased DOM concentration as well as changes in DOM characteristics which could be more problematic in terms of DBP formation. A range of SWP measures to mitigate against these risks were proposed, with many of them, such as buffer strips, improved riparian management and livestock exclusion from watercourses having well established implementation history and demonstrated effectiveness in the mitigation of a range of other pollutants such as nutrients and pesticides. Where available, some evidence of the effectiveness of these measures for DOM mitigation was provided, but much of this evidence was sporadic and sometimes contradictory. It is, therefore, important that this knowledge gap is addressed in order to more effectively consider SWP for DOM and DBP mitigation in drinking water going forward. This is even more salient given that the issues with DOM are not only about the quantity of DOM in the source water but also its chemical characteristics, which can potentially be altered both by treatment processes in the water treatment plants but also as a consequence of the SWP measure being taken. On the other hand it is also likely that many SWP measures which are

known to address organic pollution such as that arising from animal manure or soil erosion, are likely to also have some effect on DOM. As these measures are already being implemented in many places, the inclusion of DOM as an additional pollutant of concern should, therefore, be relatively straightforward. In addition, as issues with DBPs in drinking water are often linked to algal production in lakes and reservoirs, any measure which addresses nutrient input to reduce the occurrence of algal blooms, also has potential to reduce DBP risks. However, in this case additional monitoring information on the types of algae leading to bloom formation is also needed in order to fully understand the associated risk of DBP formation.

Following consultation with stakeholders in Ireland, it was found that despite an initial focus on issues in the treatment plant, there was a move toward recognition of the potential usefulness of SWP measures, with a particular focus on issues in upland areas. It was also recognised that some measures are already widely in use such as peatland rewetting and riparian buffer strips and that reduction in DOM could be an added benefit of such measures. However, there was a recognition that one of the key challenges for the effective implementation of SWP measures in Ireland was the lack of consistent government policy and lack of enforcement of current legislation. On the other hand, these governance issues were not prominent in Cyprus where water governance was less diffuse across numerous governmental departments and with SWP, particularly in a water stressed country such as Cyprus, largely concerned with water quantity issues, particularly with regards measures which enhance water storage and soil health. Nevertheless, as was the case in Ireland, despite the proposed measures being implemented to address issues other than DOM, measures such as silt traps in forest drains or the creation of native woodland buffers have some potential to mitigate against DOC. However, given the critical issues relating to water scarcity, measures focused on water supply and the use of additional technologies such as desalination are likely to become more important for the supply of drinking water. Consequently, mitigation against DBP formation in these circumstances will be less clearly mitigated through DOM reduction.

A common issue across all jurisdictions was climate change. For Spain and Cyprus, these were directly related to issues with regards water availability and drought. In Ireland the biggest concerns were related to extreme weather events which can be associated with increased rainfall which has the potential to increase DOM inputs from the catchment. In addition, there is an infrastructural risk from extreme storm and wind events in which for example electrical line damage has hampered treatment plant operation. These issues will increase the complexity of SWP mitigation by impacting biogeochemical processing of DOM but additionally will impact allocation of resources with increasing pressure placed on reactionary responses to water quality exceedances and infrastructural maintenance.

The importance of long-term monitoring and the provision of data for early warning systems were identified as an important need amongst the water managers, in addition to a better

modelling tool for the prediction of long-term risks of DOM in drinking water sources as a consequence of climate and land use changes. This in combination with improved education and enforcement of current legislation will improve understanding and encourage stakeholders to shift their perception from an end of pipe only solution to a multi-barrier approach to reduce the overall risk of DBP contamination of drinking water.

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APPENDIX A

CATEGORY	VARIABLE	VOTES	CLD GROUP VARIABLE
D1 ISSUE	Increased demand due to population growth	0	Population growth
	Seasonal changes in water quality	0	Seasonal changes in water quality
	Impact of climate change	1	Climate change
	Variability of rainfall	0	
	Climate change and unpredictability of rainfall	3	
	Increase soil erosion due to heavy rainfall and human activities	0	
	Changing climate	3	
	Weather events	0	
	Rural v Urban scheme priority	0	Rural v Urban scheme priority
	Available investment for treatment	0	Available investment for treatment
	Removal of DOM at the treatment plant to avoid secondary chlorination in the network	0	Inadequate treatment plant
	Settlement tank pretreatment tank to remove organic material	1	
	Filter water within lake sources prior to delivery to treatment plant. Lake is too large a source not to apply prior filtration to plants too many inputs to lake, heat rainfall dust etc.	1	
	Operating efficiency of plant	1	
	Length of distribution	0	
	Aging infrastructure not fit for purpose	4	
	High surface water dependence	0	High surface water dependence
	Difficulty in pin pointing when water quality will decrease	1	Lack of monitoring and prediction capabilities
	Monitor catchment area	1	
	Inability to effectively manage the changes	0	
	Unknown DBPs	2	
	Educate	1	Lack of education and public awareness
	Increased public awareness of health issue	5	
	Lack of understanding of raw water character and behaviour in treatment context	3	
	Public understanding most people not aware of issues Lack of knowledge on agricultural organic matter	0	
	Legislation	0	Enforcement
	Enforcement	0	

	Source protection measures not being implemented leading to further pressures down the road	5	
	Public health implications Potential health implications to humans where the waterbody is a source for drinking water Clarifying human health effects	2 0 0	Public health implications
	Intensification of farming on peat soils in marginal areas Peat drainage Peat soils for farming Peat extraction Drainage of peat soils for farming	1 2 0 0 1	Peat drainage
	Planting of conifer trees on peat soils	1	Conifer forestry
	For construction of windfarms through peat	0	Windfarms on peatland
	Run-off of slurry on poorly drained soils Run-off	0 0	Slurry run-off
D2 BARRIER	Lack of awareness Public ignorance of a problem in the first place Lack of awareness of the issues of activities that will impact water quality Getting information out there Public knowledge of effects of any source protection measure Knowledge dissemination	1 3 0 0 1 1	Lack of public knowledge
	Land rights / access rights Cartel purchasing land v state Lack of space at plant to add additional pre plant treatment	1 0 0	Land access rights and availability
	Conflicting messages Public/landowners need a clear strategy from Ireland's Government with regards to the goals they are trying to achieve Complex issue at Local Authority or Government level Lack of visibility of the full picture of inputs Conflicting policy and government department working in isolation from one another	2 0 1 0 0	Conflicting messaging and policies
	Farmer cooperation and intensification Mindset for landowners to change way of working Stakeholder engagement and implementation	3 3 3	Farmer co-operation and engagement

	Lack of investment Financial Money Finances Cost of implementation of measures for the landowners Intensive agriculture and not enough long term realistic payments to farmers for the restoration of nature	2 0 0 0 2 0	Cost of implementation
D3 SOLUTION	Traps on inlet drains Managing water levels on peatland Peatland restoration Drain blocking/rewetting Raising water table in peat soils	1 1 2 3 2	Peatland restoration
	Store water before treatment Pre filtration capability ahead of plant in the source water	2 2	Water storage before treatment
	More conservation and protection of aquatic species who naturally regulate the waterbody (including flora)	0	Protection of water regulating aquatic species
	Ensure vegetative cover in lands surrounding water body	1	Vegetative cover
	Blocking or breaking flow paths to surface water Bankside storage	1 1	Breaking flow paths
	Sensors in lakes	3	Sensors in lakes
	Wetlands knowledge to public Education Education of landowners to issues of DOM	0 2 2	Education
	Managed uplands	1	Managed uplands
	Improved management of slurry spreading	0	Improved management of slurry spreading
	Forestry improved management of early and deforestation stages	0	Improved management of forestry
	Alternative sources	1	Alternative sources
D4 NEEDS	Data for model from the scheme not the contractor Feasible data requirements low or zero cost Accessible in cloud	2 4 0	Low or no cost accessible data
	List of measures for catchment Produce a list of measures targeted specific for the catchment	3 0	List of targeted measures for catchment
	Likelihood of development in / around the source area in the next 1-5 years	1	Information on future developments near source
	Climate change impacts	1	Not shown on CLD for D4 as listed under D1.
	Training for managers	0	Training for managers
	Advanced warning system Water treatment needs risk assessment tool	2 1 1	Risk assessment tool

	Understandable tool outputs		
	Highlight specific aspects that are higher risks within catchments	2	Highlighting land use risks and how to minimize risks
	Produce a leaflet and highlight high risk times of the year for DOC and how to minimize risk	2	Highlight temporal risks and how to minimize risks

APPENDIX B

SURVEY

PLAIN LANGUAGE STATEMENT

Principle Researcher: Dr. Valerie McCarthy, School of History and Geography, DCU. Email: valerie.mccarthy@dcu.ie

Researcher: Katherine Molloy, BA in Climate and Environmental Sustainability DCU. Email: Katherine.Molloy@dcu.ie

What is the project?

The intoDBP research project, funded by the European Union aims to develop, test, scale-up, validate and benchmark innovative tools and strategies to protect catchments and minimize human exposure to disinfection by-products (DBP) under current and future climates, without compromising disinfection efficacy. The intoDBP project will support source protection measures in Ireland and elsewhere in Europe by focusing particularly on benefits related to the reduction of DOC, which has received less of a focus to date.

What will I have to do?

You are being asked to participate in an online survey. This survey will help us gain an understanding of what stakeholders knowledge of water quality and source water protection measures (SWP), their feasibility, cost and barriers to implementation. The information will be used to feed into the development of a risk assessment methodology to inform decision makers on potential solutions to protect drinking water quality. The survey should take approx. 15 mins to complete.

What data will DCU be collecting?

All information on this survey will be anonymous and no identifiable data will be requested. Outputs of the project will be published in peer reviewed scientific papers and made available through project reports and summarized on the project website (https://intodbp.eu/). Data may also be subject to legal limitations. All data being collected is compliant with GDPR legislation and will be stored in an appropriately secured DCU Google Drive folder on a password-protected computer. All data will be destroyed at the end of the project. If you are concerned about how your personal data is being used, you can contact Dr. Valerie McCarthy (valerie.mccarthy@dcu.ie). You have the right to lodge a complaint with the Irish Data Protection Commission.

Participation

All participation is voluntary. You can choose to withdraw from the study up to the point of submitting your data. Withdrawal after this point will not be possible as we will not be able to identify which

submission is yours due to the anonymity of the study. If participants have concerns about this study and wish to contact an independent person, please contact The Secretary, Dublin City University Research Ethics Committee, c/o Research and Innovation Support, Dublin City University, Dublin 9. Tel 01-7008000, e-mail rec@dcu.ie

INFORMED CONSENT FORM

By submitting this form, you are indicating that you have

- Read the description of the study
- Are over the age of 18
- That you agree to the terms as described in the plain language statement.

Please turn over page to start survey. Thank you.

Q1. What is your county of residence

Q1 (b) Write where your closest town/city is in the box below

_____

Q2. Select what is the principal land type in your area

- ○ Cultivated land
- ○ Forestry
- ○ Peatland
- ○ Grassland
- ○ Artificial surfaces
- ○ Wetland

- ○ Heath and Bracken
- ○ Not sure

Q3. Select from list below which best describes you. You can select more than one option if applicable

- ☐ Agricultural advisor
- ☐ Group Water Scheme Member
- ☐ Policy maker
- ☐ Representative of a farmers organization
- ☐ Water utility practitioner

Q5. Do you live or farm adjacent to one or more of the following bodies of water

- ☐ Lake
- ☐ River
- ☐ Stream
- ☐ None

Q5(b) How would you rate the quality of this waterbody? Circle the number most relevant between 0-100.

Extremely bad	Somewhat bad	Neither good nor bad	Somewhat good	Extremely good
0 10	20 30	40 50 60	70 80	90 100

Q5 (c) If you live adjacent to a water body, is it a source of drinking water?

- ○ Yes
- ○ No
- ○ Don't know

Q6. Rate how important you think each of these factors are in impacting drinking source water quality

	Not at all important	Slightly important	Moderately important	Very important	I don't know
Altered water flow	○	○	○	○	○
Animal manure	○	○	○	○	○
Forestry	○	○	○	○	○
Drained peatland	○	○	○	○	○
Erosion	○	○	○	○	○

Heather burning	○	○	○	○	○
Industrial waste	○	○	○	○	○
Nitrogen	○	○	○	○	○
Pesticides	○	○	○	○	○
Phosphorus	○	○	○	○	○
Septic tanks	○	○	○	○	○
Sediment	○	○	○	○	○
Organic matter	○	○	○	○	○
Pathogens	○	○	○	○	○

Q7. How familiar are you with the terms below and their risk to drinking water

	Not familiar at all	Slightly familiar	Moderately familiar	Very familiar	Extremely familiar

Dissolved Organic Carbon (DOC) / Dissolved Organic Matter (DOM)	○	○	○	○	○
Trihalomethanes (THM's)	○	○	○	○	○
Disinfectant by-products (DBP's)	○	○	○	○	○
Haloacetic acids (HAAs)	○	○	○	○	○

Q8. Who do you think is responsible for protecting Source Water. Rank them order of importance 1 being the most responsible and 7 being the least responsible

_____ EPA

_____ Farmers

_____ Local community

_____ Local authorities

_____ Private businesses

_____ Uisce Éireann

_____ Water treatment plants

_____ GWS

_____ Landowners close to source water

Q9. How would you rate the overall effectiveness of the following source water protection measures at improving source water quality

Q10. For each of the factors listed, select to what extent you agree or disagree that it is a barrier to implementing Source Water protection measures.

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
Negative impact on productivity	○	○	○	○	○
Cost	○	○	○	○	○
Lack of time	○	○	○	○	○
Measure is not a legal requirement	○	○	○	○	○
Not a priority for landowner	○	○	○	○	○
Small farm size	○	○	○	○	○
No training or guidance given	○	○	○	○	○

Landowner is not prepared to maintain measure into the future	○	○	○	○	○
Belief that measures will not improve water quality	○	○	○	○	○
Not a priority for policymakers	○	○	○	○	○

Q11.Select to what extent you agree or disagree that the following will incentivise landowners to implement Source Water Protection Measures

Please include any further feedback that you think would be useful to this project here.

Thank you

_____

_____

_____



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